Landmark Visualization on Mobile Maps – Effects on Visual Attention, Spatial Learning, and Cognitive Load during Map-Aided Real-World Navigation of Pedestrians

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Landmark Visualization on Mobile Maps – Effects on Visual Attention, Spatial Learning, and Cognitive Load during Map-Aided Real-World Navigation of Pedestrians

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Abstract

Even though they are day-to-day activities, humans find navigation and wayfinding to be cognitively challenging. To facilitate their everyday mobility, humans increasingly rely on ubiquitous mobile maps as navigation aids. However, the over-reliance on and habitual use of omnipresent navigation aids deteriorate humans' short-term ability to learn new information about their surroundings and induces a long-term decline in spatial skills. This deterioration in spatial learning is attributed to the fact that these aids capture users' attention and cause them to enter a passive navigation mode. Another factor that limits spatial learning during map-aided navigation is the lack of salient landmark information on mobile maps.

Prior research has already demonstrated that wayfinders rely on landmarks—geographic features that stand out from their surroundings—to facilitate navigation and build a spatial representation of the environments they traverse. Landmarks serve as anchor points and help wayfinders to visually match the spatial information depicted on the mobile map with the information collected during the active exploration of the environment. Considering the acknowledged significance of landmarks for human wayfinding due to their visibility and saliency, this thesis investigates an open research question: how to graphically communicate landmarks on mobile map aids to cue wayfinders' allocation of attentional resources to these task-relevant environmental features. From a cartographic design perspective, landmarks can be depicted on mobile map aids on a graphical continuum ranging from abstract 2D text labels to realistic 3D buildings with high visual fidelity. Based on the importance of landmarks for human wayfinding and the rich cartographic body of research concerning their depiction on mobile maps, this thesis investigated how various landmark visualization styles affect the navigation process of two user groups (expert and general wayfinders) in different navigation use contexts (emergency and general navigation tasks). Specifically, I conducted two real-world map-aided navigation studies to assess the

influence of various landmark visualization styles on wayfinders' navigation performance, spatial learning, allocation of visual attention, and cognitive load.

In Study I, I investigated how depicting landmarks as abstract 2D building footprints or realistic 3D buildings on the mobile map affected expert wayfinders' navigation performance, visual attention, spatial learning, and cognitive load during an emergency navigation task. I asked expert navigators recruited from the Swiss Armed Forces to follow a predefined route using a mobile map depicting landmarks as either abstract 2D building footprints or realistic 3D buildings and to identify the depicted task-relevant landmarks in the environment. I recorded the experts' gaze behavior with a mobile eye-tracer and their cognitive load with EEG during the navigation task, and I captured their incidental spatial learning at the end of the task. The wayfinding experts' exhibited high navigation performance and low cognitive load during the map-aided navigation task regardless of the landmark visualization style. Their gaze behavior revealed that wayfinding experts navigating with realistic 3D landmarks focused more on the visualizations of landmarks on the mobile map than those who navigated with abstract 2D landmarks, while the latter focused more on the depicted route. Furthermore, when the experts focused for longer on the environment and the landmarks, their spatial learning improved regardless of the landmark visualization style. I also found that the spatial learning of experts with self-reported low spatial abilities improved when they navigated with landmarks depicted as realistic 3D buildings.

In Study II, I investigated the influence of abstract and realistic 3D landmark visualization styles on wayfinders sampled from the general population. As in Study I, I investigated wayfinders' navigation performance, visual attention, spatial learning, and cognitive load. In contrast to Study I, the participants in Study II were exposed to both landmark visualization styles in a navigation context that mimics everyday navigation. Furthermore, the participants were informed that their spatial knowledge of the environment would be tested after navigation. As in Study I, the wayfinders in Study II exhibited high navigation performance and low cognitive load regardless of the landmark visualization style. Their visual attention revealed that wayfinders with low spatial abilities and wayfinders familiar with the study area fixated on the environment longer when they navigated with realistic 3D landmarks on the mobile map. Spatial learning improved when wayfinders with low spatial abilities were assisted by realistic 3D landmarks. Also, when wayfinders were assisted by realistic 3D landmarks and paid less attention to the map aid, their spatial learning improved.

Taken together, the present real-world navigation studies provide ecologically valid results on the influence of various landmark visualization styles on wayfinders. In particular, the studies demonstrate how visualization style modulates wayfinders' visual attention and facilitates spatial learning across various user groups and navigation use contexts. Furthermore, the results of both studies highlight the importance of individual differences in spatial abilities as predictors of spatial learning during map-assisted navigation. Based on these findings, the present work provides design recommendations for future mobile maps that go beyond the traditional concept of *"one fits all."* Indeed, the studies support the cause for landmark depiction that directs individual wayfinders' visual attention to task-relevant landmarks to further enhance spatial learning. This would be especially helpful for users with low spatial skills. In doing so, future mobile maps could dynamically adapt the visualization style of landmarks according to wayfinders' spatial abilities for cued visual attention, thus meeting individuals' spatial learning needs.

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Introduction 1

> *Most of the fundamental ideas of science are essentially simple, and may, as a rule, be expressed in a language comprehensible to everyone.*
>
> — **Albert Einstein**
> (Nobel Prize–winning Physicist)

Imagine that you just started your studies in a new, unfamiliar town and are planning to meet your new friends at a cafe in the historic downtown area. As you live in a spatially enabled society, you will probably rely on your trusted mobile navigation system to guide you to your intended destination. You type the destination into this system and let it guide you through the unknown environment. Once you approach the historic area's narrow and busy medieval streets, you realize that it is becoming harder to make destination-relevant navigation decisions. You are standing at an intersection and wondering which way to proceed. You look around in the environment and then at your mobile map, trying to visually match the map's features with the environment. From looking at the environment, you notice that some of the old town's buildings have very prominent and characteristic facades. However, your navigation system only depicts these unique buildings as plain rectangles. Hence, the visual matching process between the environment and the aided navigation device becomes even more difficult, requiring you to pay more attention to the navigation aid (Gardony et al., 2015; Hejtmánek et al., 2018), hindering your spatial learning about the environment (Dahmani & Bohbot, 2020; Ishikawa, 2019), and inducing higher cognitive demand (Wiener et al., 2009). You immediately think how easy it would be to self-localize on the map and to reach the destination if some of the old town's unique buildings were visualized as salient map symbols. Even though you eventually manage to reach your intended destination, you wonder how much environmental knowledge you acquired and whether you would be able to navigate the same route without the assistance of a navigation aid.

Moreover, navigation and wayfinding are involved not only in everyday activities like meeting your friends at a coffee shop but also in highly technical activities carried out by specialists such as pilots and ship captains (Montello, 2005). In the context of expert navigation, the consequences of reduced spatial learning and heightened cognitive demands can be severe. For example, consider a military unit that is required to intervene and assist in an area under a civil emergency. If the unit is unable to accurately perceive the task-relevant spatial information using a location-aware navigation aid, this could limit their ability to efficiently acquire spatial knowledge about their new and unfamiliar surroundings, which could be very costly. Therefore, it is of notable importance to study the impact of mobile maps on navigation aids for general and expert populations, as such maps are necessary to make destination-relevant navigation decisions in both daily life and emergency activities. For instance, mobile navigation aids that support wayfinders' spatial learning should direct their attention to task-relevant features on the mobile map, facilitate self-localization by visually matching the map features with the corresponding environmental features, and improve navigation performance while mitigating wayfinders' navigation-related cognitive load.

1.1 Motivation and problem statement

Navigation, defined as the process of determining and following a route between an origin and destination point (Golledge, 1999), is a predominant activity in everyday life. We navigate in both familiar and unfamiliar environments in order to work, shop, recreate, and engage in many other activities. We perform the navigation process with the help of our cognitive abilities to perceive, remember, and reason about various environments while using our motor abilities to produce destination-relevant movements (Montello, 2005). Although it is a daily activity, navigation is a cognitively challenging and complex process for humans (Farr et al., 2012). To reduce the navigation-related workload, humans have outsourced this task to external aids such as maps, signage, route instructions, or hand-held mobile maps (Wiener et al., 2009). Indeed, mobile maps equipped with Global Positioning System (GPS) functionalities have become ubiquitous aides for navigation and wayfinding (Dahmani & Bohbot, 2020; Wiener et al., 2009).

However, there is increasing evidence that the habitual use of mobile maps as navigation aids impairs users' abilities to acquire new spatial knowledge or to further develop orientation or wayfinding skills (Dahmani & Bohbot, 2020; Gardony et al., 2015; Ishikawa & Montello, 2006; Münzer et al., 2012; Parush et al., 2007; Ruginski et al., 2019). The reasons for these impairments are manifold. Users enter a passive mode and rely entirely on the mobile navigation system, leading to a reduced awareness of the environment and task-relevant features such as landmarks (Brügger et al., 2019; Chrastil & Warren, 2012; Gardony et al., 2015; Ishikawa et al., 2008; Montello et al., 2004; Willis et al., 2009). In addition, these systems induce higher cognitive demands on users because they require navigation skills to perform mobile map–reading tasks such as symbol identification, self-rotation, and self-localization. Moreover, users must perform a visual matching between the allocentric top-down view of the mobile map and the egocentric first-person perspective experienced as they move through the environment (Lobben, 2007; Lobben, 2004; Montello & Sas, 2006; Richardson et al., 1999; Wiener et al., 2009).

In order to facilitate the challenging navigation process, wayfinders use landmarks as visual cues to organize their spatial knowledge and orient themselves in the environment (Couclelis et al., 1987; Montello, 2005). Landmarks are objects in the environment that are easily identifiable, have high contrast with their surroundings, have prominent characteristics, and can be used as anchor and reference points for orientation, wayfinding, and communication (Lynch, 1960; Raubal & Winter, 2002; Richter & Winter, 2014; Sorrows & Hirtle, 1999). For instance, in the above example, a landmark could be a unique building with a characteristic facade. Given their role as visual cues, landmarks hold high practical importance for human wayfinding and spatial knowledge acquisition (Couclelis et al., 1987; Raubal & Winter, 2002; Richter & Winter, 2014; Siegel & White, 1975; Sorrows & Hirtle, 1999).

Despite landmarks' widely accepted importance as facilitators of spatial learning, current mobile navigation systems fail to effectively communicate information about them to pedestrians (Dahmani & Bohbot, 2020; Nothegger et al., 2004; Richter & Winter, 2014; Thrash et al., 2019). The map displays of current navigation aids either omit landmarks, depict them only as building footprints (Grabler et al., 2008), or replace them with commercial points of interest (Nothegger et al., 2004). Landmarks' omission from current mobile maps might be one reason why these navigation aids are often found to inhibit spatial learning (Dahmani & Bohbot, 2020; Ishikawa et al., 2008; Löwen et al., 2019; Ruginski et al., 2019). Current mobile navigation aids do not provide what is needed to acquire spatial knowledge during navigation (Ishikawa, 2018); they seem to shift users' attention away from the environment and task-relevant landmarks (Brügger et al., 2019; Gardony et al., 2015), thereby compromising wayfinders' ability to incorporate landmarks into spatial learning (Dahmani & Bohbot, 2020; Ishikawa, 2018; Siegel & White, 1975). As a result, there have been many design recommendations for integrating landmarks into future mobile maps for effective communication to pedestrian navigators (Raubal & Winter, 2002; Richter & Winter, 2014; Thrash et al., 2019; Yesiltepe et al., 2021). However, how to graphically visualize landmarks on mobile maps for effective communication to pedestrian navigators remains an open question (Richter & Winter, 2014).

To date, most navigation studies have focused on providing wayfinders with landmark-based turn-by-turn instructions, and they are mainly carried out in lab settings, often using virtual environments (see reviews by Richter & Winter, 2014; Yesiltepe et al., 2021). Although real-world navigation studies offer high ecological validity and have the potential to contribute important insights into human navigation behavior through direct experience (Brügger et al., 2019; Ishikawa et al., 2008; Kiefer et al., 2014; Münzer et al., 2006), they are still limited in number compared to lab-based navigation studies. Additionally, to the best of my knowledge, no existing study has focused on how to visualize landmarks on mobile maps by examining the effects of the landmark visualization style on wayfinders' spatial knowledge acquisition, distribution of visual attention, and cognitive load during a real-world route-following task (Richter & Winter, 2014; Yesiltepe et al., 2021).

In response to the above-mentioned research gap, this thesis aims to contribute new empirical evidence on how mobile map design influences humans' navigation behavior (i.e., spatial learning, visual attention, and cognitive load) during aided route-following wayfinding tasks in real-world outdoor settings.

1.2 Research question and research approach

Given the negative influence of GPS-equipped map-based mobile navigation aids on spatial learning, landmarks' acknowledged function in promoting spatial learning, and the absence of landmarks from the navigation aids, this thesis pursues the following overall research goal:

> Provide empirical evidence on the relationship between landmark visualization styles on mobile navigation aids and wayfinders' navigation performance, visual attention, spatial learning, and cognitive load during aided route-following wayfinding tasks in real-world environments.

Enhancing mobile maps with landmark information guides wayfinders' visual attention to task-relevant features. Accordingly, such information is likely to improve navigation performance, promote spatial learning, and reduce the cognitive resources required for successful navigation. To achieve this, I will address the following main research question in the present thesis:

> How can we saliently visualize landmarks on mobile maps to improve wayfinders' navigation performance, direct their visual attention to task-relevant features, and support their spatial learning of the traversed environment while mitigating the wayfinders' task-related cognitive load?

To answer this complex research question regarding the design modifications of mobile maps as navigation aids, we adopted the three-pronged framework proposed by Fabrikant (2022). This research approach (Figure 1.1) considers three distinct factors: the mobile map display design of the navigation aid, the wayfinders, and the navigation task and use context. It evaluates these factors' impact on wayfinders' effectiveness and efficiency during aided navigation. In line with this framework, we thus aim to provide empirical evidence about the following:

1. **Landmark design.** The role of landmark visualization styles in mobile map displays and their influence on the effectiveness and efficiency of the navigation process.
2. **Wayfinders.** The role of human factors such as individual (i.e., spatial abilities and cognitive states) and group (i.e., gender and expertise) differences on the effectiveness and efficiency of the navigation process.
3. **Task and use contexts.** The role of various navigation tasks (i.e., route-following and spatial learning) and mobile map use contexts (i.e., everyday activities or emergencies) on the effectiveness and efficiency of the navigation process.

At the same time, as seen in Figure 1.1, the present thesis sheds light on the following links among the three factors described above:

Human-adaptive (factors 1 and 2) link. This link provides evidence on how landmark visualization styles should be adapted on mobile maps considering wayfinders' individual and group differences, such as spatial abilities, experience, expertise, and preference over one visualization style. This, in turn, might affect wayfinders' distribution of visual attention, cognitive resources, and acquisition of spatial knowledge about the traversed environment in a real-world wayfinding task.

Context-adaptive (factors 1 and 3) link. This link provides evidence on how landmark visualization styles should be adapted on mobile maps to aid users in various wayfinding tasks and contexts of use.

Task-adaptive (factors 2 and 3) link. This link provides evidence on how wayfinders should adapt their visual attention behavior and the cognitive resources needed when performing wayfinding tasks in varying navigation use contexts (i.e., emergency or daily life navigation) with the aid of mobile maps enhanced with various landmark visualization styles.

1.3 Relevance

Why is it important to acquire spatial knowledge of familiar and unfamiliar environments when the ubiquitous mobile navigation aids provide users with what is needed to get them easily and safely from point A to B while reducing the cognitive load related to wayfinding?

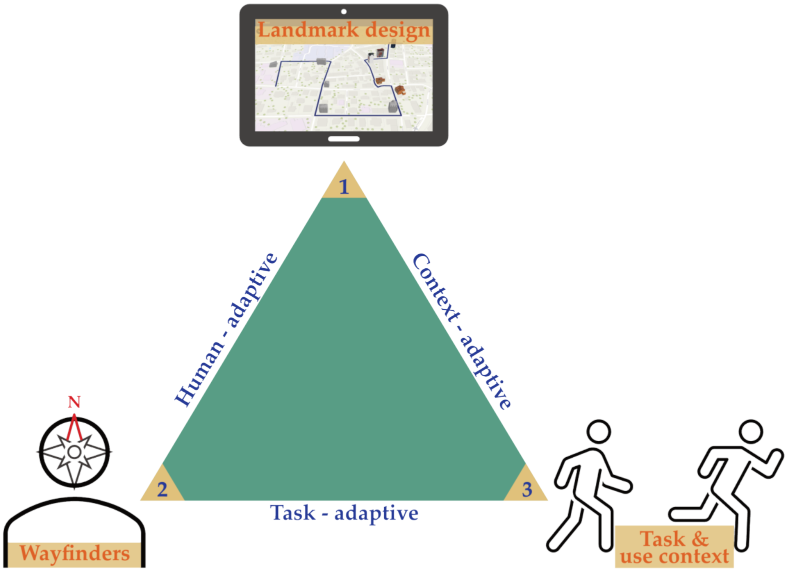

Figure 1.1: Three-pronged research approach that considers three main factors in the design of mobile navigation aids: 1) landmark design, 2) wayfinders, and 3) task and use contexts. The design also includes the links between these factors: human-adaptive (1–2), context-adaptive (1–3), and task-adaptive (2–3). Image modified after Fabrikant (2022, pp. 50).

Studying human-navigation behavior with mobile navigation systems is relevant to users' everyday life activities, as it reduces time, costs, and even catastrophic errors that might lead to the loss of life (i.e., search and rescue operations). However, the over-reliance on automated mobile navigation aids guides users' visual attention away from the environment (Brügger et al., 2019; Gardony et al., 2015), preventing users from further developing orientation and wayfinding skills (Parush et al., 2007) and impairing their spatial learning about the environment (Dahmani & Bohbot, 2020; Ishikawa, 2019; Löwen et al., 2019; Ruginski et al., 2019). Indeed, the over-reliance on GPS mobile navigation aids leads users to blindly follow the *"blue dot on the screen"*; as a result, they are prone to navigation errors in cases of weak GPS signal, aid malfunctions, and so on. The consequences of navigation errors can be severe for various user groups and use contexts. For example, navigation errors with GPS devices have led to several catastrophic incidents, colloquially referred to as *"death by GPS"* (Lin et al., 2017).

In addition to such rare yet possible catastrophic cases, using mobile navigation aids has other health implications. When wayfinders rely on mobile navigation aids, they enter a passive mode (Chrastil & Warren, 2012) and outsource the task to a system for a reduced cognitive workload during wayfinding (Parush et al., 2007; Willis et al., 2009). In return, the hippocampus part of the brain used to build an allocentric representation of spatial objects (Keefe & Nadel, 1978; Schinazi et al., 2013) or a cognitive map of the environment (Tolman, 1948) is less involved during passive GPS-guided navigation than during active goal-directed navigation (Javadi et al., 2017). Hippocampus size varies as a function of spatial abilities, where users with higher spatial abilities and higher navigation experience (i.e., taxi drivers) have a larger hippocampus volume (Maguire et al., 2000; Maguire et al., 2006; Schinazi et al., 2013). Furthermore, research has already proven that the brain's spatial navigation abilities overlap with – and can be predictive of – Alzheimer's and dementia diseases (Coughlan et al., 2018; Levine et al., 2020; Spiers et al., 2023).

Previous research has also demonstrated that people with higher spatial abilities are more likely to pursue and succeed in careers in science, technology, engineering, and mathematics (STEM; Nazareth et al., 2019; Uttal et al., 2013). Therefore, developing and designing mobile navigation systems, spatial learning curricula, and cultural activities that enhance navigation skills (Coutrot et al., 2018) and help wayfinders acquire spatial knowledge of familiar and unfamiliar environments could benefit individuals who plan a STEM career (Uttal et al., 2013). Moreover, such systems could help societies improve the early detection and prevention of degenerative brain diseases (Coutrot et al., 2018).

Finally, research over the past 60 years (Wiener et al., 2009) has paid considerable attention to how people acquire and use knowledge about their environment to determine where they are and how to find their way around (Waller & Nadel, 2013). Initially, studying human behavior fell within the scope of a wide range of disciplines such as psychology, neuroscience, cognition, and sociology (Waller & Nadel, 2013). However, among other external representations, humans rely on cartographic maps for their navigation tasks (Allen, 1999; Lynch, 1960; Montello, 2005). Therefore, spatial navigation and cognition have also become part of geography, cartography, and geographic information science (Lobben, 2007; Lobben, 2004). Even though these disciplines have made a great deal of progress in map design, there is still a lack of knowledge on how map-readers perceive, process, and use the information that maps depict (Lobben, 2007). Therefore, further research on navigation and spatial cognition to better understand humans' navigation behavior is important for these disciplines to move past *"one design fits all."* Such research will make it possible to put the focus on wayfinders' individual and group differences to design better maps that meet wayfinders' needs in various navigation tasks and use contexts (Griffin & Fabrikant, 2012; Griffin et al., 2017).

Related Work 2

> *The aim of science is to discover and illuminate truth. And that, I take it, is the aim of literature, whether biography or history or fiction. It seems to me, then, that there can be no separate literature of science.*
>
> — **Rachel Carson**
> (Author of Silent Spring)

In this chapter, I will present an extended literature review that focuses on the components of human navigation and how wayfinders acquire landmark, route, and survey knowledge during the aided pedestrian navigation process. Next, this chapter will discuss the role of omnipresent mobile maps as navigation aids and their influence on wayfinders' spatial learning and distribution of visual attention. Further, the chapter will present an overview of the existing literature on the role of landmarks in wayfinding, their characteristics, and how to graphically communicate landmarks to wayfinders on map aids considering their characteristics. Finally, this chapter will present literature on the cognitive load theory and means of assessing wayfinders' cognitive load during map-aided navigation tasks. This literature review will support the present thesis's goal of investigating the influence of landmark visualization style during map-aided navigation tasks on wayfinders' spatial learning, visual attention, and cognitive load.

2.1 Aided pedestrian navigation

The purposeful movement between an origin and a destination in the environment is a prominent activity of pedestrian navigation (Wiener et al., 2009). We are aided in our navigation quests by special navigation devices such as maps, street numbers, road signs, and signage (Allen, 1999; Lynch, 1960; Montello, 2005; Wiener et al., 2009). In our spatially enabled society, external aids such as mobile maps displayed in GPS-equipped navigation systems have become omnipresent (Ishikawa, 2019). Before elucidating the influence of such aids on humans' navigation behavior, we must first understand the process and components of navigation. Navigation is defined as a *"coordinated and goal-directed movement through the environment by organisms or intelligent machines"* (Montello, 2005, pp. 257). Montello (2005) suggests that the navigation process consists of two main components: *locomotion* and *wayfinding*.

Locomotion, in the context of pedestrian navigation, refers to humans' coordinated movements through an environment while considering the sensory and motor system feeds that interact with the local surroundings (Montello, 2005). Locomotion is used to solve navigation problems such as directing our movements toward the intended destination, crossing roads, avoiding traffic and bumping into other pedestrians, while at the same time recognizing various environmental features (Montello, 2005). Humans' locomotion in the environment can be either aided (i.e., by transportation means such as bicycles, cars, and trains) or unaided (i.e., walking or running), and it can determine how humans perceive the traversed environment (Chrastil & Warren, 2012; Montello, 2005). Distinguishing between locomotion modes is important because they can influence how we acquire spatial knowledge about our surroundings – namely, actively or passively (Chrastil & Warren, 2012; Montello, 2005). In particular, pedestrians acquire greater spatial knowledge during unaided and active locomotion compared to aided and passive locomotion; during the former, they control their movement speed and heading, leading them to pay more attention to their immediate surroundings (Chrastil & Warren, 2012; Montello, 2005). During active exploration, idiothetic information acquired through vestibular, proprioceptive, and visual cues (Save & Poucet, 2004) seems to be essential in attention and decision-making processes in spatial knowledge acquisition (Chrastil & Warren, 2012). These processes are elements of the second component of navigation: wayfinding.

Wayfinding is efficient, goal-directed, planned movement through the environment (Montello, 2005). The process of wayfinding was first introduced by Lynch (1960), who defined it as the consistent use of the generalized mental representation of the physical environment generated from sensory cues and held by an individual. This mental image is the product of present and past experiences, and it is used to interpret the acquired information and efficiently guide pedestrians' actions through the environment (Lynch, 1960). Further, Golledge

(1999, pp. 6) defined wayfinding as *"the process of determining and following a path or route between an origin and destination."* Therefore, wayfinding seems to require a destination that we wish to reach, which is usually beyond the local sensory surroundings (Montello, 2005). As a result, the internal mental representation of the environment (Lynch, 1960) stored in our nervous system, as well as external aids such as maps (Lynch, 1960; Montello, 2005; Wiener et al., 2009), play a crucial role in the wayfinding process (Montello, 2005). During wayfinding, we perform several cognitive processes such as planning, orientation and self-localization, allocation of attention, and destination-relevant decision-making (Chrastil & Warren, 2012; Kiefer et al., 2014; Meilinger et al., 2007; Montello, 2005).

Although there are cases of locomotion without wayfinding and vice versa, most navigation acts involve both components (Montello, 2005). For instance, when pedestrians navigate through an environment, they use locomotion to avoid obstacles and to safely cross roads while using wayfinding to self-localize, maintain orientation in the environment, and efficiently reach the intended destination. Locomotion and wayfinding differ in that they rely on non-declarative and declarative knowledge, respectively (Montello, 2005). For instance, moving in a straight line to a visible target involves a non-declarative, "know-how" type of knowledge that utilizes our learned skills and motor habits rather than activating our internal representation of the environment's spatial configuration. Meanwhile, declarative knowledge is a "know-that" type of knowledge that requires episodic memory of learned and experienced events in the navigation context (Montello, 2005). Therefore, in contrast to locomotion to a visible target, wayfinding requires tapping into the wayfinders working memory to retrieve one's knowledge of the spatial representation of places. While both processes are important to achieve successful navigation, navigators acquire spatial knowledge of the traversed environments only during wayfinding.

2.1.1 Spatial knowledge acquisition during wayfinding

The study of spatial knowledge is concerned with how humans acquire and maintain spatial information about their surrounding environments for accurate spatial orientation and successful wayfinding (Ishikawa, 2018). In addition, Ishikawa (2018) pointed out that successful spatial orientation and wayfinding occur when our environmental knowledge is accurate and flexible. Therefore, our spatial behavior is guided by our environmental knowledge in addition to the environment itself – in other words, it is guided by the "map in our head" (Ishikawa, 2018). Accurate and flexible inner maps enable us to stay oriented in space and make destination-relevant navigation decisions for successful navigation even when there are unforeseen changes in the environment (Ishikawa, 2018). For instance, if we have an accurate and flexible inner map of the environment, we will be able to find a new way to successfully reach our workplace when our usual route is inaccessible due to external factors (i.e., traffic jams, construction work, etc.). Such spatial knowledge is acquired and updated through our interactions with the environment. It is stored in our mind as an internal (or mental) spatial representation of the environment (Ishikawa, 2018), which has been referred to as the *cognitive map* (Tolman, 1948).

The idea of a cognitive map in humans and other living organisms was first coined by Tolman (1948) after his empirical experiments with rats in maze-like environments. Using a training phase, Tolman (1948) trained rats in multiple trials to reach a food-marked goal in a maze by following a predefined route from A to G (Figure 2.1–A). In a testing phase that assessed the rats' spatial knowledge, Tolman (1948) placed the rats in a new maze environment where a series of radiating paths were added and the original training path was blocked (Figure 2.1–B). Upon realizing that the original path leading to the food goal was blocked, 36% of the rats (Figure 2.1–C) took the path that pointed in the Euclidean direction of the goal location (Tolman, 1948). This was a higher proportion than would be expected by chance performance. The other path chosen with higher frequency, Path 1 (17%), pointed perpendicularly to the food side of the training maze. The author argues that these results suggest that the rats did not merely acquire strip-map-like knowledge that their actions during training led to food; instead, they appear to have gained a wider map-like representation of the maze, allowing them to comprehend that the food was located in a certain direction.

Downs and Stea (2011, pp. 9) defined cognitive mapping as *"a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment."* However, there is still considerable debate in the psychological literature about whether humans rely on cognitive maps or snapshot memories of locations for wayfinding (Foo et al., 2005; Tversky, 1993, 1981; Warren et al., 2017). In addition, the spatial representation of the environment is typically fragmented and distorted; it is represented as several separate bodies of knowledge about smaller chunks of the environment (Downs & Stea, 2011; Siegel & White, 1975). To account for this, Siegel and White (1975) proposed a framework in which environmental knowledge is developed over time through three distinct types of spatial knowledge, which we will discuss in the next subsection.

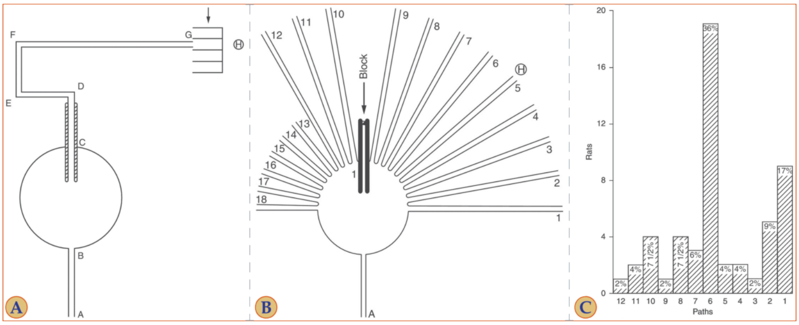

Figure 2.1: The training maze (A); The new test maze with the original path blocked (B); Results show that 36% of the rats took Path 6, which points in the same direction as the learned goal (C). Image from Tolman et al. (1946, pp. 16–19).

Types of spatial knowledge

Siegel and White (1975) stated that spatial representation in wayfinders' minds has two main functions. The primary function is to facilitate wayfinders' location and movement within the larger physical environment, which prevents them from getting lost. The second function is to organize the experience captured during their movement in the environment. For the primary function, Siegel and White (1975) argued that landmarks and routes are probably the environmental elements necessary to construct a minimal spatial representation that will facilitate wayfinding. In addition to landmark and route knowledge, configurational or survey knowledge was proposed as a gestalt spatial representation. Such a representation goes beyond the minimal map and gives wayfinders an advantage in wayfinding tasks and in organizing the captured environmental experience (Siegel & White, 1975). As a result, Siegel and White's (1975) framework for acquiring spatial knowledge of environments consists of *landmark*, *route*, and *survey* knowledge.

Landmark knowledge is the originator of a wayfinders' spatial representation of the environment according to Siegel and White (1975). The authors stated that landmarks are distinct patterns at specific locations in the environment; these patterns are stored in memory and recognized when perceived. In addition, landmarks are predominantly visual, serve as the origin and destination foci, and are used by wayfinders to maintain their intended course of movement through the environment. However, landmarks' prominent role in the early stages of wayfinders' spatial representation requires a *"recognition-in-context"* memory. For instance, it is not possible for an environmental feature to serve as a landmark unless wayfinders have already seen it in the environment or on a navigation aid. Moreover, they must be aware of its meaning or of what wayfinding decision comes next (Siegel & White, 1975).

Route knowledge is sequential sensorimotor knowledge of the environment (Siegel & White, 1975). Consequently, route knowledge brings together wayfinders' landmark sequence knowledge and the associated actions (Siegel & White, 1975) – namely, moving from one landmark to another and the associated changes in heading directions (i.e., turn left or right or continue forward) in order to reach the intended destination (Ishikawa, 2018; Montello, 1998). Siegel and White (1975) stated that the environment consists of landmarks connected by potential route segments. When landmarks are absent, wayfinders start to wonder whether they are on the right path (Siegel & White, 1975). Therefore, route knowledge binds together only the knowledge of sequential locations, not the knowledge of interrelations among these locations or landmarks (Hirtle & Hudson, 1991). The latter belongs to the third component of spatial representation development.

Survey knowledge, or configurational knowledge, constitutes the gestalt nature of environmental spatial representation (Siegel & White, 1975). Survey knowledge is derived from an accumulated knowledge of routes connected by a system of landmarks (Siegel & White, 1975). Hence, it is a map- or network-like assembly of spatial representations between separate environmental features, such as landmarks and routes, that are organized within a common reference frame (Hirtle & Hudson, 1991; Ishikawa, 2018; Montello, 1998; Siegel & White, 1975). In such a map-like representation, landmark and route knowledge – even those acquired in separate trips – are interrelated in a common reference frame as if seen from a birds-eye perspective (Ishikawa, 2018).

The framework of Siegel and White (1975) considers the development of the spatial microgenesis of a new environment, or in other words, the process of spatial knowledge development over a comparatively brief period (Ishikawa, 2018; Montello, 1998). This framework is developed through three distinct types of spatial knowledge, originating with landmark and route knowledge and finally comprising a complete survey knowledge of novel environments. In the first two stages, the wayfinders' knowledge does not contain any metric information but is instead based on the memory of landmarks and their associated actions (Ishikawa, 2018; Montello, 1998; Siegel & White, 1975). For instance, wayfinders recall only the sequence of perceived landmarks and their associated changes in bearing, which in turn constitutes the route knowledge; accordingly, the space between landmarks is perceived as *"empty"* (Siegel & White, 1975, pp. 29). The empty spatial representation receives metric scaling as the wayfinders' exposure to the environment increases (Couclelis et al., 1987), allowing survey knowledge to emerge as the final stage of microgenetic development (Ishikawa, 2018; Montello, 1998; Siegel & White, 1975).

Siegel and White's (1975) spatial microgenesis framework was branded by Montello (1998) as a *"dominant framework"* due to its influence in the spatial cognition literature. This dominant framework claims that during the first stages of exposure to a novel environment, wayfinders encode and store only pure landmark and route knowledge, with no metric survey knowledge. This claim implies that wayfinders cannot answer spatial tasks that require them to have metric or configurational knowledge of a relatively new environment (Montello, 1998). Such tasks include taking shortcuts, retracing their route to the starting point, and estimating distances and directions between locations of the new environment (Ishikawa, 2018). However, despite its dominant influence, Siegel and White's (1975) framework has been found to conflict with later empirical findings (see Montello, 1998). Indeed, Montello (2005) found that wayfinders could complete survey knowledge tasks, obviously not flawlessly, but better than chance performance and better than the presence of only non-metric knowledge would suggest (Hirtle & Hudson, 1991; Montello, 1998).

Considering these limitations of Siegel and White's (1975) dominant framework, Montello (1998) suggested an *"alternative framework"* that explains wayfinders' spatial microgenesis as a process of continuous development. The alternative framework argues that wayfinders acquire metric survey knowledge in large-scale environments through quantitative (or continuous) accumulation refined with experience rather than through qualitative (or discrete) shifts from non-metric to metric forms of knowledge (as claimed by Siegel and White's (1975) dominant framework). In support of Montello's (1998) alternative framework, Hirtle and Hudson (1991) argued that, based on empirical findings, wayfinders begin to acquire survey knowledge of a novel environment from the start of learning their routes. Nonetheless, both frameworks agree that the acquisition of survey knowledge is an intricate step of spatial microgenesis development. Moreover, it is not particularly map-like due to its incompleteness and fragmented nature (Montello, 1998; Siegel & White, 1975). Furthermore, Montello's (1998) alternative framework suggests that the extent and accuracy of spatial knowledge acquisition is highly dependent on individuals' ability to acquire environmental knowledge, their experience, and the frequency of their exposure (familiarity) to the environment. These factors point to the role of individual traits in spatial knowledge acquisition.

Individual traits in spatial knowledge acquisition

In his alternative framework presented above, Montello (1998) stated that wayfinders differ in the extent and accuracy of their environmental spatial representation. For instance, some people enjoy navigating new places and easily acquire an accurate spatial representation of the environment, which improves their wayfinding performance. In contrast, others are reluctant to visit new environments due to their poor configurational understanding of such environments (Ishikawa, 2018). These differences reflect wayfinders' fundamental abilities to acquire spatial knowledge and their strategies to encode and decode this knowledge (Montello, 1998). These individual traits profoundly affect wayfinders' ability to integrate knowledge (Montello, 1998) and could, in return, affect their confidence in spatial orientation and wayfinding tasks (Ishikawa, 2018).

The ability to learn the layout of a novel environment and maintain a sense of direction and location while moving around such an environment are fundamental cognitive functions in humans (Hegarty et al., 2018). Therefore, previous research has associated the question of *"why some individuals are better than others at wayfinding tasks"* with the large individual differences in wayfinders' ability to learn and integrate the spatial layout of novel environments (Allen, 1999; Hegarty et al., 2018; Ishikawa, 2022, 2018; Meneghetti et al., 2022; Montello, 1998; Newcombe et al., 2022). For instance, Ishikawa and Montello (2006) found that some participants exhibited an almost perfect survey knowledge acquisition after only one or two learning experiences, while others performed at the chance level or did not improve even after 10 learning trials. Other studies conducted in virtual environments (VE; i.e., Weisberg & Newcombe, 2016; Weisberg et al., 2014) have replicated the findings of Ishikawa and Montello's (2006) real-world study and attribute the results to wayfinders' individual differences. The results of individual differences in wayfinders' navigation abilities are correlated with their extensive familiarity with the environment (Allen, 1999; Couclelis et al., 1987; Montello, 1998), which leads to extensive experience and expertise, and even with different brain structures (Hegarty et al., 2018; Maguire et al., 2006; Montello, 1998; Schinazi et al., 2013; Sutton et al., 2014; Woollett & Maguire, 2010; Woollett & Maguire, 2011; Woollett et al., 2009).

To investigate the influence of expertise and experience on spatial learning abilities, Sutton et al. (2014) asked 18 pilots and 18 participants sampled from the general population (control) to explore a virtual town with six distinct landmarks in five minutes. They examined the participants' newly acquired knowledge of the VE using a direction estimation task. The results revealed that pilots were significantly more accurate than the control group at estimating directions among the six landmarks (Sutton et al., 2014). In addition, in their study of London taxi drivers (who are considered navigation experts due to the extensive navigational training they must complete to be licensed), Maguire et al. (2006) explored the influence of expertise on drivers' brain structures. Maguire et al. (2006) found that licensed taxi drivers have a larger posterior hippocampus volume and that this volume correlates with the time spent as a taxi driver. Furthermore, Maguire et al. (2006) did not find a correlation between the hippocampus volume and time spent as London bus drivers, who must follow a set of predefined routes. In a later study, Woollett and Maguire (2011) found that changes in hippocampus volume were not observed in individuals who did not pass their licensing examination. Using the same paradigm of individual differences and their effect on individuals' brain structure, Schinazi et al. (2013) found that the size of the hippocampus is a predictor of individuals' ability and performance in spatial knowledge acquisition.

Previous research has already established that there are several factors that affect wayfinders' ability to acquire spatial knowledge, including age (Newcombe, 2019), gender (Hegarty et al., 2006; Nazareth et al., 2019), cortisol and sex hormones (Newcombe et al., 2022), stress and spatial anxiety (Ishikawa, 2022; Newcombe et al., 2022), environmental structure (Coutrot et al., 2022; Coutrot et al., 2018; Spiers et al., 2023), hippocampus volume (Schinazi et al., 2013), experience (Maguire et al., 2006; Woollett & Maguire, 2011), familiarity (Couclelis et al., 1987; Montello, 1998; Nazareth et al., 2019), and intentionality in learning (Chrastil & Warren, 2012; Wenczel et al., 2017). However, these factors will not be discussed further, as the present thesis does not focus on wayfinders' individual abilities to acquire environmental spatial knowledge. Instead, these factors were used as control variables when designing the empirical real-world user studies presented in this thesis (see Chapter 4 and Chapter 5), as they greatly influence how individuals acquire spatial knowledge when aided by the omnipresent mobile maps in our spatially enabled society (Ishikawa, 2018, 2019).

2.1.2 Mobile maps as navigation aids

Human wayfinding is not only aided by internal mental spatial representations (i.e., cognitive maps) captured during exposure to the environment but also by external aids (Allen, 1999; Montello, 1998; Montello, 2005). As already pointed out (see Section 2.1), humans are aided in their everyday wayfinding tasks by external aids such as maps, signage, and route instructions (Allen, 1999; Lynch, 1960; Montello, 2005; Wiener et al., 2009). Maps have existed for thousands of years (Montello et al., 2018). While there are several types of maps and many purposes for which they are used (Montello, 2005), they have long served as a traditional tool to aid human wayfinding in familiar and unfamiliar territories (Ishikawa, 2018; Montello et al., 2018). Indeed, Montello (1998) stated that maps are the most efficient and effective way of communicating the metric properties and spatial configuration of spaces to wayfinders.

Recent developments and advances in information and communication technologies have enabled a variety of navigation aids, such as navigation systems equipped with mobile maps (Ishikawa, 2019). When it comes to aided pedestrian navigation, GPS-equipped mobile maps in navigation devices and applications (though originally developed to assist military and emergency operations) have become ubiquitous navigation aids (Dahmani & Bohbot, 2020). As a surrogate form of maps (Ishikawa, 2018), these GPS-equipped mobile maps were introduced to alleviate the workload related to the navigation process (Parush et al., 2007) and facilitate wayfinding tasks, especially for people with low spatial abilities (Ishikawa, 2018; Raubal, 2018). However, several researchers have raised questions about the effects of these advanced GPS-enabled mobile maps beyond their utility for navigation (Ishikawa, 2018; Raubal, 2018). Indeed, past empirical research suggests that such navigation aids negatively impact wayfinders' spatial knowledge acquisition of the environment (Ishikawa, 2018; Raubal, 2018).

Influence of mobile maps on spatial knowledge acquisition

Even though the use of mobile maps in navigation systems mitigates the workload of wayfinding tasks, other problems may arise as a consequence of an over-reliance on these tools (Parush et al., 2007). In general, the over-reliance on mobile maps as a pedestrian wayfinding aid encourages wayfinders to be *"mindless"* with respect to the surrounding environment. Consequently, such over-reliance precludes wayfinders from developing further wayfinding and orientation skills and even from acquiring spatial knowledge of the traversed environment that may be necessary to complete the wayfinding task when the system fails (Parush et al., 2007). Past research has already demonstrated that the use of mobile maps negatively impacts wayfinders' spatial knowledge acquisition of traveled routes compared to wayfinders who use traditional paper maps or acquire spatial knowledge through direct experience (Ishikawa et al., 2008; Münzer et al., 2006; Willis et al., 2009). However, since these tools have become increasingly prevalent in our society, the present section will focus on the negative effects of an over-reliance on these aids rather than the wayfinding performance across navigation aids.

The over-reliance on GPS-enabled mobile maps not only impairs wayfinders' spatial knowledge acquisition but also affects their spatial abilities, which are necessary for effective environmental learning (Dahmani & Bohbot, 2020; Ishikawa, 2019; Ruginski et al., 2019). Ishikawa (2019) examined the long-term effects of using mobile maps as aids in wayfinding and spatial orientation through a survey with 249 participants. From this pool, the author extracted 74 participants to conduct a real-world route-following task where participants navigated two unfamiliar routes in Tokyo with the help of a mobile map or with a paper map (not discussed here, see Ishikawa, 2019). The survey analyses showed that participants that were frequent users of navigation systems equipped with mobile maps had a low sense of direction and mental rotation skills. The results of the real-world navigation study also revealed that participants with more frequent mobile map use were more prone to navigation errors and experienced more problems when learning the traveled routes. The results of Ishikawa (2019) have also been observed in other empirical contexts (Dahmani & Bohbot, 2020; Ruginski et al., 2019).

After collecting self-reported data on the use of GPS systems for navigation, Ruginski et al. (2019) asked 201 participants to navigate two routes of a virtual campus, each equipped with four landmarks. The authors tested their pointing and distance estimation accuracy among the present landmarks. Their results indicated that the long-term use of mobile maps for navigation purposes is associated with worse spatial abilities (i.e., mental rotation and perspective-taking), which in turn predicts a decreased ability to acquire spatial knowledge of novel environments (Ruginski et al., 2019). Similarly, Dahmani and Bohbot (2020) tested the effects of the habitual use of mobile maps on navigation systems as wayfinding aids on users' spatial abilities. Using two navigation tasks in VEs, they assessed the experience, spatial memory, and spatial knowledge of 50 regular drivers with GPS-equipped mobile maps. The results indicated that people with greater habitual use of mobile maps had worse spatial memory when they were required to navigate without the aid of mobile maps (Dahmani & Bohbot, 2020). In a follow-up experiment conducted three years later, Dahmani and Bohbot (2020) retested 13 participants from the first study. Despite the small sample size, they observed that higher use of mobile maps as wayfinding aids since the first experiment was associated with a higher decline in wayfinders' spatial memory (Dahmani & Bohbot, 2020).

Considering the negative effects of mobile map use on wayfinders' spatial knowledge acquisition, researchers have tried to find explanations as to why these navigation tools, which were developed to assist wayfinders in navigating from A to B, do not support spatial learning. The negative effects of using GPS-equipped mobile maps on our cognitive skills are attributed, among other factors, to their level of automation (Brügger et al., 2019; Parush et al., 2007). Given this automation, mobile maps place wayfinders in a passive state (Chrastil & Warren, 2012; Ishikawa, 2019; Willis et al., 2009) of following the device's instructions, replacing the need to actively encode the spatial information (Münzer et al., 2006; Parush et al., 2007). In particular, most previous work claims that the use of mobile maps affects wayfinders' spatial knowledge acquisition through changes in their visual attention behavior during navigation tasks (Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018; Ishikawa et al., 2008; Willis et al., 2009). Thus, the following subsection will focus on how GPS-equipped navigation systems provided with a mobile map influence wayfinders' visual behavior.

Influence of mobile maps on visual attention

Holmqvist et al. (2011) defined visual attention as the collection and processing of information coming from the external visual scene. However, Wolfe and Horowitz (2004, 2017) argued that humans' visual attention has a selective nature. This means that our visual attention is focused on some aspects of the scene in front of us, while other parts of the visible world go relatively unattended (Wolfe & Horowitz, 2017; Wolfe & Horowitz, 2004). More specifically, Wolfe and Horowitz (2017) stated that humans' visual search is not overwhelmed by the availability of present objects but is rather guided by five factors:

1. **Bottom-up, stimulus-driven guidance,** where an object's visual properties attract more attention than other objects. Attention is attracted to items that differ from their immediate surroundings. Therefore, color and orientation serve as basic properties of an object, as they attract the deployment of attention.
2. **Top-down feature guidance,** where attention is guided to objects with properties similar to those of the intended object. For instance, when we search for a large red building parallel to the street, our attention will be drawn to large buildings with red facades that are parallel to the street. Therefore, color, size, and orientation are identified as basic object properties.
3. **Guidance by scene properties,** where users' attention is directed to areas that are most likely to contain the object of interest. For example, when a user performs a visual search for the above-mentioned red building, they will typically not be looking at the sky.
4. **Guidance by prior history,** where users' attention is guided by the history of previous searches. Therefore, if the observer is famil-

iar with the red building and its environment, this building will guide attention.

5. Guidance by the value of items, where the reward or value of an item are guiding factors. For instance, if the observer is highly rewarded for finding red buildings than buildings in any other color, they will guide their attention toward red buildings, even if they are irrelevant to the task. In this case the color is the guiding feature and the value modulates its effectiveness.

These modulations of visual attention can also apply to wayfinders during their navigation tasks. For instance, at any given time during wayfinding, attention is guided either by the source of information presented on the mobile map aid (bottom-up) or directly by the information present in the physical environment (top-down). In addition, wayfinders' attention is guided by the scene properties, their prior familiarity with the environment, and the value of successfully completing the wayfinding task. As a result of these factors modulating visual attention during wayfinding tasks, wayfinders' visual attention during navigation is divided and selective (Gardony et al., 2013; Gardony et al., 2015; Ishikawa et al., 2008; Willis et al., 2009; Wolfe & Horowitz, 2017). Previous research has shown that divided attention can have negative consequences on wayfinders' ability to acquire spatial knowledge of traversed environments (Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018; Ishikawa et al., 2008; Willis et al., 2009).

To assess the role of divided attention on wayfinders' spatial memory development, Gardony et al. (2013) asked 36 participants in a lab environment to briefly study a top-down view of a virtual town and then to navigate between landmarks following provided instructions. During the navigation task, participants were provided with either a verbal aid, nonverbal tonal aid, or no aid (for the control group). The authors found that both verbal and tonal aids increased navigation efficiency (i.e., path efficiency) but impaired wayfinders' spatial memory compared to the control group. As these results were consistent between the navigational aids, the authors concluded that the impaired spatial learning was derived from the influence of divided attention (Gardony et al., 2013). However, these results were not derived from the direct manipulation of wayfinders' attention states (Gardony et al., 2015).

Gardony et al. (2015) further extended the work of Gardony et al. (2013) by testing 24 participants using a dual-task paradigm. In this study, the verbal aid was either present or absent, and attention was either divided (by using a noisy verbal aid) or undivided (with clear verbal aid instructions). Gardony et al. (2015) replicated the results of Gardony et al. (2013): aid presence increased wayfinders' navigation efficiency but only when attention was undivided. They observed the opposite effect when wayfinders' attention was divided, but this effect vanished with an increase in navigational trials. Therefore, Gardony et al. (2015) concluded that divided attention during navigation harms navigation efficiency and that this effect can be overcome with increased exposure to the environment (Couclelis et al., 1987; Montello, 1998). Additionally, the authors observed that aid presence influenced wayfinders' spatial memory differently when attention was either divided or undivided. In the case of undivided attention, the presence of the verbal aid greatly impaired spatial memory. However, when attention was divided, the aid did not further harm spatial memory (Gardony et al., 2015).

Even though these results (Gardony et al., 2013; Gardony et al., 2015) provide empirical evidence for the negative influence of divided attention on wayfinders' spatial representation, they are limited to verbal aids and do not consider the real-world use of GPS-enabled mobile maps (Gardony et al., 2015). Furthermore, these studies did not record participants' eye movements by means of eye-tracking recordings, which is the primary data source for investigating individuals' visual attention behavior (Duchowski, 2017; Goldberg & Kotval, 1999; Holmqvist et al., 2011; Kiefer et al., 2017; Wolfe & Horowitz, 2017). Given these limitations of Gardony et al. (2013) and Gardony et al. (2015), Hejtmánek et al. (2018) conducted a lab study in which they asked 42 participants to navigate and learn the layout of a VE equipped with a GPS-like mobile map while recording participants' eye movements by means of eye-tracking methods. During the recall phase, participants were asked to point toward the start location of the learning path, navigate to that location using the shortest path possible, and point toward the start of the recalled path upon reaching the destination. The GPS-like map was hidden during both pointing tasks. The results indicated that fixating for longer periods on the GPS-like map during learning negatively influenced the navigation and pointing performance assessed during the recall task (Hejtmánek et al., 2018).

Mobile maps' negative influence on wayfinders' spatial knowledge acquisition is attributed to the fact that they reduce wayfinders' allocation of attentional resources to task-relevant features (Gardony et al., 2013; Ishikawa et al., 2008; Willis et al., 2009). However, if the mobile map aid were able to direct wayfinders' attention to task-relevant features in the environment and the mobile map, wayfinders would be able to actively encode the spatial information (Chrastil & Warren, 2012). Therefore, in order to increase spatial knowledge acquisition, wayfinders need to interact with both the mobile map aid and their surroundings to match the information on the mobile map with physical objects in the environment (Willis et al., 2009). Indeed, visually matching the information between the mobile map and the environment – thus integrating the bottom-up and top-down factors of visual attention (Wolfe & Horowitz, 2017) – is important to achieve the cognitive processes of orientation and self-localization. These processes, in turn, are quintessential for efficient wayfinding and improved spatial knowledge (Kiefer et al., 2014; Lobben, 2004; Wiener et al., 2009).

Self-localization and orientation are defined as identifying one's current position and heading direction on a map and in the environment (Kiefer et al., 2014; Meilinger et al., 2007). To do so, humans rely on the presence of environmental features such as landmarks (Chrastil & Warren, 2012; Kiefer et al., 2014; Montello, 2005; Raubal & Winter, 2002; Richter & Winter, 2014; Willis et al., 2009; Yesiltepe et al., 2021). Kiefer et al. (2014) conducted a real-world self-localization and orientation experiment that used eye-tracking to investigate the visual matching process between a mobile map depicting landmarks and the environment. The 15 participants were led to a physical position in the environment, provided with a paper map for tourists that depicted landmarks as realistic 3D building models, and asked to find and mark their position on the map. From the participants' position in the environment, only three of the 14 landmarks present on the paper map were visible. The results revealed that the successful participants spent significantly more time looking at the visible landmarks than the unsuccessful ones (Kiefer et al., 2014). Additionally, the successful participants had significantly more visual switches between the landmark symbols on the map and their corresponding physical buildings in the environment (Kiefer et al., 2014). These results are consistent with previous research showing that landmarks play a crucial role in the process of aided pedestrian navigation, as they serve as anchors and reference points and support spatial knowledge acquisition (Couclelis et al., 1987; Raubal & Winter, 2002; Richter & Winter, 2014; Sorrows & Hirtle, 1999).

2.2 Landmarks in wayfinding

Golledge (1999) stated that landmarks serve two main roles in the context of wayfinding: 1) as origin and destination focus points either toward or away from the direction of movement, and 2) as intermediate decision points for verifying the route progress and identifying the choice points where destination-relevant decisions are made. Landmarks thus act as anchor points for organizing spatial information. In addition, they are features that stand out from their surroundings (Couclelis et al., 1987; Golledge, 1999). Therefore, the use of landmarks in pedestrian-aided navigation is essential and of high practical importance (Raubal & Winter, 2002; Sorrows & Hirtle, 1999). For example, we use landmarks in our surroundings to find our location and heading on a navigation aid that directs us to the intended destination (Montello, 2005). According to Lynch (1960), landmarks constitute one of the five elements of a built environment (in addition to paths, edges, nodes, and districts). Landmarks serve as external physical points of reference for wayfinders, who rely on them for guidance through the environment (Lynch, 1960). Furthermore, Lynch (1960) stated that landmarks are more identifiable and more likely to be used by wayfinders if they have a clear form, contrast with the background, and have a prominent spatial location.

This early definition of landmarks by Lynch (1960) is still one of the most significant, as it hints at landmarks' characteristics as wayfinding tools (Yesiltepe et al., 2021). Additional characteristics of landmarks have since been discussed by other researchers (Richter & Winter, 2014; Yesiltepe et al., 2021). For instance, Couclelis et al. (1987) defined a landmark as any given environmental element that stands out from the other elements in the environment due to its distinctive features (i.e., form, color, size, visual uniqueness) or symbolic meaning (i.e., historical, religious, or socio-cultural significance). Sorrows and Hirtle (1999) defined landmarks as prominent and identifiable features of the environment that wayfinders use to self-localize and establish goals. Meanwhile, Richter and Winter (2014) stated that landmarks are geographic objects that serve as anchor points and points of reference and structure humans' mental representation of space. In addition, in a recent review of the role of landmarks in wayfinding, Yesiltepe et al. (2021, pp. 371) defined landmarks as *"any salient object that is personal (so that it can be seen and used by someone while it is not used by someone else), communicable (so that it can be described easily), and visible either from a distance or close up in an environment such that it can* *be used in the wayfinding process for various tasks (e.g., route definition, orientation, etc.)."* Hence, in the context of this thesis, landmarks are environmental features that stand out due to their distinct characteristics, are located where a destination-relevant navigation decision is required, and serve as anchor points that structure wayfinders' mental representation of space.

2.2.1 Landmark characteristics

Yesiltepe et al. (2021) categorized landmarks' wayfinding characteristics into two main categories: *visibility* and *saliency*. The visibility of landmarks depends on the scale at which a landmark is visible during the wayfinding process (Lynch, 1960). Meanwhile, landmarks' saliency is related to distinctive and prominent features that stand out compared to other features in their immediate surroundings (Caduff & Timpf, 2008; Lynch, 1960).

Landmark visibility

Lynch (1960) stated that depending on their visibility, some landmarks could be classified as distant; such landmarks are typically seen from many viewpoints and distances and even above smaller environmental features. For instance, a distant landmark could be high towers, high hills, mountains, and even mobile points whose motion is sufficiently slow and regular, such as the sun (Lynch, 1960). Distant landmarks constitute direction points that do not change with wayfinders' small movements in the environment and are thus called global landmarks (Steck & Mallot, 2000). Given their invariant direction, global landmarks bear a resemblance to a compass (Steck & Mallot, 2000).

In contrast to global landmarks, other landmark features are visible only in restricted locations and from certain viewpoints (Lynch, 1960). Landmarks that are visible only from a short distance are referred to as local landmarks (Steck & Mallot, 2000). Numerous features, such as buildings and stores and their facades and signs, can serve as local landmarks (Lynch, 1960). There is a considerable body of research on the role of local and global landmarks in wayfinding (Yesiltepe et al., 2021). Numerous studies have argued that local landmarks are used in idiosyncratic ways to help wayfinders complete navigation tasks and organize spatial information more accurately (Sorrows & Hirtle, 1999; Yesiltepe et al., 2021). While global landmarks can be seen from many locations, local landmarks are not visible from all the locations in an environment (Lynch, 1960). Therefore, wayfinders rely upon local landmarks in smaller environments and global landmarks in large-scale environments (Gardony et al., 2011).

Researchers have studied the influence of adding both types of landmarks (local and global) on wayfinders' spatial learning performance (Credé et al., 2019; Gardony et al., 2011; Ruddle et al., 2011; Steck & Mallot, 2000). In a VE experiment, Credé et al. (2019) found that participants' knowledge of the spatial configuration of global landmarks did not improve compared to the spatial configuration of local landmarks. In addition, in a 3D VE consisting of four conditions – no landmarks, only local landmarks, only global landmarks, and both local and global landmarks – Ruddle et al. (2011) found that local landmarks improved participants' route knowledge, while global landmarks had no influence. Later, in a VE experiment with the same four conditions, Gardony et al. (2011) asked participants to navigate and find invisible targets as quickly as possible. The results revealed that local landmarks were perceived as the key information when both local and global landmarks were included in the environment (Gardony et al., 2011). Finally, the presence of both types of landmarks can also hurt participants' performance compared to using only one type (Ruddle et al., 2011).

Later, in one of their experiments, Steck and Mallot (2000) found that the preference for local or global landmarks varies among participants. They found that participants used local landmarks at certain intersections and then relied on global landmarks at others. Additionally, in another experiment, they found that when one landmark type was removed, all participants relied on the other type (Steck & Mallot, 2000). This indicates that participants' preference for or use of a certain type of landmark is influenced by other landmark characteristics (Yesiltepe et al., 2021). For instance, wayfinders rely more on local landmarks during navigation if they have higher saliency compared to their surroundings (Yesiltepe et al., 2021), which leads us to saliency as the other characteristic of landmarks. Considering the above findings on the advantages of local over global landmarks for wayfinders' navigation performance, the scope of the present thesis will be on the saliency of local landmarks.

Landmark saliency

As each and every object at a decision point in the environment can serve as a landmark (Caduff & Timpf, 2008; Ishikawa & Nakamura, 2012; Siegel & White, 1975; Sorrows & Hirtle, 1999), the notion of landmark saliency is essential to denote landmark features that are preferable for assisting wayfinders in their navigation tasks (Caduff & Timpf, 2008; Yesiltepe et al., 2021). Lynch (1960) argued that a landmark becomes more easily identifiable and more likely to be chosen as a significant point of reference over other features if it has a sharp contrast with its surroundings and is situated at a prominent location. Similarly, Caduff and Timpf (2008) stated that landmarks' distinctiveness and prominence compared to other features in their immediate surroundings constitute their saliency.

Sorrows and Hirtle (1999) provided the main contribution to defining landmarks' saliency for use in wayfinding tasks in both physical and VEs. They proposed three categories of landmarks based on their characteristics: *visual*, *cognitive*, and *structural*. According to the researchers, a *visual landmark* is an object that qualifies as a landmark due to visual characteristics that make it memorable; these characteristics include higher contrast with the surrounding features and location prominence. Meanwhile, a *cognitive landmark* is an object that stands out based on its cultural or historical meaning, whether typical or atypical. Unless they bear clear signage indicating their function, cognitive landmarks can be personal and only used by some users and missed by others (Sorrows & Hirtle, 1999). For instance, my office at the university, while visually and structurally similar to the other offices, serves as a landmark for me due to its meaning, while it is just another office to other employees. Finally, a *structural landmark* is an object whose importance originates from its position in the environment (i.e., an object at a highly accessible location or at an intersection).

Sorrows and Hirtle (1999) stated that the best-suited landmarks for wayfinding purposes are the most distinct in terms of all three characteristics: visual, cognitive, and structural. As a result, saliency models were developed to assess whether an object would qualify as an attractive landmark based on its properties (Caduff & Timpf, 2008; Nothegger et al., 2004; Raubal & Winter, 2002). Based on the landmark types defined by Sorrows and Hirtle (1999), Raubal and Winter (2002) developed a model based on the visual, semantic (cognitive), and structural attraction of features in the environment to evaluate their use as landmarks for wayfinding purposes. In their non-experimental study, they used facade area (i.e., objects whose facade exceeds or falls below the surrounding facades), shape (i.e., an unorthodox shape among regular shapes), color (i.e., a red building among gray buildings), visibility (i.e., the area of the space from which the landmark is visible), and other visual properties (e.g., building texture and condition) to measure the landmark's visual attractiveness. Regarding the semantic or cognitive attractiveness of landmarks, Raubal and Winter (2002) used an object's cultural and historical importance (i.e., whether the object had a cultural, archaeological, or architectural status), explicit marks (i.e., building signage), and other semantic properties (i.e., prototypicality or implicit semantics, such as deducing that a building is a coffee shop when people are sitting and drinking coffee inside). Moreover, they used nodes, boundaries, and districts – Lynch's (1960) elements of the city – to determine the structural saliency of a landmark.

Nothegger et al. (2004) extended the work of Raubal and Winter (2002) to determine the most salient building facades in an urban environment. They used street-level images and ortho-images and an online database to extract the same visual and semantic (cognitive) measures of buildings' attractiveness for nine intersections in Vienna. To test their computed saliency results, they conducted a test with 40 subjects using a web-based questionnaire. They showed 360° panoramic images to the participants for each intersection in a randomized order and then asked them to rate the most prominent facade. Specifically, they asked the participants, *"Which is, in your opinion, the most prominent facade?"* which was followed by the additional instructions *"It could also be the one that you would quote when giving directions or the one that is the easiest to describe"* (Nothegger et al., 2004, pp. 128). The computed visual and semantic saliency model results were consitent with the human choice of landmarks at the tested intersections (Nothegger et al., 2004).

Caduff and Timpf (2008) argued that the above landmark saliency models are attributed only to distinct features (i.e., facade, shape, function) and thus fail to consider the three-pronged relationship between a landmark's perceptual saliency, the wayfinders' cognitive characteristics, and the task-based context. They describe perceptual saliency as the exogenous allocation of attention, which is a bottom-up process in which the users' attention is captured by salient features in the environment (Wolfe & Horowitz, 2017). Moreover, they developed an attention-based approach to assess landmarks' perceptual saliency based on the hypothesis that landmarks attract users' attention. With this approach in mind, landmarks' perceptual saliency was categorized as location-based (size, shape, and texture orientation), object-based (size, shape, and object orientation), or attention based on scene context (topology and metric refinements such as distance and direction; Caduff and Timpf 2008). In contrast to perceptual saliency, cognitive saliency modulates attention via a top-down approach (Wolfe & Horowitz, 2017) by focusing on the wayfinders' experience and knowledge (Caduff & Timpf, 2008). Wayfinders' internal mental representation is retrieved based on their degree of recognition (single observation or memorized features) and the idiosyncratic relevance based on their familiarity (personal, cultural, or historical significance) with individual features (Caduff & Timpf, 2008). Contextual saliency defines how much attention is needed to recognize potential landmarks and depends on task-based (i.e., route-planning, following, and learning) and modality-based (means of locomotion through the environment such as walking, driving, etc.) contexts (Caduff & Timpf, 2008).

While several saliency models have been proposed to identify the measurable visual properties of landmarks (Caduff & Timpf, 2008; Nothegger et al., 2004; Raubal & Winter, 2002), landmarks' structural saliency is the area of research with the greatest consensus (Yesiltepe et al., 2021). This consensus arises from the hypothesis that given their visual and cognitive qualities, landmarks located at decision points are more easily seen and better remembered (Lynch, 1960; Yesiltepe et al., 2021). Such landmarks serve as reference points of one's orientation and markers when a change in wayfinding trajectory is required, thus constituting effective wayfinding aids (Michon & Denis, 2001; Richter & Winter, 2014; Yesiltepe et al., 2021). Lovelace et al. (1999) used four different landmark conditions to study the importance of landmark location for participants who were familiar or unfamiliar with a campus area. They used choice-point landmarks (along the route and at intersections), potential choice-point landmarks (along the route but not at intersections), along-the-route landmarks (but not at intersections), and off-route landmarks. The authors asked the participants to provide route directions for the traversed route, retrace the route, and remember whether they were exposed to a scene during the navigation task. The results revealed that the landmarks along – but not necessarily at – decision points were used for familiar and unfamiliar route descriptions (Lovelace et al., 1999). These results indicate landmarks' importance not only at destination-relevant decision points but also along the route.

Given their visual, cognitive or semantic, and structural characteristics (Caduff & Timpf, 2008; Nothegger et al., 2004; Raubal & Winter, 2002; Sorrows & Hirtle, 1999), landmarks have undeniable importance for aided wayfinding (Raubal & Winter, 2002; Sorrows & Hirtle, 1999; Wiener et al., 2009); in particular, they develop and structure wayfinders' mental representation of the environment (Richter & Winter, 2014; Siegel & White, 1975). Hence, Richter and Winter (2014, pp. 50) stated that *"The fundamental role of landmarks for orientation and wayfinding stems from a strong correspondence between an experience captured in (spatial) memory and a location in the physical environment."* As salient environmental features, landmarks capture wayfinders' attention and help them to establish a link between the allocentric view of the map display and the egocentric, first-person perspective experienced during locomotion and wayfinding (Kiefer et al., 2014; Lobben, 2004; Richter & Winter, 2014; Wiener et al., 2009). Consequently, directing wayfinders' visual attention to task-relevant features on the mobile map and in the environment will facilitate the visual matching between the information sources. This, in turn, will help them to actively encode spatial information about the traversed environment (Chrastil & Warren, 2012; Richter & Winter, 2014; Willis et al., 2009).

Considering landmarks' undisputed role in wayfinding, methods of visualizing landmarks on mobile maps remain to be discussed, despite such visualization's potential to guide wayfinders' visual attention to task-relevant features on the aid and in the environment and thus improve visual matching and spatial knowledge acquisition. Unfortunately, there has been little research on the visualization of landmarks on mobile maps as wayfinding aids (Richter & Winter, 2014).

2.2.2 Landmark visualization

All maps, paper-based or digital, are products of design (Montello et al., 2018). They serve as effective and efficient communication tools when they are visually well-designed, clear, engaging, understandable, and depict relevant information, among other criteria (Montello et al., 2018). As the map creator and curator, the cartographer's role is to choose a graphical map design appropriate to a specific purpose and function (Slocum et al., 2022). There are many types of maps and tasks they support, and human navigation is one such task (Montello, 2005). A map's overall purpose as a wayfinding aid is to efficiently and successfully guide wayfinders through space (Allen, 1999; Slocum et al., 2022). Lynch (1960) stated that maps serving as wayfinding tools should be clear, readable, and contain a surplus of environmental cues, such as landmarks, to facilitate the wayfinding process and avoid the risk of getting lost.

The presentation design of environmental features on mobile maps may affect wayfinders' navigation performance and spatial learning (Montello, 2005; Montello et al., 2018; Richter et al., 2010). Despite landmarks' acknowledged importance to the wayfinding process, they are not visualized on the omnipresent mobile maps that serve as wayfinding aids (Grabler et al., 2008; Nothegger et al., 2004; Richter & Winter, 2014; Willis et al., 2009). When we perform a place search on these mobile map aids, they provide us with an optimal route and a sequence of directions to help us reach the searched destination. These directions are often enriched with points of interest (POIs), which serve as landmark substitutes (Nothegger et al., 2004; Richter & Winter, 2014). However, there are major differences between POIs and landmarks. While landmarks are distinctive environmental features used as navigation cues, POIs are locations designated as potential destinations because of their presumed attractiveness or for commercial gain (Nothegger et al., 2004). As a result, mobile maps often leave out landmarks altogether or depict them only as building footprints similar in style to other buildings (Grabler et al., 2008).

The lack of landmarks on mobile maps appears to negatively affect the matching process between the objects on the map and those in the physical environment (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009). Consequently, these aids consume wayfinders' visual attention, which, in turn, reduces their attention to task-relevant environmental features (Taylor et al., 2008) and their spatial knowledge of the traversed environment (Chrastil & Warren, 2012; Ishikawa et al., 2008; Willis et al., 2009). Thus, some scholars have suggested that, in order to support better spatial knowledge acquisition of the environment, mobile maps should enrich their wayfinding instructions by presenting landmark information to the users (Chrastil & Warren, 2012; Nothegger et al., 2004; Raubal & Winter, 2002; Richter & Winter, 2014; Thrash et al., 2019; Willis et al., 2009). Given that landmarks must have visual, structural, and cognitive saliency to support wayfinding (Caduff & Timpf, 2008; Nothegger et al., 2004; Raubal & Winter, 2002; Sorrows & Hirtle, 1999), the question arises of how to depict landmarks on mobile maps in a perceptually salient way in order to facilitate wayfinding and spatial knowledge acquisition (Elias & Paelke, 2008).

The cartographic design process has a tremendous arsenal of visual forms to effectively and efficiently communicate objects on mobile maps, ranging from abstract geometric symbols to texturized photo-realistic 3D models (Montello et al., 2018). One of the most common cartographic design techniques is to represent a physical object as a symbol on a map (MacEachren, 2004). Hence, MacEachren (2004) suggested a continuum from mimetic to arbitrary symbols for the representation of objects on maps (Figure 2.2). The author stated that the concept of representation and meaning in mapping should clearly distinguish between visually arbitrary (i.e., representing buildings with dots; right side of Figure 2.2) and mimetic symbols (i.e., representing buildings as realistic 3D objects; left side of Figure 2.2). Mimetic representations on a map retain the graphic characteristics of the represented objects. This makes it easier for the user to visually match them to the real-world objects, as no graphic interpretation is required (MacEachren, 2004).

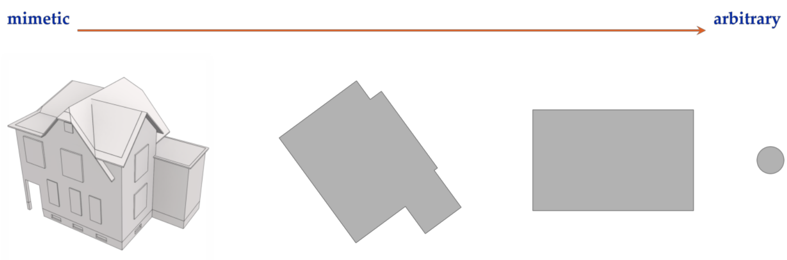

Figure 2.2: Example of the mimetic to arbitrary design continuum of map symbols for building visualization. Image modified after MacEachren (2004, pp. 259).

Elias and Paelke (2008) proposed a visualization of landmarks on mobile maps using various levels of abstraction to appropriately communicate their characteristics. The abstraction continuum (Figure 2.3) depicts landmarks on mobile maps ranging from realistic (i.e., realistic 3D models; far left panel of Figure 2.3) to abstract representation (i.e., abstract 2D labels; far right panel of Figure 2.3). Elias and Paelke (2008) denoted four building types that can be used as landmarks in route instructions: shops' trade names (i.e., Marriott, Lindt & Sprüngli, Zara, etc.) or type (i.e., hotel, bakery, fashion, etc.), a building's general function (i.e., school, church, library, etc.), and its visual properties (i.e., the yellow building, etc.). These building types resulted from a lab-based study in which the authors asked 20 participants to describe two familiar routes for people who were unfamiliar with them. In a second lab study, Elias and Paelke (2008) depicted each building type as realistic images, sketches, and symbols on a mobile map. They asked 20 participants to describe what they saw and to choose the best-suited visualization style. The results revealed that buildings with a characteristic architectural style, salient facades, a specific function, or a prominent location are easily recognized in the real world if depicted on the mobile map as a realistic 3D model, a detailed drawing, or at least a sketch of their outline (Elias & Paelke, 2008).

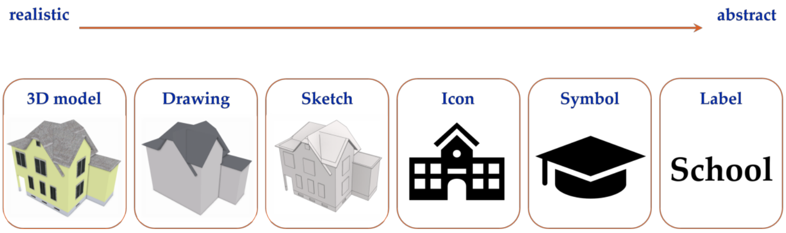

Figure 2.3: Levels of abstraction continuum for depicting landmarks on mobile maps. Image modified after Elias and Paelke (2008, pp. 44).

Although they may constitute adequate means for visualizing landmarks on mobile maps, the design guidelines of Elias and Paelke (2008) were not tested in a wayfinding context. Several wayfinding studies, mostly conducted in lab environments, have investigated the influence of different landmark visualization styles on wayfinders' visual attention and spatial knowledge acquisition. These studies have depicted landmarks using various levels of symbology (vignette, icon, or text; Franke and Schweikart 2017), dimensionality (2D vs. 3D; Liao et al. 2017), and abstraction (abstract vs. realistic; Plesa and Cartwright 2008; Lokka and Çöltekin 2019).

In a lab experiment, Franke and Schweikart (2017) depicted 10 landmarks with an increasing degree of abstraction, ranging from vignettes to icons and finally to text. The authors asked 21 participants (seven per landmark visualization style) to memorize a predefined route shown in a 10 x 10 grid in three minutes. The participants were asked to recall the memorized landmarks and draw the sequence of route directions on the same grid-like map template. The authors recorded the participants' eye-movement behavior during the memorization phase using a mobile eye-tracking device. They did not find an influence of landmark visualization styles on wayfinders' landmark recall, route sequence recall, or visual attention (fixation count and duration). The only influence of the landmark visualization style was found in the correlation between higher fixation counts on text landmarks and their improved recall accuracy. However, the improved recall of text landmarks did not translate to an improved route sequence recall (Franke & Schweikart, 2017). Among other suggestions, the authors recommended that future work should consider other forms of graphic variations (i.e., abstraction and realism) on mobile maps as wayfinding aids.

Liao et al. (2017) investigated the wayfinding performance and visual attention of 20 participants navigating with either the omnipresent abstract 2D map (Google Maps) or with a realistic 3D geo-browser (Google Earth) in a desktop-based navigation task. In the first task, they showed participants their position in the environment using Google Street View and then asked them to identify their position on the respective 2D or 3D map. In a second task, participants were asked to read and memorize a predefined route and to retrieve this knowledge in a third navigation task. The results of the first task revealed that the participants in the 2D group relied more on street names, while the 3D group relied more on landmarks to self-localize. However, there was no difference in the time required to complete the first task across the two groups. However, the results of the map-reading and memorization task, during which participants acquired spatial knowledge, revealed that the participants of the 3D group required more time to memorize the environment than the 2D group. In addition, the 3D group searched wider areas on the screen and had more fixations to obtain sufficient information for memorizing the environment. In contrast, the spatial distribution of fixation for the navigation task revealed that the 2D group searched more extensively for visual cues than the 3D group. Furthermore, participants using the abstract 2D map had more fixations, indicating that they processed more visual information. This resulted in a slower navigation performance (i.e., completion time) than the participants navigating with the realistic 3D geo-browser. The faster performance of the 3D group during the navigation task was associated with the use of landmarks for self-orientation and localization at decision points. Liao et al. (2017) argued that the 3D group's more efficient performance reflected the fact that its participants relied more on landmarks; moreover, they could easily match the visual information of the 3D geo-browser with the information experienced through Google Street View due to the more realistic depiction.

In another lab-based study, Lokka and Çöltekin (2019) investigated the influence of various levels of realism on wayfinders' navigation performance. The stimuli were designed as either fully abstract 3D, fully realistic 3D, or a mixed design. In the latter, only landmarks were depicted as realistic 3D features, while the rest of the environment was depicted as abstract 3D representations. The authors asked 42 participants to memorize a wayfinding route from origin to destination after watching videos of the three visualization types. As a first task, they provided screenshots of intersections and asked participants to recall whether they had seen them. In a second task, they asked participants to identify the facing direction at the end of the route after providing the starting orientation and the number of turns they took. Finally, participants were asked to recall the turning direction in a third task after seeing screenshots of all the intersections. Lokka and Çöltekin's (2019) results revealed that when asked to recall screenshots, the participants performed better with the mixed and realistic designs than the abstract design (no significant difference was observed between the mixed and realistic designs). Regarding the recall of the facing direction, the results did not reveal differences across the design conditions. In contrast, when asked to recall the turning direction at each intersection, the participants performed better with the mixed design than with the abstract or realistic design. In addition, when testing participants' long-term (after one hour and one week) recall accuracy, Lokka and Çöltekin (2019) found that their performance was again better with the mixed visualization depicting only landmarks as realistic 3D features.

The potential benefits of realistic 3D landmark visualization in the above-detailed studies (Liao et al., 2017; Lokka & Çöltekin, 2019) are attributed to the representations' increased visual saliency. This increased saliency facilitates the matching of information between the top-down perspective of the wayfinding aid and the first-person perspective experienced during wayfinding, enhancing participants' ability to actively encode spatial information (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009; Yesiltepe et al., 2021). Other benefits of a realistic 3D depiction include being perceived as more efficient, intuitive, memorable, desirable, and preferable (Liao et al., 2017; Lokka & Çöltekin, 2019; Parush et al., 2007; Zanola et al., 2009). For instance, Lokka and Çöltekin (2019) asked participants to rate their preference regarding the visualization type before and after the experiment. Before the experiment, 88% of participants preferred the fully realistic 3D visualization, while 12% preferred the mixed design, where only landmarks were depicted as realistic objects; no one preferred the abstract 3D visualization. However, after completing the experiment, participants' preferences swung in favor of the mixed design, with a 69% preference rate; the remaining 31% favored the realistic 3D visualization. In addition, other studies have found that a realistic 3D visualization even boosts participants' confidence in data accuracy (Zanola et al., 2009). Nevertheless, despite these design solutions' general benefits and popularity, wayfinders that employ them are not necessarily more effective or efficient (Franke & Schweikart, 2017; Kray et al., 2003; Oulasvirta et al., 2009; Thrash et al., 2019).

The extent to which one visualization style leads to better navigation performance and spatial learning is not affected only by the level of realism but also by individual and group differences (among other factors; Franke & Schweikart, 2017; Hegarty et al., 2009; Liao et al., 2017; Lokka & Çöltekin, 2019; Wilkening & Fabrikant, 2011). A fully realistic 3D visualization's higher visual complexity leads to information overload due to the extraneous details or *"visual clutter"* (Rosenholtz et al., 2007) presented to the users. Thus, the presence of task-irrelevant visual information impairs wayfinders' navigation performance (Liao et al., 2017; Lokka & Çöltekin, 2019). For instance, returning to Liao et al.'s (2017) study, the authors found that participants in the 3D group searched a wider area and required more time to memorize the map due to the higher visual complexity of the realistic 3D geobrowser. Additionally, in another study evaluating the effectiveness of realistic versus non-realistic 3D visualizations for wayfinding purposes, Plesa and Cartwright (2008) stated that a non-photorealistic 3D visualization – similar to the drawing or sketch design proposals of Elias and Paelke (2008) – provides the necessary visual information for an effective wayfinding task. In a map inference task, (Hegarty et al., 2009) found that an added level of realism on weather maps impaired the task performance of novice users. However, such realism did not impair the performance of expert users, revealing the role of individual and group differences between participants (Hegarty et al., 2009). In addition, in the above-presented study comparing three landmark visualization styles (vignette, icon, and text), Franke and Schweikart (2017) found that participants with higher spatial abilities had better recall accuracy when landmarks were depicted in vignette style. Similarly, Lokka and Çöltekin (2019) found that the mixed design improved the overall task recall accuracy of participants with both low and high spatial abilities scores compared to the fully realistic or fully abstract designs.

How much information to present to wayfinders appears to be a key decision when visualizing environmental features on mobile maps serving as wayfinding aids. For instance, Liao et al. (2017) used eye-tracking metrics such as pupil dilation to assess the cognitive workload of information processing. During the map-reading and memorization task, Liao et al. (2017) found that pupil dilation increased significantly in participants that had to memorize the fully realistic 3D geo-browser compared to the abstract 2D map. Presenting more visual information to wayfinders through mobile map aids will require higher cognitive resources for map-reading and information-processing, thereby increasing cognitive load and impairing navigation performance and spatial learning (Liao et al., 2017; Lobben et al., 2014; Lobben, 2004). Thus, Liao et al. (2017) suggested that abstract 2D maps should be enriched with realistic 3D landmarks and that realistic 3D maps should depict only task-relevant landmarks in 3D. These design recommendations reduce the amount of visual information presented to the user, enhance the visual matching process between the sources of information, and improve wayfinding performance and spatial learning, while reducing wayfinders' cognitive load.

2.3 Measuring cognitive load during navigation

Cognitive load describes the mental resources that users allocate to process the presented information and solve the task at hand (Sweller, 1988; Sweller et al., 1998; Van Merriënboer & Sweller, 2010). Sweller et al. (1998) stated that the primary concern of cognitive load theory is the ease with which the presented information is processed in humans' limited working memory (Shah & Miyake, 1999). Sweller et al. (1998) identified three types of cognitive load that affect humans' working memory: 1) *intrinsic load*, which is associated with the intrinsic demand of the task itself; 2) *extraneous load*, associated with how the task's material is designed and presented to the users, describing the detrimental effect on learning when cognitive resources are allocated to task-irrelevant information; and 3) *germane load*, associated with the actual learning occurring during the task. Sweller et al. (1998) conceptualized cognitive load as having a task-based dimension (i.e., the mental load imposed by the task) and a user-based dimension (i.e., the mental effort allocated to accommodate task demands), both of which affect learning performance. To improve users' learning performance, cognitive load theory focuses on the types of cognitive load and aims to develop design guidelines for better task instructions

(Sweller et al., 1998; Van Merriënboer & Sweller, 2010). While better instructions cannot alter intrinsic cognitive load without altering the task or the act of learning, they can alter both the extraneous and germane cognitive load (Sweller et al., 1998; Van Merriënboer & Sweller, 2010). In particular, improved task instructions reduce extraneous cognitive load and increase germane cognitive load by avoiding the effort required to process poorly designed task information (Sweller et al., 1998; Van Merriënboer & Sweller, 2010). Sweller et al. (1998) stated that these simultaneous changes in extraneous and germane cognitive load involve redirecting learners' attention away from task-irrelevant information and toward task-relevant information.

Cognitive load theory (Sweller, 1988; Sweller et al., 1998; Van Merriënboer & Sweller, 2010) plays an important role in the context of navigation, as wayfinders' cognitive demand is an important aspect of effective and efficient wayfinding and improved spatial learning performance (Lobben et al., 2014; Lobben, 2007; Lobben, 2004; Wiener et al., 2009). In the navigation context, intrinsic cognitive load corresponds to cognitively challenging and demanding wayfinding tasks (Farr et al., 2012; Ishikawa & Montello, 2006; Lobben, 2007; Montello, 2005). In cases of wayfinding aided by mobile maps, the intrinsic cognitive load increases, as wayfinders must identify map symbols and decipher their meaning, mentally rotate objects, establish a match between the allocentric and egocentric views, and self-localize (Lobben et al., 2014; Lobben, 2004; Wiener et al., 2009). However, spatial knowledge acquisition during aided wayfinding can be improved by simultaneously decreasing the extraneous cognitive load and increasing the germane cognitive load (Sweller et al., 1998; Van Merriënboer & Sweller, 2010). As cognitive load theory suggests, these changes in the extraneous and germane cognitive load can be achieved by improving the design of task instructions (Sweller et al., 1998; Van Merriënboer & Sweller, 2010). In the case of aided wayfinding, this includes improving the design of mobile maps (Bunch & Lloyd, 2006; Thrash et al., 2019).

Maps are cartographic products used as cognitive tools to help users navigate familiar and unfamiliar environments (Montello et al., 2018). The map is the most important transmission *"channel"* of information about the physical environment for pedestrians as map readers and users (Montello, 1998; Montello, 2005; Montello et al., 2018). Thus, the cartographer *"encodes"* the information of the physical environment, and the wayfinder *"decodes"* it to successfully complete the wayfinding task at hand (Montello et al., 2018). Cartographers have long realized that map design influences a map user's mind (Montello et al., 2018), and Montello (2002, pp. 283) labeled this recognition as *"intuitive map psychology"*. Relatedly, Montello et al. (2018) identified *"cognitive map-design"* and *"map psychology"* as two prominent approaches to understanding maps from a cognitive standpoint. The *cognitive map-design* approach focuses on designing effective and easy-to-use maps by considering human cognitive abilities (Montello et al., 2018). Meanwhile, the *"map psychology"* approach focuses on fundamental research questions concerning human cognition of and with maps (Montello et al., 2018).

The question of why some people can read maps better than others – and consequently navigate the environment more efficiently and acquire better spatial knowledge – has long intrigued psychologists and cartographers investigating the cognitive processes that occur during map reading (Lobben, 2004). To answer this question, psychologists mainly address their attention to human cognitive abilities, often ignoring the type and quality of the maps used for navigation (Lobben, 2007; Lobben, 2004). Meanwhile, cartographic research is interested in the cognitive principles of creating, designing, reading, and understanding maps (MacEachren, 2004; Montello, 2002; Montello et al., 2018). Therefore, the focus of research in cartography is on how map design influences the map user's mind (Bunch & Lloyd, 2006; Lobben, 2007; Lobben, 2004; Montello et al., 2018), as well as how we can design cognitively adequate maps for various user groups (e.g., novices and experts; Bunch and Lloyd 2006) and task contexts (e.g., wayfinding in emergency situations; Fabrikant 2022; Fabrikant and Lobben 2009). However, cartographers may lack a deeper understanding of cognitive psychology, its theoretical constructs, and the methodological frameworks and tools used to investigate humans' cognitive processes (Lobben, 2007; Lobben, 2004; Schinazi & Thrash, 2018).

Eye-tracking is one of the most frequent methods used by cartographers to investigate how map design influences users' cognitive states (Kiefer et al., 2016; Kiefer et al., 2017). The technique captures humans' gaze behavior in response to changes in stimuli (e.g., a map) by recording eye movements (Duchowski, 2017; Holmqvist et al., 2011; Kiefer et al., 2017). To identify the cognitive load users must endure when using maps, researchers have employed eye-tracking metrics such as pupil diameter (Holmqvist et al., 2011; Kiefer et al., 2016; Kiefer et al., 2017; Krejtz et al., 2018; Liao et al., 2017; van der Wel & van Steenbergen, 2018). Previous research has already demonstrated that an increase in pupil diameter (i.e., dilation) is associated with increased task difficulty, which elicits higher mental activity (Holmqvist et al., 2011; Kiefer et al., 2016; Krejtz et al., 2018; Liao et al., 2017). However, pupil dilation is indirectly linked to stimuli and humans' internal state, as it is subject to individual differences and sensitive to the environment due to light changes (Beatty & Lucero-Wagoner, 2000; Holmqvist et al., 2011; van der Wel & van Steenbergen, 2018). Hence, pupil diameter constitutes only an indirect methodology for investigating wayfinders' cognitive load (Beatty & Lucero-Wagoner, 2000; Holmqvist et al., 2011; van der Wel & van Steenbergen, 2018). In order to address these shortcomings, cartography researchers started using methods from psychology and cognitive neuroscience to investigate the cognitive processes connected with map use for wayfinding purposes (Lobben et al., 2005; Lobben & Lawrence, 2015; Lobben et al., 2009; Lobben et al., 2014; Lobben, 2007; Montello et al., 2018; Schinazi & Thrash, 2018).

These methods vary from self-reports of perceived cognitive load (Hart & Staveland, 1988) to dual-task paradigms (i.e., concurrently performing a primary navigation task and a secondary working memory task (Credé et al., 2020; Meneghetti et al., 2021)). However, as participants normally self-report cognitive load after the wayfinding task is completed, this method cannot capture cognitive load in real time. Meanwhile, the dual-task paradigm, where wayfinders complete a working memory task (e.g., a tapping task; Credé et al. 2020; Meneghetti et al. 2021) while traversing the environment, interferes with and interrupts participants' learning of the environment's spatial configuration. Another method deployed to investigate wayfinders' cognitive load is to examine their neural brain activity during wayfinding (Chrastil, 2013; Epstein et al., 2017; Montello et al., 2018; Schinazi & Thrash, 2018). This method was derived from Tolman's (1948) *"cognitive map"* hypothesis (see Section 2.1.1), which proposes that rats' brains build a unified spatial representation of the environment to support spatial memory and guide present and future movement through the environment (Epstein et al., 2017). This hypothesis received neurobiological support when place cells were discovered in the rats' hippocampus, which fire as a function of rats' spatial position (Keefe & Nadel, 1978; O'Keefe & Dostrovsky, 1971). Recent work suggests a similar functional organization of the human brain, providing insights into how cognitive maps are used during spatial navigation (Epstein et al., 2017). Several brain regions are associated with processing high-level cognitive information for spatial navigation (see reviews by Chrastil, 2013; Epstein et al., 2017; Schinazi & Thrash, 2018). Nevertheless, the methodological focus of the present thesis will be on neuroscientific approaches applied in cartographic research as direct measures of brain activity during cognitively demanding, map-aided wayfinding tasks.

Functional magnetic resonance imaging (fMRI) is the cognitive neuroscience method most frequently adopted by cartographers to investigate the brain's neural activity during map-aided spatial navigation (Chrastil, 2013; Montello et al., 2018; Schinazi & Thrash, 2018). fMRI is a brain-scanning method that measures wayfinders' brain activity through changes in blood flow (Chrastil, 2013; Epstein et al., 2017; Huettel et al., 2004; Montello et al., 2018). The technique records the blood oxygen level–dependent contrast in brain cells, as brain regions are assumed to require more blood oxygen to perform more demanding cognitive tasks (Chrastil, 2013; Huettel et al., 2004; Montello et al., 2018). Lobben et al. (2005) and Lobben et al. (2014) were the first researchers to employ fMRI in cartography to investigate neural brain activations during map use. Lobben et al. (2005) used fMRI to investigate participants' map memory (i.e., route recognition on maps), map rotation (i.e., identifying whether two maps are flipped and rotated or only rotated from each other), and sleuthing (i.e., identifying the facing direction on a map given an image of the environment from the first-person perspective and the location of the image marked on the map). The behavioral data revealed that participants required more time for sleuthing than for the other tasks, and the performance on sleuthing and map rotation tasks were correlated (Lobben et al., 2005). Moreover, the authors' fMRI analyses with only one participant revealed higher brain activations for the sleuthing than for the map rotation task (Lobben et al., 2005). Lobben et al. (2014) extended their previous work by examining the neural activation differences between the mental rotation of maps with labels, maps without labels, and simple geometric features. Their fMRI results revealed both similarities and differences between participants' brain activations associated with the map conditions (i.e., with and without labels) and geometric features (Lobben et al., 2014). Despite the advances of Lobben et al. (2005) and Lobben et al. (2014) in the field of cartography, Schinazi and Thrash (2018) pointed out shortcomings related to the sample size, the lack of stimulus complexity, and the exploratory approach of the neuroimaging data, which focused on the whole brain rather than investigating hypothesis-driven brain regions.

Although it is the most popular method, fMRI has several shortcomings for investigating cognitive load during wayfinding tasks (Delaux et al., 2021; Epstein et al., 2017). While it provides a high degree of spatial resolution in measuring the brain, it lacks temporal resolution, as the changes in cells' blood flow take time (Chrastil, 2013; Delaux et al., 2021; Sherrill et al., 2015). Furthermore, fMRI navigation experiments are performed only in the lab; participants must remain stationary in the scanner, where they perform virtual navigation or spatial memory recall tasks or view navigation-relevant stimuli such as maps (Delaux et al., 2021; Epstein et al., 2017; Lobben et al., 2005; Lobben et al., 2014). Additionally, fMRI navigation studies miss the vestibular and proprioceptive inputs from locomotion through the environment, which are important in acquiring spatial knowledge (Epstein et al., 2017; Montello, 1998; Montello, 2005; Siegel & White, 1975). Consequently, fMRI is an unsuitable method for investigating cognitive load during locomotion in real-world wayfinding tasks (Delaux et al., 2021; Epstein et al., 2017; Zaitsev et al., 2015). However, recent technological developments in the field of neuroimaging have opened the possibility of recording humans' brain activity with electroencephalography (EEG) devices during active wayfinding tasks in real-world environments (Debener et al., 2012; Liebherr et al., 2021; Park et al., 2018; Reiser et al., 2019; Wunderlich & Gramann, 2021a). EEG captures the brain's electrical activity at a higher temporal resolution and can assess wayfinders' cognitive load without interfering with the navigation task, thus providing high ecological validity (Cheng et al., 2022; Chrastil, 2013; Cohen, 2014; Park et al., 2018).

EEG is an established method to measure wayfinders' cognitive load during navigation tasks in psychology and cognitive neuroscience (Bohbot et al., 2017; Delaux et al., 2021; Gehrke et al., 2018; Gramann et al., 2010; Liebherr et al., 2021; Sharma et al., 2017; Wunderlich & Gramann, 2018). However, with some exceptions, the method has yet to be applied in geography and cartography to better understand how wayfinders extract information from and navigate with map stimuli (Montello et al., 2018). In one of the few studies conducted by geographers, Cheng et al. (2022) utilized EEG to measure wayfinders' cognitive load during a VE navigation task. In particular, Cheng et al. (2022) investigated wayfinders' spatial knowledge acquisition and cognitive load by modifying the number of landmarks on a mobile map that they had to learn during a route-following task. They exposed participants to three VEs equipped with either three, five, or seven realistic 3D landmarks and asked them to follow the predefined route as quickly as possible and learn the landmarks depicted along the route. After each navigation trial in each city, the authors assessed the participants' landmark, route, and survey knowledge acquisition. Meanwhile, the participants' brain activity was recorded with a mobile EEG throughout the experiment. The behavioral results revealed that the participants' landmark and route knowledge improved when the number of landmarks shown on the mobile map increased from three to five, while no further improvement was observed in the seven-landmarks condition. However, no improvement in spatial knowledge acquisition performance was observed when exposing wayfinders to three, five, or seven landmarks depicted on the mobile map. Further, the EEG analyses revealed that wayfinders' cognitive load increased in the seven-landmark condition. Cheng et al.'s (2022) results concerning cognitive load are in line with previous work demonstrating that an increase in the number of elements to be learned may increase cognitive load (Sweller, 1988; Sweller et al., 1998; Van Merriënboer & Sweller, 2010). Cheng et al. (2022) stated that while visualizing landmarks on mobile maps improves wayfinders' acquisition of spatial knowledge about traversed novel environments, map designers should design mobile maps that do not exceed wayfinders' cognitive capacities.

According to cognitive load theory, users' cognitive states are affected not only by the amount of information present but also by their individual and group differences (e.g., their level of expertise and experience; Sweller 1988; Sweller et al. 1998; Van Merriënboer and Sweller 2010). Bunch and Lloyd (2006) stated that users' expertise and cognitive load are key aspects to successful map-reading and enhanced spatial learning (Bunch & Lloyd, 2006). Therefore, users with different levels of expertise process spatial information differently with various map designs (Bunch & Lloyd, 2006). Consequently, in order to minimize cognitive effort, novice users might benefit more from simple map designs (Bunch & Lloyd, 2006). In contrast, such a design might not provide what experts need to solve complex tasks and further enhance their spatial learning abilities (Bunch & Lloyd, 2006). For instance, Lanini-Maggi (2017) was one of the first studies in the domain of geography to use EEG as a method of assessing cognitive load across expertise. The authors found that, in general, novice air traffic controllers exhibited a higher cognitive load than experts when performing an aircraft movement detection task. However, Lanini-Maggi (2017) did not find differences in cognitive load across animation design conditions (i.e., semi-static vs. continuous) or expertise (i.e., novice vs. experts). Similarly, Keskin et al. (2020) did not find differences in cognitive load across experts and novices (i.e., based on education background in geo-related fields) or various map designs (i.e., varying in levels of depicted environmental features such as roads, parks, rivers, and lakes) when performing a map recall task. Despite the lack of observed differences in cognitive load among various map design conditions and expertise, these studies (Keskin et al., 2020; Lanini-Maggi, 2017) have made an important methodological contribution to the fields of geography and cartography by incorporating neuroscientific methods of investigating users' cognitive states when using maps (Montello et al., 2018; Schinazi & Thrash, 2018).

Some studies have employed EEG as a neuroscientific method of investigating cognitive load in the geo-domain (i.e., geography, cartography, and GIScience) in recent years (Cheng et al., 2022; Keskin et al., 2020; Lanini-Maggi, 2017; Lobben et al., 2005; Lobben et al., 2014). However, all these studies have been conducted in controlled lab-based environments, and only some have investigated a navigation context. In one study of navigation, Cheng et al. (2022) presented empirical evidence that five landmarks represent the necessary amount of information on mobile maps to support wayfinders' spatial knowledge acquisition and mitigate cognitive load while navigating a route of approximately 1 km. Nevertheless, their navigation study was conducted in a controlled, lab-based environment and focused on the number of landmarks; it did not address how to effectively visualize task-relevant landmarks on mobile map aids to support wayfinders' spatial knowledge acquisition and cognitive load. According to cognitive load theory, wayfinding is an intrinsically demanding task (Lobben et al., 2014; Lobben, 2004). Consequently, in order to improve spatial knowledge acquisition, cartographers must design better wayfinding maps that will reduce wayfinders' extraneous cognitive load and increase their germane cognitive load (Bunch & Lloyd, 2006). Therefore, mobile maps serving as wayfinding aids must focus on landmarks to guide wayfinders' attention to these task-relevant features on the mobile map and in the environment, which will facilitate spatial learning and mitigate cognitive load (Chrastil & Warren, 2012; Richter & Winter, 2014; Thrash et al., 2019; Willis et al., 2009). Yet, to the best of my knowledge, no empirical study conducted in real-world environments has employed EEG to investigate how various landmark visualization styles depicted on mobile maps influence wayfinders' cognitive load and spatial learning.

2.4 Summary

Human navigation, with its locomotion and wayfinding components, is an important skill that facilitates our daily activities (Montello, 2005). Through wayfinding, humans continuously acquire spatial knowledge of the environment in the form of landmark, route, and survey knowledge (Montello, 1998; Siegel & White, 1975). Humans are aided in their wayfinding quests by their internal cognitive map (Tolman, 1948) and external wayfinding map aids (Allen, 1999; Wiener et al., 2009). However, the use of mobile map aids negatively impacts wayfinders' visual attention and spatial knowledge acquisition (Dahmani & Bohbot, 2020; Gardony et al., 2015; Hejtmánek et al., 2018; Ishikawa, 2019). To ameliorate this effect, previous research indicates that mobile maps should cue wayfinders' visual attention to task-relevant landmarks on the map aid and in the environment (Chrastil & Warren, 2012; Richter & Winter, 2014; Willis et al., 2009). Landmarks are environmental features that stand out from their surroundings due to their characteristics (Sorrows & Hirtle, 1999) and serve to structure humans' mental representation of spaces (Richter & Winter, 2014). Due to their characteristics, landmarks serve as attention-grabbing features and help wayfinders to visually match the allocentric view of the mobile map and the egocentric, first-person view of the physical environment (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009). Therefore, landmarks bear high practical importance for human wayfinding and spatial knowledge acquisition (Couclelis et al., 1987; Raubal & Winter, 2002; Richter & Winter, 2014).

Despite their acknowledged importance for human wayfinding, landmarks are not depicted on the ubiquitous mobile map aids (Grabler et al., 2008; Nothegger et al., 2004; Thrash et al., 2019; Willis et al., 2009). Prior research has proposed design guidelines for depicting landmarks on mobile maps along an abstraction continuum from abstract 2D labels to realistic 3D models (Elias & Paelke, 2008). Considering their predominant visual and structural characteristics (Sorrows & Hirtle, 1999) and the importance of bottom-up, stimulus-driven guidance (Wolfe & Horowitz, 2017) using task-relevant features on the mobile map, landmarks should be visualized in a perceptually salient way on mobile maps (Elias & Paelke, 2008; Liao et al., 2017; Lokka & Çöltekin, 2019). However, no prior research has directly compared the effectiveness of various landmark visualization styles on mobile maps for spatial learning during real-world navigation tasks. Furthermore, the potential effects of various landmark visualization styles on wayfinders' gaze behavior during aided real-world navigation and on their spatial knowledge acquisition remain to be investigated.

The current mobile maps not only fail to depict task-relevant landmarks but also present wayfinders with a large amount of extraneous visual information (Lokka & Çöltekin, 2019; Thrash et al., 2019). Cognitive load theory (Sweller, 1988; Sweller et al., 1998) has indicated that an increase in wayfinders' extraneous load will impair users' learning performance, as their cognitive resources are allocated to task-irrelevant information. Cognitive load theory suggests that to improve wayfinders' learning performance, we should decrease their extraneous cognitive load while increasing their germane load (Bunch & Lloyd, 2006; Sweller et al., 1998; Van Merriënboer & Sweller, 2010). One possible way to achieve these changes in spatial learning performance would be to present wayfinders with mobile maps that depict landmarks and guide their attention to these task-relevant features (Bunch & Lloyd, 2006; Chrastil & Warren, 2012; Richter & Winter, 2014). However, there is a lack of empirical research examining the influence of landmark visualization styles on wayfinders' spatial learning and cognitive load by means of EEG during mobile map–aided, real-world wayfinding tasks.

Previous research has shown that how wayfinders acquire knowledge about the spatial configuration of novel environments depends on individual and group differences in their spatial abilities (Hegarty et al., 2018; Ishikawa, 2022; Montello, 1998; Newcombe et al., 2022). However, experience and expertise in a particular domain can influence task performance and make it less sensitive to individual differences in spatial abilities (Hegarty et al., 2009; Keehner et al., 2004; Woollett & Maguire, 2010; Woollett et al., 2009). In addition, experts are more efficient at guiding their visual attention to task-relevant features and thus are less distracted by task-irrelevant information (Lanini-Maggi et al., 2021; Ooms et al., 2014). Furthermore, they are trained to endure the cognitive demands of the task, in contrast to non-experts (Lanini-Maggi, 2017). While most empirical navigation research rightly controls for the influence of individual and group differences in spatial ability (Cheng et al., 2022; Credé et al., 2019, 2020; Lokka & Çöltekin, 2019), there is a lack of empirical wayfinding studies conducted with expert navigators to investigate the influence of various landmark depiction styles on their visual attention, spatial learning, and cognitive load.

In summary, the present thesis aims to close these research gaps by investigating the influence of various landmark visualization styles on wayfinders' navigation efficiency and effectiveness, spatial knowledge acquisition, visual attention, and cognitive load when using mobile maps. To achieve this aim, I conducted one real-world wayfinding study with expert wayfinders and one with wayfinders sampled from the general population. In both studies, I controlled for wayfinders' interpersonal variability in spatial abilities, utilizing the methodological approach detailed in the following chapter.

METHODOLOGY 3

> *The experiment is the most powerful and most reliable lever enabling us to extract secrets from nature.*
>
> — **Wilhelm Conrad Röntgen**
> (Nobel Prize–winning Physicist)

As of yet, and to the best of my knowledge, no studies have empirically investigated how landmark visualization styles depicted on mobile maps influence wayfinders' human navigation behavior in real-world environments. In this chapter, I will present the methodological framework adopted to address the main research question: how landmarks can be displayed to wayfinders on a mobile map to direct their visual attention to task-relevant features and improve their spatial learning while mitigating the navigation task's intrinsic cognitive load. This chapter presents an overview of the methodology common to both empirical navigation studies conducted as part of this thesis. A detailed description of each study is provided in the methods sections of Chapter 4 and Chapter 5. First, in Section 3.1, I will elucidate the advantages of real-world wayfinding experiments for understanding human spatial *"cognition in the wild"* (Hutchins, 1995, pp. xiii) – that is, cognition in its natural surroundings, outside of controlled laboratory settings. Second, in Section 3.2, I will describe the design of the mobile map applications (i.e., hardware and software) used to aid wayfinders throughout the navigation tasks. Finally, in Section 3.3, I will provide an overview of the experimental variables. First, I will describe the landmark visualization style as the manipulated independent variable, then present all the dependent variables utilized to measure wayfinders' navigation performance, spatial knowledge acquisition, visual attention, and cognitive load.

3.1 Real-world wayfinding studies

Although there is an extensive literature investigating human navigation behavior and spatial cognition with mobile maps, empirical wayfinding studies aided by mobile maps in real-world environments are scarce (Chrastil & Warren, 2012; Ishikawa et al., 2008; Montello et al., 2004). In contrast, many wayfinding experiments take place in desktop *"virtual reality"* (VR) setups, where the wayfinders control their movements in simulated *"virtual environments"* (VE; Chrastil & Warren, 2012; Montello et al., 2004). Such studies allow researchers to design fully controlled VEs and experimental variables across participants and conditions (Chrastil & Warren, 2012; Coutrot et al., 2019; Credé, 2019; Hejtmanek et al., 2020; Montello et al., 2004). However, while past research has found some concordance in wayfinders' navigation performance across VR and real environments (Coutrot et al., 2019; Montello et al., 2004; Richardson et al., 1999), real-world environments still outperform VR setups in terms of wayfinders' spatial knowledge acquisition (Chrastil & Warren, 2012; Hejtmanek et al., 2020; Montello et al., 2004). Therefore, empirical wayfinding studies conducted in VR must be cautious not to draw conclusions about real-world navigation behavior (Hegarty et al., 2006). VR studies' limitations concerning spatial knowledge acquisition are attributed to the lack of bodily motion cues and active learning (Chrastil & Warren, 2012; Credé, 2019; Hejtmanek et al., 2020; Montello et al., 2004; Park et al., 2018). These limitations are still present despite technological advancements in VR systems that try to mimic real-world locomotion by using, for instance, foot-paddles (Cheng et al., 2022; Credé, 2019; Credé et al., 2020) or even full immersion (Hejtmanek et al., 2020; Park et al., 2018).

In their review of active real-world and passive VR wayfinding studies, Chrastil and Warren (2012) suggested that the passive exposure to and active exploration of real-world environments have important implications for how wayfinders acquire landmark, route, and survey knowledge. Although VR wayfinding experiments include some physical movements (i.e., hand, head, or body movements in fully immersive VR), this process is quite different from actually walking around an environment; in particular, the latter provides qualitatively different motor, proprioceptive, and vestibular information (Chrastil & Warren, 2012; Montello et al., 2004). Therefore, it is intuitively obvious that wayfinders' spatial learning will be more thorough when actively exploring a physical environment than when passively exposed to it (Chrastil & Warren, 2012). Chrastil and Warren (2012, p. 2) identified five components of active exploration that contribute to improved spatial knowledge acquisition: 1) efferent outward motor movements that determine locomotion of a traveled route; 2) reafferent proprioceptive and vestibular information about bodily movement; 3) allocation of attention to task-relevant navigation features in the environment; 4) cognitive decisions regarding the direction of the route or travel; and 5) mental manipulation or transformation of spatial information in working memory.

Chrastil and Warren (2012) found that idiothetic information – the combination of efferent and reafferent components (Mittelstaedt & Mittelstaedt, 2001) – collected when walking in a real-world environment contribute to path integration and the acquisition of metric survey knowledge. In addition, the idiothetic information, in combination with active decision-making regarding the traveled route, can contribute to route and survey knowledge (Chrastil & Warren, 2012; Montello et al., 2004). Furthermore, Chrastil and Warren (2012) found that allocating attention to task-relevant landmarks in the environment facilitates the acquisition of route and survey knowledge. Finally, Chrastil and Warren's (2012) results revealed that spatial knowledge acquisition during real-world navigation might be enhanced by the active manipulation and transformation of the spatial information encoded in working memory. Hence, the idiothetic information present during active exploration of the environment is crucial in revealing the influence of visual attention and active decision-making in spatial knowledge acquisition (Chrastil & Warren, 2012; Hejtmanek et al., 2020; Park et al., 2018). However, real-world navigation is difficult to recreate in the lab, which may explain VR studies' mixed results (Chrastil & Warren, 2012; Hejtmanek et al., 2020; Montello et al., 2004; Park et al., 2018).

Wayfinding in real-world environments affects not only spatial knowledge acquisition but also how wayfinders' brains capture, disseminate, represent, and interact with continuous and highly complex inputs from the external world (Park et al., 2018; Spiers & Maguire, 2006). Researchers in the domain of spatial cognition have provided significant contributions in identifying the brain regions associated with spatial navigation (see reviews by Chrastil, 2013; Epstein et al., 2017; Schinazi & Thrash, 2018). However, due to the limitations of traditional imaging techniques (e.g., fMRI), most of these studies have been carried out in controlled laboratory settings (Epstein et al., 2017; Park et al., 2018; Spiers & Maguire, 2006). Although controlled fMRI experiments provide useful insights into neural responses (Epstein et al., 2017; Park et al., 2018; Spiers & Maguire, 2006) to map stimuli (Lobben et al., 2005; Lobben et al., 2014), Spiers and Maguire (2006, p. 1826) stated that *"they cannot hope to mirror the challenges faced by the brain in the real world"*. Consequently, technological advancements in mobile brain imaging, such as mobile EEG, have provided an excellent opportunity to examine how the brains of wayfinders respond while actively perambulating real-world environments (Gramann et al., 2014; Gramann et al., 2011; Klug et al., 2022; Park et al., 2018).

Despite the established advantages of understanding human navigation behavior, real-world wayfinding empirical experiments also pose challenges. One of the most significant is that wayfinding experiments in a dynamic, ever-changing real-world environment cannot be entirely controlled (Brügger, 2020; Coutrot et al., 2019; Credé, 2019; Park et al., 2018; Wunderlich & Gramann, 2021b). As a result, every participant will encounter different environmental conditions (e.g., weather, lighting, traffic, passersby) that might influence their navigation behavior and spatial knowledge acquisition (Brügger, 2020; Park et al., 2018). The main concern with regard to such environmental conditions is that data analysis in real-world wayfinding studies becomes more challenging due to noise and external artifacts (Brügger, 2020; Kiefer et al., 2014; Klug et al., 2022; Park et al., 2018; Wunderlich & Gramann, 2021a). Nevertheless, the challenges of real-world studies are overshadowed by their high ecological validity (Brügger, 2020; Kiefer et al., 2014; Park et al., 2018). Furthermore, developments in technologies such as mobile eye-tracking, mobile EEG, GPS mobile map aids, and analysis methods make it possible to capture and examine relevant human navigation behaviors away from the controlled lab and in the real world (Klug et al., 2022; Park et al., 2018).

Considering their high ecological validity, I conducted two real-world navigation studies and utilized mobile eye-tracking and EEG to record wayfinders' visual attention and cognitive load, respectively. These measurements were recorded while the participants actively explored two real-world environments aided by a mobile map enriched with landmarks.

3.2 Mobile map aids

During both studies, participants were asked to navigate two real-world environments equipped with mobile map aids. The mobile maps were presented as a map application (Figure 3.1–A) and were displayed on a Samsung Galaxy Tab A 10.1″ tablet (Figure 3.1–B) with a 1920 × 1200 display resolution. The mobile map applications were set to display a *north-up* map at the start. They did not allow for activating, deactivating, or switching layers (i.e., changing the base map), thus ensuring that all the participants were exposed to the same map features. However, to ensure a realistic navigation experience similar to their personal devices, wayfinders could zoom, pan, rotate, and tilt the map display as desired. The map applications remained in the original north-up orientation and the initial zoom level if the wayfinder did not interact with the display. Contrary to the navigation experience with current GPS-equipped mobile navigation systems, the mobile map applications developed for both studies did not show users' location during the navigation task. I did not implement the common *"blue dot"* in the map applications because I was interested in investigating how wayfinders complete self-localization and orientation with the help of landmarks (Kiefer et al., 2014). Furthermore, relying on the *"blue dot"* for self-localization and orientation has been found to deteriorate wayfinders' spatial knowledge (Brügger, 2020).

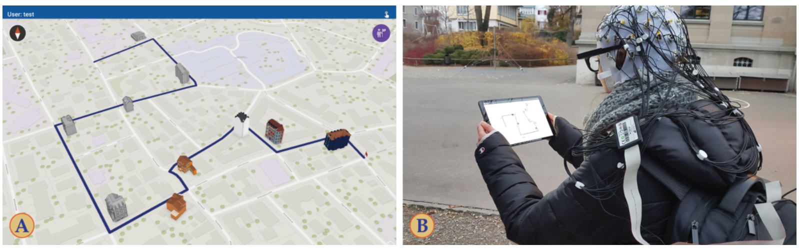

Figure 3.1: The mobile map application depicts landmarks, a route, and the destination point (A); Wayfinder using the mobile map application in a tablet device and equipped with eye-tracking glasses and an EEG cap attached to a laptop in the wayfinder's backpack (B).

The main elements of the map applications were the mobile map and the user interface buttons, which were presented as icons. The interface buttons consisted of zoom-in and zoom-out buttons that participants could use to zoom in and out to areas of interest (in addition to double-tapping and using the two-fingers gesture), a home button that participants could use to bring the mobile map to the initial position and scale, and a north arrow that showed participants the direction of north on the map and adapted after changes in map orientation. The mobile map (Figure 3.1–A) consisted of a topographic base map[1] provided by Esri Suisse[2], a predefined route that participants had to follow, a map symbol to mark the destination point (i.e., a red flag), and the landmarks depicted along the route (see Section 3.3.1 for

[1]World Topographic Swiss Style (VT) base map; https://www.arcgis.com/home/item.html?id=c29bcd10cc4d48749c4c05cc348fa754
[2]Esri Suisse, Zurich, Switzerland; https://www.esri.ch/de-ch/home

the design of landmarks). I used ArcGIS Pro 2.8.0[3] to design the maps and share them as web maps on the ArcGIS Online platform.[4] For Study I, I used the shared web map to create a mobile map application in ArcGIS Web AppBuilder.[5] For Study II, I incorporated the web map with the ArcGIS Runtime API for Android[6] and created a mobile map application using Android Studio version Arctic Fox 2020.3.1.[7] Throughout this thesis, the mobile map applications displayed on the tablet are referred to as the *"mobile map."*

3.3 Experimental variables

Table 3.1 shows an overview of the independent and dependent variables used in Studies I and II. The remainder of this section (structured accordingly) will provide a detailed description of how I manipulated the independent variable (Section 3.3.1) and which test measurements I utilized as dependent variables (Section 3.3.2).

Table 3.1: Overview of the independent and the dependent variables of Studies I and II.

	Independent Variable			
		Landmark visualization styles		
Study I		Abstract 2D	vs.	Realistic 3D
Study II		Abstract 3D	vs.	Realistic 3D
	Dependent Variables			
	Navigation performance	*Spatial knowledge*	*Visual attention*	*Cognitive load*
Study I	Task accuracy Completion time	Survey knowledge	Eye-tracking	EEG Self-reports
Study II	Task accuracy	Landmark knowledge Route Knowledge Survey knowledge	Eye-tracking	EEG Self-reports

3.3.1 Independent variable

Two wayfinding studies were conducted in real-world settings. The independent variable for both studies was the landmark visualization style. This independent variable originated from landmarks'

[3]Esri, CA, USA; https://www.esri.com/en-us/arcgis/products/arcgis-pro
[4]Esri, CA, USA; https://www.esri.com/en-us/arcgis/products/arcgis-online
[5]Esri, CA, USA; https://www.esri.com/en-us/arcgis/products/arcgis-web-appbuilder/resources
[6]Esri, CA, USA; https://developers.arcgis.com/android/
[7]Google LLC, CA, USA; https://developer.android.com/studio

established role in wayfinding (see Section 2.2) and design recommendations that mobile maps should focus on the depiction of landmarks to guide users' attention to task-relevant features for improved spatial knowledge acquisition (Chrastil & Warren, 2012; Richter & Winter, 2014; Thrash et al., 2019; Willis et al., 2009). Considering landmark characteristics (see Section 2.2.1), previous research on landmark visualization (see Section 2.2.2) has proposed the depiction of landmarks across a mimetic to arbitrary continuum (Figure 2.2; MacEachren 2004) or across a realistic to abstract continuum (Figure 2.3; Elias and Paelke 2008). Per their empirical results, Liao et al. (2017) and Lokka and Çöltekin (2019) suggested a design solution for landmark visualization: including first-person viewing of 3D landmarks on planar mobile maps and increasing the visual saliency of landmarks while excluding other irrelevant features from mobile maps.

Based on these design recommendations, in Study I, landmarks were depicted as either common abstract 2D building footprints or realistic, high-fidelity 3D building models (Figure 3.2–A). Although 3D landmark visualization facilitates visual matching and spatial learning (Liao et al., 2017; Lokka & Çöltekin, 2019), increased realism does not necessarily translate to improved navigation performance and spatial learning (Franke & Schweikart, 2017; Hegarty et al., 2009; Lokka & Çöltekin, 2019; Plesa & Cartwright, 2008; Wilkening & Fabrikant, 2011). For instance, as noted earlier (see Section 2.2.2), Plesa and Cartwright (2008) found that an abstract 3D landmark visualization provides the necessary visual information for effective wayfinding and spatial knowledge acquisition. For this reason, in Study II, landmarks were visualized as either abstract or realistic 3D building models (Figure 3.2–B).

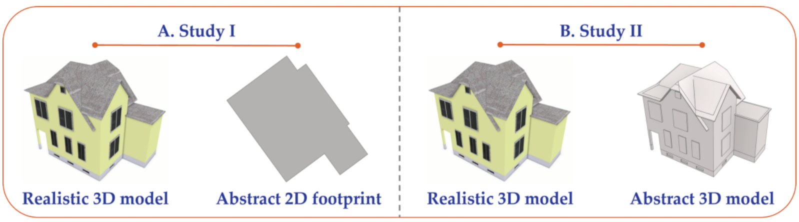

Figure 3.2: Examples of landmark visualization style as the independent variable for Studies I (A) and II (B).

Like the other spatial features (i.e., predefined route and destination point; [see Section 3.2]), the abstract 2D building footprints were designed in ArcGIS Pro 2.8.0 and shared as web map features on the

ArcGIS online platform to create the mobile maps. To create the 3D building models used in both studies, I used the freely available *swissBUILDINGS3D 2.0*[8] dataset provided by the Swiss Federal Office of Topography – *swisstopo*.[9] This vector-based dataset depicts buildings as 3D models, including roof geometries and overhangs. Despite the dataset's high degree of 3D detail, accurate building volumes, and the high coverage of Switzerland's territory, these 3D models are not rendered with facade or roof details and texture. Therefore, I used ArcGIS CityEngine 2019.0[10] to design high-fidelity abstract and realistic 3D building models (Figure 3.2) from the *swissBUILDINGS3D 2.0* dataset. Specifically, I imported the dataset into ArcGIS CityEngine and kept only the 3D models corresponding to the task-relevant landmarks. A detailed description of the procedure used to select task-relevant landmarks for each study is provided in Chapter 4 and Chapter 5. To create the abstract 3D models, I manually added facade and roof details (e.g., doors, windows, chimneys, etc.) to the volumetric 3D models of the *swissBUILDINGS3D 2.0* dataset in ArcGIS CityEngine. I used photographs of the respective landmarks to texturize the facades and roofs of the newly created abstract 3D models, thus generating visually realistic 3D building models. The photographs were taken after a physical inspection of the task-relevant landmarks in each study area. They were captured under the same weather conditions to control for lighting effects (Winter et al., 2005). The designed abstract and realistic 3D models were exported as multipatch geometries into a geodatabase file,[11] which supports textures. Finally, this database file was imported into ArcGIS Pro and, together with the other spatial features, was used to create the mobile maps.

3.3.2 Dependent variables

In both studies, the participants were equipped with a mobile map depicting a predefined route and task-relevant landmarks (see Figure 3.1–A). They were asked to follow the predefined route and identify the corresponding landmarks in the environment. During and at the end of each navigation task, I measured several dependent

[8] swissBUILDINGS3D 2.0; https://www.swisstopo.admin.ch/en/geodata/landscape/buildings3d2.html
[9] Federal Office of Topography – *swisstopo*, Bern, Switzerland; https://www.swisstopo.admin.ch/en/home.html
[10] Esri, CA, USA; https://www.esri.com/en-us/arcgis/products/arcgis-cityengine/overview
[11] FileGDB (Esri File Geodatabase); https://doc.arcgis.com/en/cityengine/2021.0/help/help-export-filegdb.htm

variables to assess wayfinders' navigation behavior in response to manipulations of the landmark visualization style as the independent variable. The utilized dependent variables can be grouped into four main categories: navigation performance, spatial knowledge acquisition, visual attention, and cognitive load. Consequently, the present section is organized according to these four categories. This section provides an overview of all the dependent variables used across both studies. However, other test instruments used to collect demographic data and assess wayfinders' individual spatial abilities, as well as the details of data preprocessing, are described in the respective study sections (Chapters 4 and 5).

Navigation performance

Previous research on navigation behavior has suggested examining wayfinders' performance during aided navigation by utilizing standard measures of task efficiency (i.e., time to task completion), effectiveness (i.e., task accuracy), and interactions with the mobile map (Brügger et al., 2019; Dillemuth, 2005; Liao et al., 2017; Wilkening & Fabrikant, 2011, 2013). I recorded completion time to examine the influence of landmark visualization styles on wayfinders' navigation efficiency. Completion time refers to the total amount of time it took for wayfinders to complete the navigation task from start to destination. Furthermore, I manually recorded participants' navigation accuracy using pencil and paper. Navigation accuracy was measured by noting participants' deviations from the predefined route (i.e., navigation errors) and failure to identify the corresponding landmarks in the environment (see experimental procedure of Study I and Study II). Also, during Study II, participants' interactions (i.e., zooming, tilting, panning, and rotating) with the mobile map display were automatically recorded in a log file. However, map interactions will not be part of the analyses in the present thesis, as the thesis focuses on the influence of landmark visualization style on wayfinders' spatial learning, visual attention, and cognitive load.

Spatial knowledge acquisition

As stated in Section 2.1.1, wayfinders continuously acquire landmark, route, and survey knowledge of the traversed environment during navigation tasks (Montello, 1998; Siegel & White, 1975). Therefore, I administered several questionnaire-based measures to assess the wayfinders' acquisition of landmark, route, and survey knowledge.

Landmark knowledge tests were employed to assess wayfinders' acquisition of landmark knowledge. In these tests, the participants were presented with snapshots of landmarks as seen from their perspective during navigation for better recognizability (Christou & Bülthoff, 1999). They were then asked whether the landmarks were part of the previously traversed route or not. To minimize participants' chance performance (and following previous studies by Cheng et al. (2022), Wunderlich and Gramann (2021b), and Wunderlich et al. (2023)), I used three landmark types based on their location on the predefined route: 1) *relevant landmarks* (REL) refer to landmarks depicted on the mobile map and located at route intersections where a destination-relevant navigation decision was required; 2) *irrelevant landmarks* (IRL) refer to landmarks that were located at straight segments along the navigation route and not depicted on the mobile map; and 3) *novel landmarks* (NOL) refer to landmarks that were neither depicted on the mobile map nor present along the predefined route (i.e., other buildings in the study area) but were similar in style to the landmarks along the navigation route. In another landmark test called free reconstruction of order, participants were presented with all the images of REL landmarks depicted on the mobile map and located at route intersections. Then, the participants were required to sort the images of the REL landmarks in the order they encountered them along the predefined navigation route (Hilton et al., 2020; Hilton et al., 2021b; Wunderlich & Gramann, 2021b).

Route knowledge acquisition was investigated by utilizing a test measurement to assess wayfinders' memory recall of associated route directions during the navigation task. The wayfinders were presented with images of landmarks and were asked to recall the turning direction (i.e., right turn, left turn, or straight ahead) they took after passing each landmark (Cheng et al., 2022; Wunderlich & Gramann, 2021b).

Survey knowledge acquisition assesses participants' knowledge of the relative directions, relative distances, or both between landmarks (Hegarty et al., 2006; Huffman & Ekstrom, 2019). The last several decades have seen an advancement in various tasks used to assess wayfinders' survey knowledge acquisition (Huffman & Ekstrom, 2019). Huffman and Ekstrom (2019) stated that most of these tasks fall into three categories: 1) *pointing tasks*, which assess participants' knowledge of the relative directions between landmarks (Hegarty et al., 2006; Ishikawa & Montello, 2006); 2) *distance estimation tasks*, which investigate wayfinders' relative distance estimation between landmarks (Hegarty et al., 2006; Ishikawa & Montello, 2006); and 3) *sketch-map tasks*, which assess wayfinders' estimates of the relative directions and distances between landmarks (Hegarty et al., 2006; Ishikawa & Montello, 2006; Schwering et al., 2014). While pointing and distance estimation tasks provide valuable test measurements to assess wayfinders' survey knowledge (Chrastil & Warren, 2013; Hegarty et al., 2006; Huffman & Ekstrom, 2019; Ishikawa & Montello, 2006), sketch-map tasks might not be appropriate, as they require participants to possess special drawing skills and introduce unnecessary noise to the collected data (Chrastil & Warren, 2013). Consequently, I relied only on pointing and distance estimation tasks to investigate wayfinders' survey knowledge acquisition during real-world aided wayfinding.

In pointing tasks, participants are asked to point to the direction of landmarks relative to their current egocentric position and heading in the environment (Huffman & Ekstrom, 2019); accordingly, they are dubbed *"egocentric pointing tasks"* (Waller & Hodgson, 2006). Therefore, to assess wayfinders' relative direction and distance knowledge, I utilized a paper-based test combining pointing and distance estimation tasks (Ishikawa & Montello, 2006). For instance, on an A4 paper format, I showed participants photographs and names of two REL landmarks and a 10-cm radius circle with the name of one of the landmark pairs at the center of the circle (Figure 3.3–A). I asked participants to imagine being at a landmark they had seen during the navigation task, facing the direction of travel before passing the landmark. Then, I asked them to draw a line from the center of the circle indicating the direction of the second landmark of the pair (Ishikawa & Montello, 2006). Additionally, the participants had to estimate the beeline distance in meters between the landmarks in each pair.

In addition to the egocentric pointing task (Waller & Hodgson, 2006), I utilized an allocentric pointing task called the *"judgments of relative direction (JRD)"* task (Huffman & Ekstrom, 2019). JRD is a validated test method (Cheng et al., 2022; Credé et al., 2019, 2020; Huffman & Ekstrom, 2019) that asks a participant to recall the locations and directions of landmarks relative to each other, irrespective of the participant's current egocentric position and heading (Huffman & Ekstrom, 2019). Thus, the participants point to landmarks relative to their imagined position and heading (Huffman & Ekstrom, 2019). The most typical version of the JRD test asks wayfinders to imagine standing near a landmark, facing another landmark, and indicating the direction of a third landmark (Huffman & Ekstrom, 2019). Furthermore, I incorporated a distance estimation task into the JRD task, asking participants to indicate the beeline distance between the landmarks that they were standing at and pointing to. For instance, on a paper-based JRD task, I presented participants with three images of REL landmarks and a 10-cm radius circle (Figure 3.3–B), then asked them the following: *"Imagine you are standing at building 5, facing building 1. Please indicate the direction of building 2 in the circle and the beeline distance between buildings 5 and 2."*

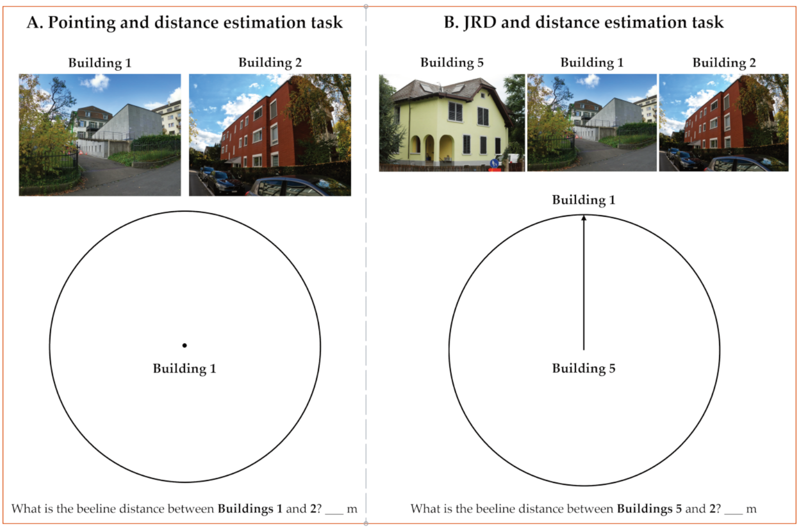

Figure 3.3: Examples of pointing (A) and JRD (B) tasks combined with distance estimation tasks.

Visual attention

I utilized eye-tracking, which is a validated physiological method, to collect wayfinders' eye movement data and investigate their gaze behavior (Duchowski, 2017; Holmqvist et al., 2011; Kiefer et al., 2017). Eye-tracking allows us to assess wayfinders' visual attention, providing a rich source of information on what spatial features of the environment and the mobile map are being attended to and for how long (Kiefer et al., 2017). Therefore, in both the real-world navigation studies presented in this thesis, the wayfinders wore head-mounted mobile eye-tracking glasses (see Figure 3.1–B) to investigate their visual attention. Depending on weather conditions, I equipped participants with mobile eye-tracking glasses fitted with either shaded or non-shaded lenses. This was done to reduce infrared interference from other environmental light sources on wayfinders' pupils and prevent them from squinting, thus ensuring higher-quality eye movement recordings. The eye-tracking glasses were connected to an external device (i.e., laptop or mobile phone) that the participants carried in a backpack throughout the experiment (see Figure 3.1–B). This external device was used for calibration purposes and for recording participants' eye movements. A detailed description of the hardware and software used to collect the wayfinders' eye movements, as well as discussions of recording quality, data processing, and the eye-tracking measures employed, are provided in Chapters 4 and 5.

Cognitive load

I employed mobile electroencephalography (EEG) to investigate the influence of various landmark visualization styles during both real-world navigation studies. As stated in Section 2.3, EEG is an empirically validated method used to assess wayfinders' cognitive load without interfering with the navigation task. EEG records electrical brain activity at a high temporal resolution (i.e., milliseconds) by utilizing a set of electrodes attached to wayfinders' scalp surface (see Figure 3.1–B). In both the real-world wayfinding studies of the present thesis, EEG data were continuously recorded using a 64-channel EEG device[12] with active electrodes[13] suitable for mobile recordings. The active electrodes are placed on an elastic cap with electrode holders.[14] The electrodes were placed following the extended 10% system (Oostenveld & Oostendorp, 2002). All electrodes were referenced to FCz with a ground electrode to Fpz (Cheng et al., 2022), and the impedance level was kept below 10 kOhm. In addition to the brain's electrical activity, the mobile EEG system used in this thesis is equipped with a built-in acceleration sensor to capture motion data in three separate channels (x, y, z). The EEG data were recorded at a 500-Hz sampling rate and wirelessly streamed to a laptop via Bluetooth. As seen in Figure 3.1–B, the participants carried the laptop in a backpack.

EEG data capture rhythmic electrical brain activity (Cohen, 2014). This activity reflects neural oscillations and represents fluctuations in the populations of neurons that discharge simultaneously (Cohen, 2014; Klimesch, 1999). Neural oscillations are grouped into distinct fre-

[12] LiveAmp 64, Brain Products GmbH, Gilching, Germany; https://www.brainproducts.com/solutions/liveamp

[13] actiCAP slim, Brain Products GmbH, Gilching, Germany; https://www.brainproducts.com/solutions/acticap

[14] actiCAP snap, Brain Products GmbH, Gilching, Germany; https://www.brainproducts.com/solutions/acticap

quency bands, such as the delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz) bands, among others (Cohen, 2014; Dressler et al., 2004; Gevins & Smith, 2003; Klimesch, 1999; Niedermeyer & da Silva, 2005). Meanwhile, the changes in the synchronization of neural activity influence the EEG signal's power modulations over these distinct frequency bands (Cohen, 2014; Dressler et al., 2004; Klimesch, 1999). The power changes over these bands have been found to correlate with several task demands, including perceptual, cognitive, mnemonic, emotional, and many more functional processes (Cohen, 2014). Among the EEG power spectrum frequencies, previous research has already associated the theta (4–8 Hz) and alpha (8–13 Hz) bands with spatial navigation as indicators of memory processes and attention (Bohbot et al., 2017; Gevins & Smith, 2003; Klimesch, 1999; Klimesch et al., 2008; Sauseng et al., 2005; Sauseng et al., 2010; Sharma et al., 2017). However, the power levels of theta and alpha frequency bands react in opposite ways (Gevins & Smith, 2003; Klimesch, 1999). In particular, the theta frequency band power gauged over the frontal cortex increases (synchronizes) during high-cognitive-load tasks compared to low-cognitive-load tasks (Gevins & Smith, 2003; Klimesch, 1999). In contrast, the alpha frequency band power recorded over the parietal cortex decreases (desynchronizes) in high-cognitive-load tasks (Gevins & Smith, 2003; Klimesch, 1999). Consequently, during the two real-world wayfinding studies presented in this thesis, I performed power spectrum analyses of the frontal theta (4–8 Hz) and parietal alpha (8–13 Hz) band oscillations, which is an established and standard method of investigating wayfinders' cognitive load (Cheng et al., 2022; Dressler et al., 2004).

After the wayfinding tasks, I employed the NASA Task Load Index (NASA TLX; Hart & Staveland, 1988) questionnaire to assess wayfinders' perceived cognitive load for the completed navigation tasks. NASA TLX is a widely used (Hart, 2006) subjective questionnaire measure that records users' self-reports in six categories: 1) *mental demand* – how mentally demanding was the task? (very low to very high); 2) *physical demand* – how physically demanding was the task? (very low to very high); 3) *temporal demand* – how hurried was the pace of the task? (very low to very high); 4) *performance* – how successful were you in achieving the task requirements? (perfect to failure); 5) *effort* – how hard did you work to achieve your level of performance? (very low to very high); and 6) *frustration* – how insecure, irritated, and stressed were you during the task? (very low to very high). Participants rate their perceived demand in each category using a scale ranging from 0 to 100 in increments of five (Hart & Staveland, 1988). The data processing and analyses of the objective EEG and subjective NASA TLX methods adopted to investigate the wayfinders' cognitive load are detailed in the respective study chapters (Chapter 4 and Chapter 5).

STUDY I

4

By visualizing information, we turn it into a landscape that you can explore with your eyes: a sort of information map. And when you're lost in information, an information map is kind of useful.

— **David McCandless**
(Data-journalist)

This chapter contains parts of the following published research articles:

*1. **Kapaj, A.**, Lanini-Maggi, S., Hilton, C., Cheng, B., and Fabrikant, S. I. (2023). How does the design of landmarks on a mobile map influence wayfinding experts' spatial learning during a real-world navigation task? Cartography and Geographic Information Science, 50:2, 197-213. https://doi.org/10.1080/15230406.2023.2183525.*[1]

*2. **Kapaj, A.**, Lanini-Maggi, S., and Fabrikant, S. I. (2021). The influence of landmark visualization style on expert wayfinders' visual attention during a real-world navigation task. In UC Santa Barbara: Center for Spatial Studies, Proceedings of the 11th International Conference on GIScience. https://doi.org/10.25436/E2NP44.*

*3. **Kapaj, A.**, Lanini-Maggi, S., and Fabrikant, S. I (2021). The impact of landmark visualization style on expert wayfinders' cognitive load during navigation. Abstracts of the International Cartographic Association, 3, 138. https://doi.org/10.5194/ica-abs-3-138-2021.*

Mobile maps have become ubiquitous tools in aiding our wayfinding tasks in familiar and unfamiliar environments (Dahmani & Bohbot, 2020; Ishikawa, 2018, 2019). However, these navigation aids negatively influence wayfinders' spatial knowledge acquisition (Section 2.1.2), visual attention (Section 2.1.2), and cognitive load (Section 2.3). The negative influence of mobile map aids could have severe

[1] Author contributions: AK, SLM, BC, and SF designed the study. AK and BC performed data collection. AK and CH performed data analyses and drafted the manuscript. All authors were involved in revising, editing, and approving the final manuscript.

and life-threatening consequences for several communities or user groups (Aporta & Higgs, 2005; Gardony et al., 2011). For instance, consider a military unit deployed as first responders in an unfamiliar area during a natural disaster. If the unit is impeded from accurately perceiving the task-relevant information on the mobile map aid and thus is limited in their spatial learning of the environment, this could have severe outcomes. As a result, it is important to investigate mobile maps' influence on expert wayfinders' (e.g., military personnel, first aid responders, search and rescue teams, etc.) visual attention, spatial knowledge acquisition, and cognitive load. However, even though GPS-equipped navigation systems were developed to facilitate military operations in areas under emergency conditions, the existing empirical research is not focused on this user group. Furthermore, despite landmarks' role as facilitators of wayfinding (Section 2.2), there is a lack of empirical research on how landmark visualization style influences expert wayfinders' visual attention, spatial knowledge acquisition, and cognitive load. In order to close these research gaps, in Study I, I investigated the influence of landmark visualization styles on expert wayfinders' visual attention, survey knowledge acquisition, and cognitive load. Based on two continua of landmark design – mimetic to arbitrary (Figure 2.2) and realistic to abstract (Figure 2.3) – and on Liao et al.'s (2017) landmark design recommendations, I enhanced the mobile map design by depicting only task-relevant landmarks as either realistic 3D building models or abstract 2D building footprints (see Figure 3.2–A and Section 4.2.3).

4.1 Research questions and hypotheses

In the present study, I investigated expert wayfinders' (i.e., military personnel) navigation performance, visual attention, spatial knowledge acquisition, and cognitive load during an emergency real-world navigation task. The expert wayfinders were assisted by a mobile map depicting landmarks as either realistic 3D building models or abstract 2D building footprints. In this study, I sought to specifically answer the following research questions (RQ) and linked hypotheses (H), which were derived from the main research question (see Section 1.2):

RQ1: How do various landmark visualization styles (i.e., realistic 3D vs. abstract 2D) influence expert wayfinders' navigation performance, spatial knowledge acquisition, visual attention, and cognitive load during a real-world wayfinding task?

As discussed in Section 2.2, landmarks serve as attention-grabbing features (Richter & Winter, 2014) and modulators of bottom-up visual attention (Wolfe & Horowitz, 2017). As a result, they facilitate visual matching between the information depicted on the mobile map and directly experienced in the environment (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Thrash et al., 2019; Willis et al., 2009). Therefore, I hypothesized the following:

H1: The expert wayfinders aided by the mobile map depicting landmarks as realistic 3D building models will exhibit 1) better navigation performance (i.e., fewer navigation errors); 2) better spatial knowledge acquisition of the traversed environment; 3) greater visual attention to task-relevant information (i.e., the traversed environment and the landmarks) and fewer gaze switches between the landmarks and other map elements; and 4) lower cognitive load than the experts' navigating with the mobile map depicting landmarks as abstract 2D building models.

RQ2: What is the role of visual attention allocation in expert wayfinders' spatial knowledge acquisition?

Considering the empirical findings on how divided attention and higher visual attention to the map display (see Section 2.1.2) inhibit wayfinders' spatial knowledge acquisition, I hypothesized the following:

H2: Expert wayfinders demonstrating higher visual attention to the environment and task-relevant landmarks and lower attention to the mobile map will exhibit improved spatial knowledge acquisition of the traversed environment.

4.2 Methods

4.2.1 Participants

Since I was interested in investigating the influence of landmark visualization styles on an expert population, this first study was carried out with participants from the Engineering and Rescue Troops of the Swiss Armed Forces.[2] The Engineering and Rescue Troops are deployed to perform search and rescue operations in response to disaster relief and humanitarian aid contexts at home and abroad. This group was deemed appropriate for this study because their spatial training qualifies them as expert wayfinders. Furthermore, the group had a keen interest – expressed during a pre-study interview with the contact person at the Swiss Army – in improving the design of mobile maps for more efficient and effective support during their work activities. Twenty-two trained experts (20 males and two females) with various functions, ranks, and years of experience participated in this real-world wayfinding study. The experts' mean age was 37.1 years, ranging from 24 to 58 years (M = 37.1, SD = 11.7). The study was conducted in German, and the experts were voluntarily recruited through an internal platform set up by the contact person at the Swiss Army Engineering and Rescue Troops. Considering the challenges of recruiting from an expert population, this sample size was the largest I could achieve within a reasonable time window for data collection.

The procedures carried out in this study received ethical approval (*No. 19.6.10*) from the University of Zurich Ethics Committee. All participants gave written informed consent before the start of the experiment. Furthermore, they were informed that they could end their participation in the experiment at any time and without consequences. The participation criteria for this study were as follows: normal or corrected to normal vision and no history of psychiatric disorders that could influence visual attention and cognitive states. Participants with corrected eyesight could join the study only by wearing contact lenses, as eyeglasses would interfere with the mobile eye-tracking glasses. The experimental procedures lasted a total of two hours, and no incentives were provided for participation.

[2] Schweizer Armee - Lehrverband Genie/Rettung/ABC; https://www.vtg.admin.ch/de/organisation/kdo-ausb/lvb-g-rttg-abc.html

4.2.2 Experimental design

For the present study, I used a between-subject experimental design (Martin, 2007) with landmark visualization style (i.e., realistic 3D building models vs. abstract 2D building footprints; Figure 3.2–A) as the independent variable. Furthermore, I used a matched-group design to control for individual differences between groups of participants (Martin, 2007). Consequently, the 22 expert wayfinders were equally distributed across the two landmark manipulation groups (realistic 3D and abstract 2D) according to their self-reported individual spatial abilities (see Questionnaire on spatial strategies) and gender. Moreover, I counterbalanced the predefined route's starting position by reversing the direction of travel for half of the sample in each group, thus controlling for landmark and route ordering effects (Martin, 2007). As dependent variables, I assessed the expert wayfinders' navigation performance (i.e., task accuracy and completion time), survey knowledge (i.e., incidentally acquired environmental knowledge), visual attention (i.e., gaze behavior), and cognitive load (including subjective and objective measurements).

4.2.3 Materials and apparatus

Navigation route

The study was conducted in a residential area in Brugg, Aargau, Switzerland. As part of the learning phase, participants had to navigate a predefined route in an unfamiliar area. This route was approximately 1 km long and contained four right turns, six left turns, and one intersection where participants had to continue straight ahead (Figure 4.1). I selected five buildings from five different intersections to serve as landmarks. These landmarks were selected after inspections of the study area and because they meet the criteria for good landmarks provided by Richter and Winter (2014) and Yesiltepe et al. (2021). In particular, these buildings were visually salient in color and form and structurally salient because they were located where a navigation decision was required.

Mobile map design

During the navigation task, the expert wayfinders were aided by a mobile map (Figure 4.1) that depicted the task-relevant landmarks, the predefined route, and a blue dot to mark the destination point (see Mobile map aids for more information on the design process of the interactive mobile maps). Based on the landmark manipulation styles as the independent variable, the navigation aid resulted in two mobile maps, each depicting landmarks as either: 1) realistic 3D building models with high fidelity (Figure 4.1–A) or 2) abstract 2D building footprints (Figure 4.1–B). The mobile maps were displayed on a tablet device, and participants could freely interact with the map (i.e., zoom, pan, rotate, and tilt). However, the experts' interactions with the mobile map aids were not recorded. Furthermore, the mobile maps did not show or track the experts' location along the predefined route during the navigation task.

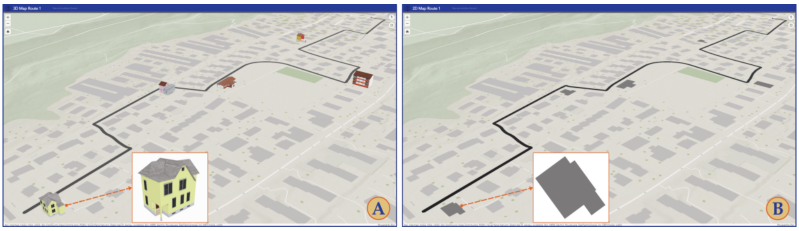

Figure 4.1: Interactive mobile maps depicting landmarks as realistic 3D building models (A) or abstract 2D building footprints (B). The inset view depicts a zoomed-in landmark in both visualization styles.

Sensory recordings and questionnaire measures

Mobile eye-tracking (MET) glasses were employed to record expert wayfinders' gaze behavior. I used the Eye Tracking Glasses 2 Wireless (ETG 2W) from SensoMotoric Instruments (SMI).[3] SMI ETG 2W is a binocular head-mounted MET that records eye movements at a sampling rate of 60 Hz. This MET is equipped with a scene camera that records at a resolution of 1280 × 960 px and is fixed at 24 frames per second. Due to individual differences in users' eyeball size, shape, and geometry, I performed a three-point calibration using the SMI iView software to ensure data quality (Holmqvist et al., 2011). The calibration was performed using a laptop; the same laptop was later used for data recording and was carried by the expert wayfinders in a backpack. The processing and analyses of the eye-tracking data carried out to examine the expert wayfinders' visual attention during the navigation task are detailed in Section 4.2.5.

[3] No longer operational.

Electroencephalography (EEG) was used to objectively assess the expert wayfinders' cognitive load during the navigation task. See Section 3.3.2 for a detailed description of the EEG device utilized in this study and Section 4.2.5 for the EEG data processing and analyses.

The NASA Task Load Index (NASA TLX; Hart & Staveland, 1988) questionnaire was employed to assess the expert wayfinders' subjective workload during the navigation task. I used a paper-based version to capture experts' self-perceived workload across several categories: mental demand, physical demand, temporal demand, performance, effort, and frustration (see Section 3.3.2). For the NASA TLX analysis procedure, see Section 4.2.5.

The Questionnaire on Spatial Strategies (QSS; Münzer & Hölscher, 2011) was utilized to assess the expert wayfinders' spatial abilities. QSS is a 19-item questionnaire employing a 7-point Likert scale where participants self-report the extent to which they rely on landmark, route, survey, and directional knowledge (i.e., cardinal directions) when navigating in various environments (i.e., familiar, unfamiliar, indoor, and outdoor environments; Münzer et al., 2016). I computed the average score of the 19 questions. This average was used to control for experts' individual spatial abilities before assigning them to one of the two landmark visualization conditions (realistic 3D or abstract 2D). I used an online version of the QSS which, in addition to the 19 questions, also included demographic questions such as age, gender, education, profession, and mobile map use.

The Perspective Taking and Spatial Orientation Test (PTSOT; Hegarty & Waller, 2004) was used to investigate the experts' ability to imagine mental spatial rotations and perspective changes of various perceived objects. PTSOT uses a picture of an array of seven objects, a circle with an arrow originating from the center and meeting the circle at 0° (similarly to Figure 3.3–B), and a question regarding the direction between objects. For instance, PTSOT instructs participants to imagine that they are standing at one object in the array (e.g., flower) labeled at the beginning of the arrow and facing another object (e.g., tree) labeled above the arrowhead. Then, they are asked to indicate the direction of a third object (e.g., cat) by making a mark on the circle (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). This example is used as a training session, and participants are given as much time as they need to become familiar with the test and ask questions about it. The test phase of PTSOT includes 12 trials in a booklet. It asks participants to imagine different perspectives or orientations in space for different combinations of the seven objects. The participants are given five minutes and are not allowed to pick up, turn, or rotate the booklet or to make marks on the array of objects (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). Unanswered items are marked as 90° corresponding to chance performance (Friedman et al., 2020; Hegarty & Waller, 2004). Participants whose average error is higher than the 90° chance performance should be excluded from analyses, as this indicates that the participants did not understand the task (Friedman et al., 2020; Hegarty & Waller, 2004). In the present study, the expert wayfinders completed all 12 PTSOT items within five minutes, and their average error was lower than the 90° chance performance.

The Judgment of Relative Direction (JRD; Huffman & Ekstrom, 2019) task (see Section 3.3.2) was employed to assess expert wayfinders' acquisition of spatial knowledge about the traversed environment. I utilized a combined paper-based JRD and distance estimation task in which the expert wayfinders were asked to recall the direction and distance of the five task-relevant landmarks relative to each other. Figure 3.3–B shows an example of the JRD test modified with images of landmarks; the landmarks were shown from the experts' perspectives during the real-world navigation task for better recognizability (Christou & Bülthoff, 1999). Out of 60 possible permutations of landmark triplets (5*4*3), I randomly selected 30 triplets that resulted from excluding one of the triplet pairs with symmetrical angles (i.e., -45° and 45°; Credé, 2019; Credé et al., 2019, 2020). For instance, I randomly selected one of the following permutation trials: 1) standing at Building 1, facing 2, and pointing at 3 (1–2–3); and 2) standing at Building 1, facing 3, and pointing at 2(1–3–2).

4.2.4 Experimental procedure

The real-world navigation experiment was conducted on days without precipitation in August, September, and October 2019. The experts completed the online QSS and demographic questionnaire before the navigation day. This procedure allowed me to calculate their spatial ability score, which I used to assign them to either the 3D or 2D group while controlling for their individual spatial abilities and gender. On the day of the experiment, the experts were welcomed in a meeting room near the study area. The participants read and signed a consent form after receiving answers to any questions regarding participation. Following the informed consent procedures, the experts were provided with an overview of the upcoming experimental procedure (see

Figure 4.2 for a detailed procedure). Next, the experts were presented with the paper-based PTSOT test and were instructed on how to complete it. After completing the test, the experts were presented with the tablet device and asked to familiarize themselves with its functionalities using a test mobile map. Meanwhile, the experimenters prepared the EEG cap with electrodes and assisted the experts in putting it on. Then, electrolyte gel was applied to bridge the gap between the experts' scalp and the electrode sensors and ensure high connectivity and good data quality. This procedure was performed using the BrainVision Recorder software.[4] Following the EEG setup, I helped the experts to put on the MET glasses and then performed a three-point calibration, during which the experts were asked to keep the tablet device at arm's length and fixate on its corners. Then, I started the EEG and MET data recordings using a laptop that the experts carried in a backpack throughout the experiment. Next, I led the experts to the starting position of the predefined route, where they were presented with the study scenario. The scenario below (translated from German) was developed in collaboration with the contact person at the Swiss Army Engineering and Rescue Troops. It aimed to mimic a real-world situation that experts could face in their disaster relief and humanitarian aid deployments.

> *Imagine that the residential area you are in is under a civil emergency and urgently needs assistance. Five buildings have been selected to be immediately assessed for possible assistance. These buildings are highlighted on the mobile map and differ from other map elements due to their display color or style. Please follow the route as quickly as possible without running to identify the five target buildings along the predefined route. Raise your hand once you are next to a target building. Once you have visited all five buildings, proceed to the final destination point marked with a blue pin on the map and await further instructions.*

I shadowed the experts during their real-world exploration and took notes regarding their navigation behavior without interfering with the task. Specifically, I took notes regarding the experts' completion time and accuracy during the navigation task. Concerning task accuracy, if the expert wayfinders failed to follow the predefined route by taking a wrong turn, I allowed time for them to self-correct their direction. If

[4] Brain Products GmbH, Gilching, Germany; https://www.brainproducts.com/downloads/recorder

no correction occurred and they continued in the wrong direction, I called the experts back to the intersection where the wrong turn was made. After arriving at the predefined destination point, I removed the EEG and MET devices. Then, I blindfolded, disoriented, and moved the experts to another nearby location where the predefined route was not visible. There, I asked the experts to fill out the NASA TLX questionnaire. After being provided with the test instructions, they were asked to complete the paper-based JRD test consisting of 30 trials. Finally, the expert wayfinders were provided with a debriefing information sheet and thanked for their participation. Figure 4.2 provides a detailed overview of all the activities constituting the experimental procedure of Study I, including questionnaires, instructions, and setups.

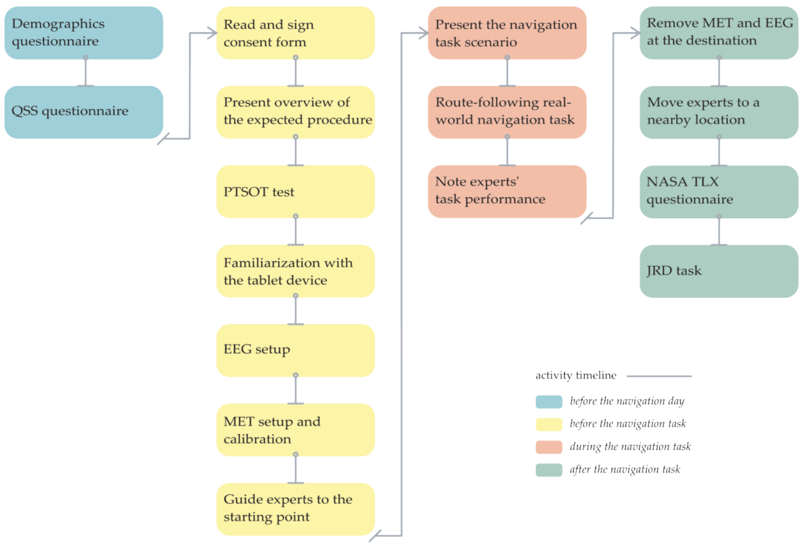

Figure 4.2: Detailed experimental procedure of Study I, including all the questionnaire measures, instructions, and sensory setups, color-coded based on their timeline appearance.

4.2.5 Data processing and analyses

As mentioned in Section 4.2.2, the dependent variables of the present study are experts' navigation performance, survey knowledge, visual attention, and cognitive load. Additionally, to answer the second research question (RQ2), I investigated how visual attention allocation influenced experts' incidental spatial learning. All the statistical tests used to analyze the influence of the independent variable manipulations on the dependent variables were performed in R (version 4.2.1; R Core Team, 2022). The significance threshold was set at $p <$ .05. The analysis results of the two between-subject design groups (3D vs. 2D landmark visualization) are reported following the recommendations of Field et al. (2012). Furthermore, to measure the effect size of landmark visualization on the dependent variables, I used an effect size model proposed by Field et al. (p.380 2012). The model relies on Pearson's correlation coefficient r and varies from -1 (perfect negative effect) to 0 (no effect) to 1 (perfect positive effect). The results plots were produced using the *ggplot2* package (Wickham, 2016). For reproducibility purposes, this section presents a more detailed explanation of the data processing steps and statistical tests utilized for the dependent variables.

Navigation performance measures

As stated in Section 3.3.2, I relied on task accuracy and completion time to analyze the experts' navigation performance. Since there were only a few navigation errors across the landmark visualization groups (3D vs. 2D), I did not perform any statistical tests on task accuracy data. Regarding expert wayfinders' completion time, I first checked the data distribution using the Shapiro–Wilk test before deciding on the statistical tests to analyze the data. The test suggested that the completion time data departed significantly from normality (W = 0.9, p = .03). However, a visual inspection of the QQ plot revealed only minor violations of normality. Therefore, to analyze experts' completion time, I utilized a non-parametric Mann–Whitney U test and an independent t-test. Both tests revealed consistent results. Thus, as the violations of normality were minor, I will report the outcomes of the independent t-test for the sake of readability.

Survey knowledge measures

The expert wayfinders' incidental acquisition of spatial knowledge about the traversed environment was assessed using the judgment of relative direction (JRD) task (see Section 4.2.3). Their pointing accuracy for the target landmark in relation to the reference landmarks was calculated using the absolute angular difference between the estimated and actual directions (Credé, 2019). The angular errors for the JRD task vary from 0° (high spatial learning) to 180° (low spatial learning). For each expert wayfinder, I calculated the mean JRD angular value across the 30 possible JRD trials to assess their overall performance in survey knowledge acquisition. I performed the same procedure for the expert wayfinders' distance estimation between the reference and target landmarks. A Shapiro–Wilk normality test revealed evidence of normality violations for experts' mean angular error ($W = 0.9$, $p = .004$) but not for their distance error ($W = 0.9$, $p = .07$). Therefore, I decided to analyze the experts' angular and distance errors using an independent t-test and a non-parametric Mann–Whitney U test to confirm the results. Both tests revealed consistent results. Thus, for readability purposes, I will report the outcomes of the independent t-test.

Visual attention measures

The expert wayfinders' visual attention during the real-world route-following navigation task was recorded using mobile eye-tracking (MET) glasses (see Section 4.2.3). Unfortunately, due to technical and data quality issues with the MET glasses, I was able to analyze only 13 (3D group: n = 6; 2D group: n = 7) of the 22 experts' gaze recordings. I only analyzed the MET recordings with a tracking ratio (i.e., the percentage of the experimental time during which the experts' eye movements were captured) higher than 65%. Even after removing the nine experts with faulty MET recordings, the spatial ability scores measured with the QSS questionnaire (see Section 4.2.3) did not differ between the two experimental groups. I used the SMI BeGaze 3.5 software[5] to analyze the MET recordings. BeGaze uses a built-in event detection algorithm to classify gaze data into four categories: fixations, saccades, blinks, and undefined visual intake events shorter than 50 ms (SMI, 2015).

To analyze the experts' gaze behavior, I employed the conventional method of annotating each fixation to a corresponding area of interest (AOI) on a reference frame (Brügger, 2020; Brügger et al., 2019). I annotated the fixation data in two ways. First (see Figure 4.3), I used the Semantic Gaze Mapping function (SMI, 2015) to manually perform a fixation-by-fixation mapping technique to assign each fixation to one of the following four AOIs on a reference image: 1) the mobile map display (*MAP*); 2) the environment (*ENV*); 3) the five landmarks depicted on the mobile map (*LmMAP*); and 4) the corresponding five landmarks in the environment (*LmENV*). Second, and specifically for fixations on the MAP AOI, I used a precise mapping method (SMI, 2015) that allowed me to assign experts' fixations to their precise location on the mobile map. Thus, I used a reference image containing

[5]No longer operational.

only the mobile map of the study area to generate a fixation kernel density map, allowing me to assess the distribution of expert wayfinders' visual attention on the MAP AOI. After the annotation processes, I exported the AOI metrics and utilized fixation duration, one of the most widely used eye-tracking metrics, to analyze the users' visual information processing (Holmqvist et al., 2011; Kiefer et al., 2017). Before analyzing experts' fixation duration on AOIs, I excluded fixations shorter than 100 ms and longer than 2,000 ms, as the remaining fixations are associated with users' cognitive and learning processes (see Holmqvist et al., 2011, for a discussion of fixation duration thresholds). Subsequently, I normalized experts' fixation duration by their navigation task completion time (Holmqvist et al., 2011), computed as follows:

$$Normalized\ Fixation\ Duration[\%] = \frac{Fixation\ duration\ on\ AOI\ [ms]}{Completion\ time\ [ms]} \times 100 \quad (4.1)$$

The Shapiro–Wilk test revealed evidence of non-normality for experts' fixation duration on the LmENV (W = 0.8, p = .02) AOI. However, there was no evidence of normality violations for the ENV (W = 0.9, p = .07), TAB (W = 0.9, p = .20), or LmTAB (W = 0.9, p = .08) AOIs. Therefore, I analyzed experts' fixation duration on AOIs using an independent t-test and confirmed the results with a non-parametric Mann–Whitney U test. Since the two tests produced consistent results, I will report the outcomes of the independent t-test for readability purposes.

To further assess the influence of landmark visualization style on expert wayfinders' gaze behavior, I investigated their eye-movement sequences, which serve as indicators of the strategies employed during visuospatial tasks (Çöltekin et al., 2010; Lanini-Maggi, 2017; Ponsoda et al., 1995). Thus, I employed transition matrices (TMs) and entropy metrics as indicators of the predictability of eye-movement sequences between and within AOIs using an R script developed by Krejtz et al. (2014). TMs indicate the probability of eye movement transitions between and within this study's four specific AOIs (Krejtz et al., 2015; Krejtz et al., 2014). Specifically, TMs indicate the probability that the next fixation will fall within the same AOI as the preceding fixation or will transit into one of the other three AOIs. While TMs provide qualitative means of sequential gaze pattern analysis, they are not suited for statistical comparisons across experimental conditions (Krejtz et al., 2015; Krejtz et al., 2014). For this reason, I employed entropy metrics such as stationary entropy (SE) and transition entropy (TE) to quantitatively compare experts' allocation of visual attention among the four present AOIs. Krejtz et al. (2014) and Krejtz et al. (2015) stated that TE corresponds to the complexity of eye-movement sequences between the AOIs, whereas SE represents the subject's focus on a certain AOI. High TE values indicate frequent gaze switches among the present AOIs, suggesting a more exploratory visual search behavior, while low TE values indicate a longer focus on specific AOIs and frequent gaze switches between certain AOIs. Meanwhile, high SE values indicate a homogeneous distribution of visual attention among the present AOIs, suggesting that the AOIs hold equal interest for the participants in relation to solving the task at hand. In contrast, lower SE values indicate that users' gaze behavior is more drawn to certain AOIs (Krejtz et al., 2015; Krejtz et al., 2014). Thus, entropy metrics (TE and SE) allow a better understanding of whether the landmark visualization style influenced experts' visual search strategies when solving the navigation task. Consequently, after data normality checks with a Shapiro–Wilk test (TE: $W = 1$, $p = .80$; SE: $W = 1$, $p = .90$), I performed an independent t-test to compare TE and SE across the experimental conditions.

Figure 4.3: Snapshot of the annotation process performed using the BeGaze software. Panel (B) shows the gaze of an expert upon a task-relevant landmark on the mobile map display (red circle); in panel (A), including the four AOIs, I manually assign this fixation to the *LmMAP* AOI (red circle).

Cognitive load measures

EEG was utilized as an objective measure of the expert wayfinders' cognitive load during the navigation task (Section 3.3.2). However, EEG recordings of wayfinders' brain activity are accompanied by noise artifacts, especially during real-world studies (Gramann et al., 2014; Klug et al., 2022; Niedermeyer & da Silva, 2005; Wunderlich & Gramann, 2021a). These artifacts can originate from active movements of real-world, biological (e.g., eye movements, muscular activity, heart rate, etc.), and mechanical (e.g., loosely attached electrodes, cable movements, etc.) sources, external factors in the environment (e.g., loud noises, traffic noise, passersby interrupting wayfinders, etc.), and other causes (Gramann et al., 2014; Niedermeyer & da Silva, 2005; Wunderlich & Gramann, 2021a). Consequently, the raw EEG data must be processed and cleaned before examining the expert wayfinders' cognitive load. Before the data processing procedure, I removed the non-task-related recordings (e.g., walking from the meeting room to the start of the route) from the EEG data. Unfortunately, due to technical issues, one expert's EEG data was not recorded. Subsequently, the EEG data of the 21 experts for the navigation task (2D group: n = 10; 3D group: n = 11) were processed using the *BeMoBIL* pipeline (Klug et al., 2022) in MATLAB (R2020b; version 9.9.0)[6] toolbox *EEGLAB* (version 2022.0 Delorme & Makeig, 2004). This pipeline is designed to improve the signal-to-noise ratio of mobile EEG data (Klug et al., 2022).

Using the pipeline, I first downsampled the task-related EEG data to 250 Hz. Then, I removed frequency-specific artifact peaks at 50 Hz using the *Zapline-plus* function (Klug & Kloosterman, 2022). Next, to identify bad (i.e., noisy) EEG channels, I ran 10 iterations of the *EEGLAB* automated rejection function *clean_artifacts*. Channels that were detected three or more times as bad channels were rejected. The rejected channels were reconstructed using a spherical interpolation of the neighboring channels and then re-referenced to the common average reference. Subsequently, I applied independent component analysis (ICA; Makeig et al., 1995) using the adaptive mixture independent component analysis algorithm (AMICA; Palmer et al., 2012) on the cleaned EEG data. The resulting AMICA independent components (ICs) were localized to the estimated source location using an equivalent dipole model using the *DIPFIT* (Oostenveld & Oostendorp, 2002) plugin for *EEGLAB*. Afterward, using the default classifier of the *ICLabel* algorithm (Pion-Tonachini et al., 2019), the ICs were classified as brain, eye, muscle, or other components. To analyze the expert wayfinders' cognitive load, I retained only the ICs reflecting brain activity with a probability of 30% or higher. Finally, a bandpass filter

[6]MathWorks, Natick, Massachusetts, USA; https://ch.mathworks.com/products/matlab.html

from 0.5 Hz to 30 Hz was applied to remove irrelevant high-frequency EEG signals.

As stated in Section 3.3.2, in order to investigate the expert wayfinders' cognitive load when aided by a mobile map depicting landmarks as either abstract 2D building footprints or realistic 3D building models, I performed power spectral analyses of the theta (4–8 Hz) and alpha (8–13 Hz) frequency bands. Based on previous research (Cheng et al., 2022; Wei & Zhou, 2020), three electrodes in the frontal (FC1, FCz, FC2) and parietal (O1, Oz, O2) brain regions were selected to analyze the experts' theta and alpha power, respectively. I used relative theta and alpha power to mitigate individual differences in the modulation of the theta and alpha frequency bands' power (Cheng et al., 2022; Nishiyori et al., 2021). Each electrode's relative theta (FC1, FCz, FC2) and alpha (O1, Oz, O2) power were computed by dividing the absolute theta and alpha power over the entire bandwidth's (1–30 Hz) absolute power, as illustrated in the following equations:

$$\textit{Relative theta power} = \frac{\textit{Absolute theta power}}{\textit{Absolute (delta + theta + alpha + beta) power}} \times 100 \quad (4.2)$$

$$\textit{Relative alpha power} = \frac{\textit{Absolute alpha power}}{\textit{Absolute (delta + theta + alpha + beta) power}} \times 100 \quad (4.3)$$

Finally, the relative theta and alpha power were obtained by averaging the frontal (FC1, FCz, FC2) and parietal (O1, Oz, O2) electrodes, respectively. The expert wayfinders' relative theta and alpha power were analyzed using an independent t-test, as the Shapiro–Wilk tests revealed no violations of normality (theta: $W = 1$, $p = .50$; alpha: $W = .9$, $p = .07$).

NASA TLX was used to assess experts' self-perceived workload during the navigation task across six categories (Section 3.3.2). I used the raw NASA TLX analysis method (Hart, 2006), which averages the ratings – varying from 0 (low load) to 100 (high load) – of all six categories to reach an overall score for the task's workload. The overall workload rating of the 22 expert wayfinders had minor violations of the normality assumption according to the Shapiro–Wilk test ($W = 0.9$, $p = .04$). A visual inspection of the density plot also revealed only minor violations of data normality. Therefore, I performed the experts' workload analyses using an independent t-test and confirmed the results with a non-parametric Mann–Whitney U test. The results were consistent between the two tests. Hence, I will report the results of the independent t-test for the sake of readability.

Measuring the effect of visual attention on spatial learning

To investigate the influence of visual attention allocation on the expert wayfinders' incidental spatial learning, I used linear mixed-effect models (LME) using the *lme4* package (Bates et al., 2015). LME models are a generalized form of regression analysis appropriate for nested study designs (Gelman & Hill, 2006); the approach was appropriate here as I administered 30 JRD trials nested within each expert wayfinder. To identify the LME model that would reach convergence, I first created a model that includes JRD angular error as a response variable with no fixed effects and a maximal random effects structure attuned to the experimental design (Barr et al., 2013). If the model did not converge, I iteratively reduced the random effects structure by eliminating first the random slopes and then the random intercepts until it reached convergence. In cases where more than one LME model reached convergence, I selected the model of best fit based on the Aikake Information Criterion (AIC; Field et al., 2012). Next, I centered the continuous variables at the mean value and contrast-coded dichotomous categorical variables to -0.5 and 0.5. Finally, with the selected LME model including a by-subject random intercept, I added the experts' fixation duration (FD) for each of the four AOIs, the experimental condition (i.e., 3D vs. 2D), the PTSOT error, and two two-way interactions of the FD on the AOI and the PTSOT error with the condition as fixed effects. Hence, I fitted four separate models, only varying the AOI FD as the fixed effect predictor:

$$JRD\ error \sim FD\ on\ ENV * Condition + PTSOT\ error * Condition + (1|Subject) \tag{4.4}$$

$$JRD\ error \sim FD\ on\ MAP * Condition + PTSOT\ error * Condition + (1|Subject) \tag{4.5}$$

$$JRD\ error \sim FD\ on\ LmENV * Condition + PTSOT\ error * Condition + (1|Subject) \tag{4.6}$$

$$JRD\ error \sim FD\ on\ LmMAP * Condition + PTSOT\ error * Condition + (1|Subject) \tag{4.7}$$

These models assess the influence of AOI FD on experts' spatial learning while controlling for the condition and the experts' PTSOT baseline survey learning abilities. The models were executed on the 13 experts with MET recordings (see Section 4.2.5), generating a total of 390 JRD data points (30 JRD trials $\times$ 13 experts).

4.3 Results

4.3.1 Navigation performance

All 22 expert wayfinders managed to finish the navigation task. Regarding task accuracy, there were a total of three navigation errors per experimental condition: two wrong turns at the predefined intersections and a failure to identify one of the five task-relevant landmarks. Three experts from each landmark visualization condition (realistic 3D vs. abstract 2D) made these errors. Hence, there was no evidence that the landmark visualization style affected the expert wayfinders' task accuracy. Next, I analyzed the expert wayfinders' predefined route completion time. Overall, the experts' completion time varied from 9 to 15 minutes (M = 11.6, SD = 1.35). The independent t-test results revealed no significant differences ($t(20) = -0.5$, $p = .60$, $r = .11$) in the completion time between the experts of the 3D group (M = 11.7, SD = 1.48) and those of the 2D group (M = 11.4, SD = 1.26).

4.3.2 Incidental spatial learning

In total, the 22 expert wayfinders produced 660 JRD pointing and distance estimation trials of the five task landmarks relative to each other. The overall mean pointing error regarding landmark position was 36.9° (SD = 39.1), whereas the mean distance error was 141 m (SD = 144). Regarding the influence of landmark visualization style on the expert wayfinders' accuracy when recalling landmarks' position (3D: M = 34.1, SD = 17.2; 2D: M = 39.7, SD = 26.3), the independent t-test revealed no significant results ($t(17) = 0.6$, $p = .60$, $r = .14$).

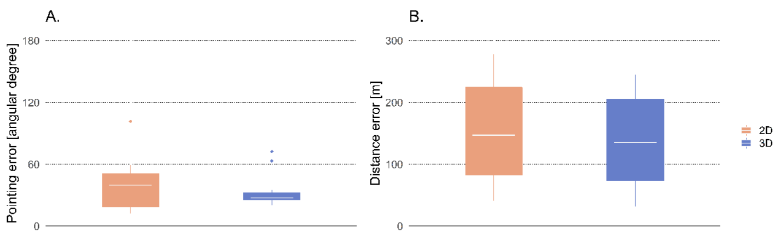

Figure 4.4: Landmark visualization style does not influence expert wayfinders' recall accuracy of landmarks' relative position (A) or distance (B). *Note: White bars indicate means, and dots indicate outliers.*

Nevertheless, a visual inspection of Figure 4.4–A indicates variance differences in pointing error between the experimental conditions.

However, Levene's test revealed no violation of the homogeneity of variances between the groups for the JRD pointing error (F(1,20) = 2.18, p = .16). Moreover, the results of an independent t-test revealed no significant differences in the recall accuracy of landmark distances (t(20) = 0.3, p = .70, r = .08) between the experts in the 3D (M = 135, SD = 77.5) and 2D (M = 147, SD = 84.1) groups (Figure 4.4–B).

4.3.3 Visual attention

In this section, I report the findings concerning expert wayfinders' allocation of visual attention to the *ENV*, *MAP*, *LmENV*, and *LmMAP* AOIs. The results of the independent t-test revealed no significant differences (t(10) = 1, p = .30) in the allocation of visual attention on the ENV AOI (Figure 4.5–A) across the 2D (M = 16.74, SD = 14.78) and 3D (M = 9.47, SD = 8.05) groups. Similarly, there were no significant differences (t(10) = 1, p = .30) in the fixation duration on the MAP AOI (Figure 4.5–B) across the landmark visualization conditions (2D group: M = 14.6, SD = 10.52; 3D group: M = 9.7, SD = 6.3). However, both test results revealed a medium-sized effect of landmark visualization style on experts' fixation duration on the ENV (r = .34) and MAP (r = .31) AOIs.

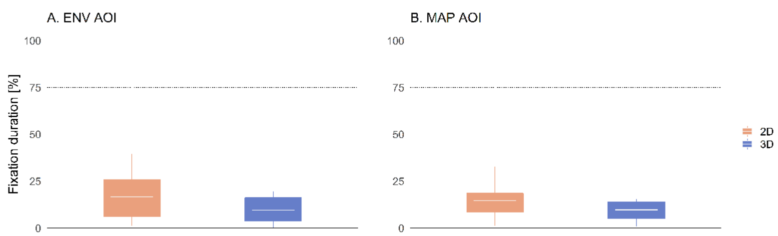

Figure 4.5: Landmark visualization style does not influence expert wayfinders' fixation duration on the ENV (A) or MAP (B) AOIs. *Note: White bars indicate means.*

Meanwhile, the independent t-test results for the experts' fixation duration on the LmENV AOI (Figure 4.6–A) revealed no significant differences (t(11) = 0.8, p = .50, r = .23) across the 2D (M = 1.05, SD = 1.1) and 3D (M = 0.66, SD = 0.76) groups. Finally, the independent t-test results for the LmMAP AOI revealed that the experts aided by the mobile map depicting landmarks as abstract 2D building footprints (M = 0.67, SD = 0.46) spent marginally less time fixating on the visualized landmarks (t(6) = -2, p = .07; Figure 4.6–B) than those who were aided by the mobile map depicting landmarks as realistic 3D building models (M = 1.96, SD = 1.36). This marginally significant result represented a large effect size (r = .67).

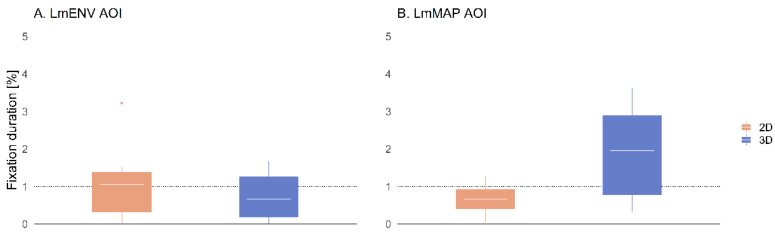

Figure 4.6: Landmark visualization style does not influence expert wayfinders' fixation duration on the (A) LmENV or (B) LmMAP AOIs. *Note: White bars indicate means, and the dot indicates an outlier.*

As stated in Section 4.2.5, I used a precise mapping method to further investigate the distribution of expert wayfinders' visual attention to the MAP AOI by assigning their gaze fixations to a precise location on the mobile map display. The output of this method was a kernel density map of experts' fixations on the MAP AOI (Figure 4.7). Visual inspection of the kernel density maps suggests that the experts navigating with landmarks depicted as abstract 2D footprints (Figure 4.7–A) searched a wider area around the predefined route to obtain the necessary spatial information to successfully complete the wayfinding task. In contrast, the experts navigating with the mobile map depicting landmarks as realistic 3D building models (Figure 4.7–B) seem to focus their visual attention more closely on and around the depicted landmarks.

I used transition matrices (TMs) and entropy analyses (Section 4.2.5) to further investigate the influence of landmark visualization style on expert wayfinders' visual search behavior by assessing their eye-movement sequences. First, the analyses of TM probabilities of eye-movement sequences between and within AOIs revealed similar patterns between the experimental conditions (Figure 4.8). The numbers in both TMs in Figure 4.8 indicate the probability that the subsequent fixation remains on the same AOI shown in the diagonal axes or moves to another AOI. Therefore, the darker cells along the diagonal axes indicate that it is more likely that when experts fixate on an AOI, the following fixation stays upon the same AOI. The TMs of both groups in Figure 4.8 reveal similar probabilities that the subsequent fixation remains on the same AOI. For instance, when the expert wayfinders of the 2D (Figure 4.8–A) and 3D (Figure 4.8–B) groups fixate on the MAP AOI, there is a high probability (0.81 and 0.79, respectively) that the next fixation remains on the same MAP AOI. This probability pattern is similar across the experimental groups for the ENV and LmENV AOIs.

Figure 4.7: Landmark visualization style (A: abstract 2D; B: realistic 3D) influences experts' distribution of visual attention on the MAP AOI.

The largest across-group differences in experts' gaze transition probability patterns appear when fixating on the LmMAP AOI and gaze probability transitions between the LmMAP and MAP AOIs. The TM of the 2D group (Figure 4.8–A) reveals that when this group's experts fixate on the task-relevant landmarks depicted on the mobile map (LmMAP AOI), there is a low probability (0.19) that the next fixation will remain on the same AOI. In contrast, the TM indicates (blue squares in Figure 4.8–A) that when the experts of the 2D group fixate on the LmMAP AOI, there is a probability of 65% that the next fixation would be on the MAP AOI. Like the kernel density map, this probability pattern suggests that the expert wayfinders in the 2D group had to scan a wider area around the predefined route to acquire the necessary spatial information for successful wayfinding. While both the kernel density map (Figure 4.7) and TMs (Figure 4.8) reveal important visual behavior patterns, they do not provide the means to statistically compare the groups' performance. Consequently, I quantified the experts' TMs gaze patterns through transition (between AOIs) and stationary (within a single AOI) entropy metrics, which are reported next.

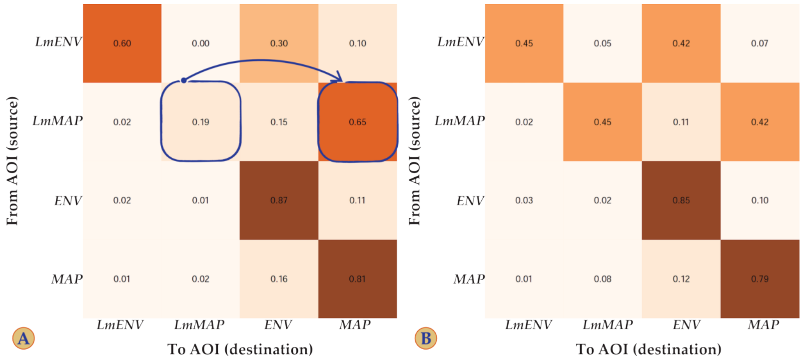

Figure 4.8: Transition matrices of the 2D (A) and 3D (B) groups. Cell values and shading indicate the magnitude of the probability. The darker the shaded cell, the higher the gaze transition probability.

The independent t-test revealed that the 3D group (M = 0.47, SD = 0.09) had a marginally higher (t(11) = -0.2, p = .05) TE (Figure 4.9–A) than the 2D group (M = 0.37, SD = 0.09). The results convey a large effect size (r = .55). They indicate more exploratory visual search behavior among all four AOIs for the experts navigating with realistic 3D landmarks. Conversely, the visual attention of the experts navigating with the landmarks depicted as abstract 2D building footprints focused only on specific AOIs (i.e., LmENV, ENV, and MAP). Similarly, the independent t-test (Figure 4.9–B) revealed a significantly higher SE (t(8) = -0.5, p < .001) for the 3D group (M = 0.74, SD = 0.06) than the 2D group (M = 0.59, SD = 0.04). The significant differences were supported by a large effect size (r = .87). The SE results indicate that the visual attention of the experts in the 3D group was homogeneously distributed among the AOIs, suggesting equal importance of the four AOIs to the wayfinding task. In comparison, the visual attention of the experts in the 2D group was drawn more toward the LmENV, ENV, and MAP AOIs while solving the task.

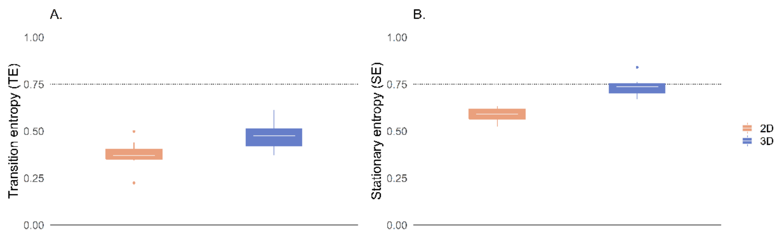

Figure 4.9: The 3D group exhibited higher transition (A) and stationary (B) entropy values than the 2D group. *Note: White bars indicate means, and dots indicate outliers.*

4.3.4 Cognitive load

EEG results

Before running the independent t-test on the relative theta and alpha power, I used the *EEGLAB* toolbox to plot topographic scalp density maps averaged over the theta (4–8 Hz) and alpha (8–13 Hz) frequency ranges for all the EEG channels across experimental conditions (Figure 4.10). Visual inspection of the topographic scalp maps indicated a higher power spectral density in the parietal regions of the theta (Figure 4.10–A) and alpha (Figure 4.10–B) frequency bands, especially for the experts navigating with realistic 3D landmarks. According to previous research, the parietal lobe is activated during visual information processing tasks (Bullier, 2001; Colby, Goldberg, et al., 1999; Xu, 2018). This is also the case in the present study, as the expert wayfinders had to process the visual-spatial information from a mobile map display. Therefore, a posthoc assessment of the absolute parietal power in the theta and alpha frequency bands was performed by averaging the absolute power across the three parietal electrodes (O1, Oz, O2; see Section 4.2.5). Due to normality violations in the data on parietal power in the theta ($W = 0.6$, $p < .001$) and alpha ($W = .7$, $p < .001$) bands, the analyses were performed using non-parametric Mann–Whitney U tests. The test revealed that the spectral parietal power in the theta frequency band was marginally ($W = 30$, $p = .08$) higher for the experts of the 3D group ($Mdn = 35.4$, $SD = 81.0$) compared to those of the 2D group ($Mdn = 6.25$, $SD = 37.6$). Meanwhile, the test results revealed a similar pattern regarding the parietal spectral power in the alpha frequency band (3D: $Mdn = 29.1$, $SD = 49.2$; 2D: $Mdn = 6.36$, $SD = 31.2$); however, the results were not significant ($W = 32$, $p = .10$). Nevertheless, the group differences in parietal spectral power were supported by a medium effect size in the theta (r = .38) and alpha (r = .35) frequency bands.

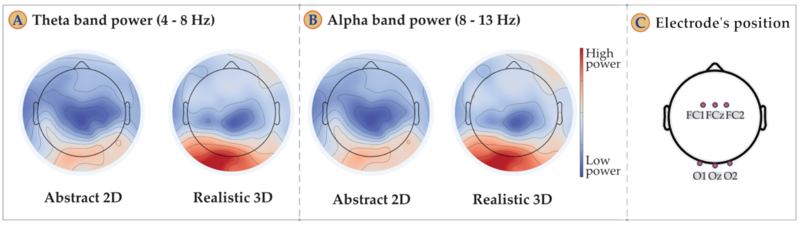

Figure 4.10: Topographic scalp maps reveal pronounced power spectral density of the parietal lobe in the theta (A) and alpha (B) frequency bands. Panel C shows the selected electrode's position in the frontal and parietal lobes.

As observed in previous research and noted in Section 3.3.2, frontal theta power increases and parietal alpha power decreases when users perform cognitive tasks. However, a visual inspection of the topographic scalp maps in Figure 4.10 did not reveal an enhanced frontal theta power (Figure 4.10–A) or attenuated parietal alpha power (Figure 4.10–B) across the landmark visualization conditions. The lack of a visual pattern was also confirmed by the non-significant results of the independent t-test on the relative frontal theta power ($t(19)$ = -0.2, p = .80, r = .06) and relative parietal alpha power ($t(18)$ = 0.4, p = .70, r = .09) across the 2D and 3D groups (Figure 4.11).

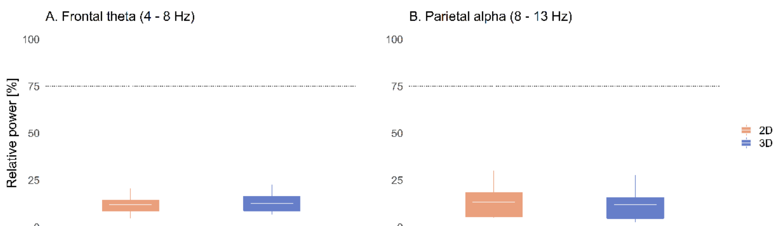

Figure 4.11: Relative frontal theta (A) and parietal alpha (B) power do not differ across experimental conditions. *Note: White bars indicate means.*

NASA TLX results

The lack of differences in experts' objective cognitive load as measured by the EEG was followed by no observed differences in their self-perceived workload during the navigation task assessed with the NASA TLX questionnaire. The independent t-test results revealed no significant differences ($t(16) = 1$, $p = .30$, $r = .27$) in experts' NASA TLX score (Figure 4.12) when navigating with abstract 2D ($M = 35.7$, $SD = 13.86$) or realistic 3D ($M = 30.3$, $SD = 8.15$) landmarks.

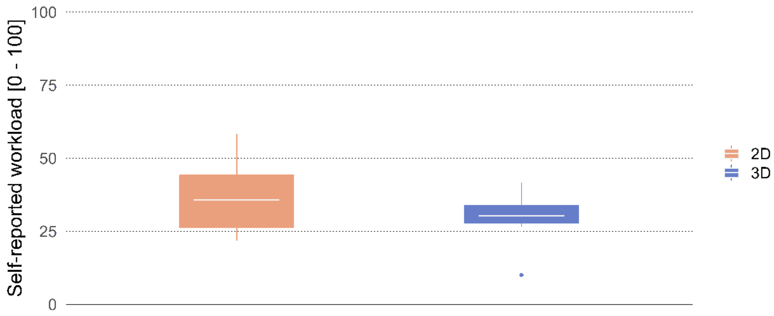

Figure 4.12: Landmark visualization style does not influence expert wayfinders' self-reported workload during the navigation task. *Note: White bars indicate means, and dot indicates an outlier.*

4.3.5 The effect of visual attention on spatial learning

The results of the linear mixed-effects model (LME; Equation 4.4) revealed significant main effects of the fixation duration (FD) on the ENV AOI and PTSOT error, as well as a significant interaction between the landmark visualization style and PTSOT error on experts' JRD pointing errors (see Table 4.1–A, and Figure 4.13–A). Specifically, when the expert wayfinders had a higher fixation duration in the environment (ENV AOI), their JRD pointing error was significantly lower ($\beta = -1.12$, $p = .01$). Furthermore, the model revealed that the experts with a higher PTSOT error had a significantly lower JRD pointing error ($\beta = -1.61$, $p = .02$). Additionally, the significant interaction term indicated that experts in the 3D group with higher PTSOT error had lower JRD pointing error ($\beta = -1.85$, $p = .005$). However, the LME model did not reveal a significant relationship between the landmark visualization style and the JRD pointing error (3D: $\beta = -3.64$, $p = .40$; see Table 4.1–A), and there was no significant interaction of FD with the 3D condition ($\beta = -0.54$, $p = .23$).

As Table 4.1–B shows, the LME model (Equation 4.5) revealed no significant main effects for the influence of FD on the MAP AOI ($\beta = -0.39$, $p = .62$), landmark visualization condition (3D: $\beta = -0.47$, p

Table 4.1: Fixed effects parameter estimation for the relationship between experts' JRD pointing error and fixation duration on the ENV and MAP AOIs.

	A. ENV AOI			*B. MAP AOI*		
	β	*CI*	*p*	β	*CI*	*p*
Intercept	34.93	26.41 – 43.46	**<.001**	34.97	24.08 – 45.86	**<.001**
Main effects						
Fixation duration (FD)	-1.12	-2.00 – -0.24	**.01**	-0.39	-1.94 – 1.16	.62
Condition [3D]	-3.64	-12.16 – 4.89	.40	-0.47	-11.36 – 10.42	.93
PTSOT error	-1.61	-2.91 – -0.31	**.02**	-1.48	-3.23 – 0.27	.10
Two-way interactions						
FD * Condition [3D]	-0.54	-1.42 – 0.34	.23	-0.83	-2.38 – 0.72	.29
PTSOT error * Condition [3D]	-1.85	-3.15 – -0.55	**.005**	-2.08	-3.83 – -0.33	**.02**

= .93; see Figure 4.13–B), interaction of FD and 3D condition (β = -0.83, p = .29), or PTSOT error (β = -1.48, p = .10) on expert wayfinders' JRD pointing error. However, the LME model revealed a significant interaction between the experimental condition and the PTSOT error. Similarly to the results discussed above, this result indicated that in the 3D group, higher PTSOT error corresponded to lower JRD pointing error (β = -2.08, p = .02).

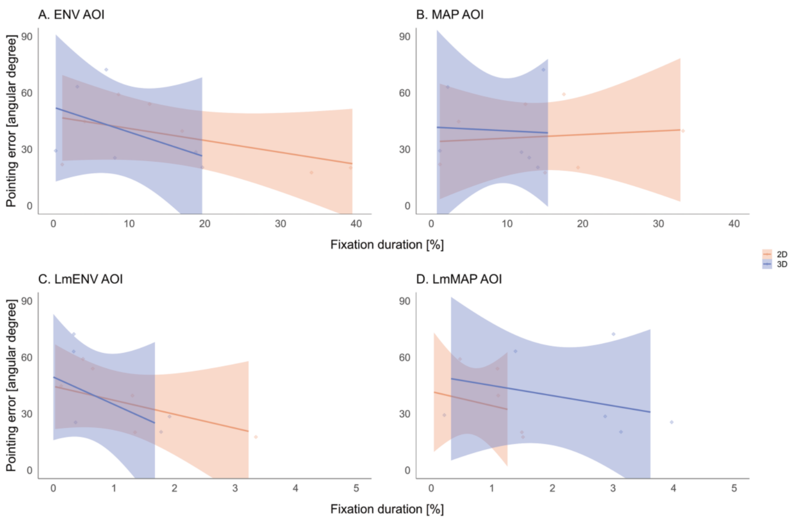

Figure 4.13: The relationship between fixation duration on the ENV (A), MAP (B), LmENV (C), and LmMAP (D) AOIs and JRD pointing error across landmark visualization conditions. *Note: Dots indicate experts' average pointing error and fixation duration per AOI, and shaded areas indicate 95% confidence intervals.*

The LME model results (Table 4.2–A) revealed that experts' FD on the LmENV AOI significantly influenced their JRD pointing error (β =

-12.11, p = .02). More precisely, a one-percent increase in experts' FD on the LmENV AOI was associated with a 12.11° reduction in JRD pointing error. Furthermore, the model revealed a significant influence of PTSOT error (β = -1.58, p = .02): a 1° increase in PTSOT error was associated with a 1.58° decreased in pointing error. Moreover, the influence of PTSOT error on JRD pointing error was stronger for the experts in the 3D group, as revealed by the models' significant interaction term (β = -1.82, p = .009). Nevertheless, the results did not reveal an influence of landmark visualization style on experts' JRD pointing error (3D: β = -1.84, p = .67; see Figure 4.13–C), and no significant interaction between FD and 3D condition was observed (β = -5.58, p = .30). Finally, the LME model (Equation 4.7) results (Table 4.2–B) revealed that the experts' JRD pointing error was not significantly influenced by their FD on the LmMAP AOI (β = -4.16, p = .67; see Figure 4.13–D), condition (3D: β = 3.49, p = .66), the interaction of FD with the 3D condition (β = -1.04, p = .91), or PTSOT error (β = -1.32, p = .13). However, the JRD pointing error was significantly influenced by the interaction of PTSOT error and landmark visualization style. Specifically, the higher the PTSOT error of the experts' in the 3D group, the lower their JRD pointing error (β = -1.72, p = .048).

Table 4.2: Fixed effects parameter estimation for the relationship between experts' JRD pointing error and fixation duration on the LmENV and LmMAP AOIs.

	A. LmENV AOI			*B. LmMAP AOI*		
	β	*CI*	p	β	*CI*	p
Intercept	35.97	27.51 – 44.42	**<.001**	38.18	22.87 – 53.49	**<.001**
Main effects						
Fixation duration (FD)	-12.11	-22.57 – -1.64	**.02**	-4.16	-23.23 – 14.91	.67
Condition [3D]	-1.84	-10.30 – 6.61	.67	3.49	-11.82 – 18.80	.66
PTSOT error	-1.58	-2.94 – -0.22	**.02**	-1.32	-3.02 – 0.39	.13
Two-way interactions						
FD * Condition [3D]	-5.58	-16.05 – 4.89	.30	-1.04	-20.12 – 18.03	.91
PTSOT error * Condition [3D]	-1.82	-3.18 – -0.45	**.009**	-1.72	-3.43 – -0.02	**.048**

Although PTSOT error was used as a control variable underlying experts' baseline survey learning abilities, give the expectation that a higher PTSOT error would also be reflected in a higher JRD pointing error, the results of Equation 4.4 and Equation 4.6 indicated the opposite. In particular, a higher PTSOT error across experimental conditions led to a significantly lower JRD pointing error (Table 4.1–A, and Table 4.2–A). To better understand these significant effects, Figure 4.14 visualizes the relationship between the experts' average PTSOT error and their JRD pointing error for each landmark visualization style. Figure 4.14 suggests that while the JRD pointing error increases with PTSOT error for the experts navigating with the abstract 2D landmarks, those navigating with realistic 3D landmarks exhibit a lower JRD pointing error for a higher PTSOT error. Consequently, the significant influence of the PTSOT error on the JRD pointing error shown in Table 4.1–A and Table 4.2–A was influenced by the PTSOT error of the experts in the 3D group. The observed relationship between the PTSOT error and the realistic 3D group was also supported by the significant results (Table 4.1 and Table 4.2) of the interaction term in all four LME models. These results indicated that the experts with low survey learning abilities (i.e., high PTSOT error) would improve their incidental spatial learning of the traversed environment only when navigating with the mobile map depicting landmarks as realistic 3D building models.

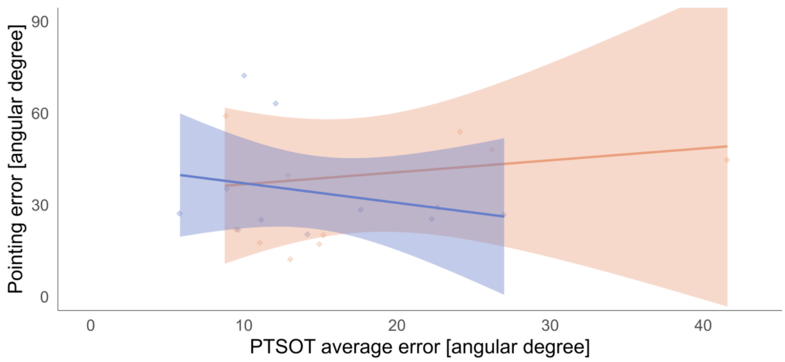

Figure 4.14: The relationship between experts' JRD pointing error and PTSOT average error by condition. *Note: Dots indicate experts' average JRD pointing error and PTSOT error, and shaded areas indicate 95% confidence intervals.*

4.4 Discussion

The present study investigated (RQ1) how depicting landmarks as either abstract 2D building footprints or realistic 3D building models on mobile map aids influences expert wayfinders' navigation performance, visual attention, spatial learning, and cognitive load during an aided, real-world, route-following navigation task. I hypothesized (H1) that when navigating with realistic 3D landmarks, the experts would exhibit better navigation performance, higher visual attention to task-relevant features, fewer gaze switches between the depicted landmarks and the map features, improved spatial learning, and lower cognitive load. Additionally, I examined (RQ2) whether experts' visual attention behavior could predict their incidental spatial learning when aided by a mobile map with either style of landmark depiction. Specifically, I hypothesized (H2) that experts' spatial learning would improve when their visual attention was guided more toward the environment and landmarks in it as opposed to the mobile map. The results of the present study are discussed in more detail in the following sections.

4.4.1 Navigation task unaffected by landmark visualization

Contrary to hypothesis H1.1, the results revealed no differences in experts' task accuracy and completion time when navigating with landmarks depicted as abstract 2D building footprints or realistic 3D building models. These results do not align with previous contradictory findings favoring realistic (Liao et al., 2017) or abstract (Dillemuth, 2005; Kray et al., 2003) map visualization styles on navigation performance in the general population. In the general population, both the main benefits and drawbacks of realistic 3D visualizations originate from the increased amount of information necessary to process with added realism, which can lead to either enhanced or deteriorated identification of task-relevant landmarks and higher or lower completion time (Dillemuth, 2005; Kray et al., 2003; Liao et al., 2017; Plesa & Cartwright, 2008; Wilkening & Fabrikant, 2011). However, expert wayfinders' navigation performance in the present study aligns with previous research considering similar user groups. These studies have established that domain expertise and a knowledge-driven approach to focus on task-relevant information facilitate experts' task performance (Hegarty et al., 2009; Keskin et al., 2020; Lanini-Maggi et al., 2021; Maggi et al., 2016).

Considering expert wayfinders' higher spatial abilities (Hegarty et al., 2006), domain expertise and experience (Woollett & Maguire, 2010), and habitual use of 2D maps (Wilkening & Fabrikant, 2013), the translation and visual matching from abstract 2D landmark designs to real-world 3D features may not have been challenging for them. Consequently, it is possible that, contrary to normal populations (Chrastil & Warren, 2012; Dahmani & Bohbot, 2020; Richter & Winter, 2014; Willis et al., 2009), expert wayfinders can handle landmark encoding even with reduced visual information during map-aided navigation. Accordingly, landmark encoding may not constitute a limiting factor of their navigation performance. Indeed, skilled navigators possess higher spatial working memory (Newcombe, 2018), facilitating their ability to encode landmarks' spatial configuration (Credé et al., 2020). The advantage of higher spatial working memory for enhanced navigation performance is evident in other expert populations, such as expert athletes (Meneghetti et al., 2022) and licensed taxi drivers (Maguire et al., 2006; Woollett & Maguire, 2011). Therefore, not all user groups require or benefit from design improvements in mobile maps as normal populations do, highlighting the necessity of population- and task-specific cartographic design solutions for navigation aids (Fabrikant, 2022; Griffin & Fabrikant, 2012; Griffin et al., 2017; Thrash et al., 2019).

4.4.2 Spatial learning unaffected by landmark visualization

Contrary to hypothesis H1.2, the JRD task results revealed no significant improvement in experts' incidental spatial learning when navigating with the mobile map depicting landmarks as realistic 3D building models. On the one hand, this lack of significant differences could be attributed to the fact that a perceptually salient depiction of landmarks on mobile maps, regardless of the visualization style, enhanced the experts' active encoding of landmark configurational knowledge and improved spatial learning (Chrastil & Warren, 2012; Thrash et al., 2019; Willis et al., 2009). On the other hand, asking expert wayfinders to explicitly indicate when a depicted landmark on the mobile map was reached in the environment may have improved their memory encoding about the real-world landmarks and the spatial relationships between them, leading to the lack of differences in spatial learning across the visualization styles. Therefore, future work should consider the influence of landmark visualization styles on expert wayfinders' spatial learning without priming them with explicit instructions to identify the landmarks in the environment.

In accordance with previous research, the lack of spatial learning differences can also be explained by the expert wayfinders' enhanced expertise and experience (Hegarty et al., 2009; Maguire et al., 2006; Sutton et al., 2014; Woollett & Maguire, 2010; Woollett & Maguire, 2011; Woollett et al., 2009). For instance, Sutton et al. (2014) reported a significantly lower JRD pointing error for expert pilots ($M = 44.23$) compared to a control group ($M = 65.04$). These findings align with previous work with the general population that has reported average pointing errors of 55–75 angular degrees between tested landmarks after one route exposure (Cheng et al., 2022; Credé et al., 2020; Huffman & Ekstrom, 2019). After only one route exposure, the expert wayfinders in the present study produced JRD pointing errors (M = 36.9°) lower than Sutton et al.'s (2014) expert pilots and much lower than the general population groups. These results confirm the navigation expertise and experience of the expert group sampled for this study.

4.4.3 Landmark visualization modulates visual attention

The results partially support hypothesis H1.3, which affirms that landmark visualization style would influence experts' allocation of attention to task-relevant information and gaze behavior during wayfinding. Specifically, the results revealed no significant differences in the distribution of fixation duration on the ENV, MAP, and LmENV AOIs. However, there was a marginal difference in experts' fixation duration on the *LmMAP* AOI. This marginally significant difference was supported by a visual inspection of the kernel density map (see Figure 4.7) depicting the distribution of experts' visual attention on the *MAP* AOI. Contrary to Liao et al.'s (2017) findings, the kernel density map revealed that the experts in the 2D group had to scan a wider area around the depicted route and landmarks compared to those in the 3D group, whose attention was mainly focused on and around the depicted landmarks. The experts' distribution of visual attention on the realistic 3D landmarks is in line with previous work suggesting that visually salient landmarks attract more visual attention (Richter & Winter, 2014; Wenczel et al., 2017; Yesiltepe et al., 2021). Therefore, depicting only landmarks as realistic 3D building models on a 2D basemap (rather than depicting all buildings as 3D models) in the present study cued experts' visual attention to these task-relevant features and facilitated the visual matching process between the mobile map and the environment, as suggested by previous research (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009). Meanwhile, as the abstract 2D landmarks were less salient, the experts using them for navigation had to scan a wider area of the mobile map to gather the spatial clues necessary to match the map information to the environment (Keil et al., 2020; Liao et al., 2017).

The results of the transition matrices (TMs), which were utilized to investigate experts' visual search strategies, revealed results similar to the kernel density map. For instance, the TMs results showed that, for the 2D expert group, a fixation on the depicted landmarks (LmMAP AOI) was more likely to be followed by a fixation on another section of the mobile map (MAP AOI). This suggests that the experts of the 2D group had to scan a wider area around the visualized landmarks, presumably due to their limited visual saliency and the lack of reference points needed to visually match the map display information with the physical environment, as highlighted by Keil et al. (2020), Kiefer et al. (2014), and Liao et al. (2017). Moreover, the entropy analysis results employed to quantify TMs suggest that experts in the 3D group showed a marginally higher transition entropy (TE) and a significantly higher stationary entropy (SE) than those in the 2D group. TE and SE reflect the overall bottom-up (i.e., driven by stimulus saliency) and top-down (i.e., driven by users' expertise) modulations of gaze behavior on a visual scene (Shiferaw et al., 2019). Higher TE and SE indicate a homogeneous distribution of visual attention over the present AOIs, while lower TE and SE indicate that visual attention is narrowly focused on specific AOIs (Krejtz et al., 2015; Krejtz et al., 2014; Shiferaw et al., 2019). This could mean that the increased realism and perspective viewing of the 3D landmarks facilitated the visual matching and identification of task-relevant landmarks in the environment. In contrast, navigation with abstract 2D landmark visualizations required focused visual attention on specific AOIs, such as the mobile map, to gather additional spatial information (Keil et al., 2020; Kiefer et al., 2014; Liao et al., 2017). The entropy results of the expert wayfinders in the present study are consistent with previous findings demonstrating that low entropy values reflect modulations of gaze behavior during difficult tasks (Lanini-Maggi et al., 2021; Shiferaw et al., 2019; Tole et al., 1982).

4.4.4 Cognitive load unaffected by landmark visualization

The cognitive load results do not support hypothesis H1.4, which states that the experts navigating with realistic 3D landmarks would exhibit lower cognitive load than those navigating with the abstract 2D landmarks. The objective EEG and self-reported NASA TLX results revealed no differences in experts' cognitive load across the visualization conditions. These results align with previous findings for both static (Keskin et al., 2020) and animated (Lanini-Maggi, 2017; Lanini-Maggi et al., 2021) displays revealing no influence of visualization styles on experts' cognitive load during visuospatial and spatial memory tasks. The lack of significant differences in the experts' cognitive load when navigating with abstract 2D or realistic 3D landmarks can be attributed to their enhanced spatial abilities, experience, expertise, and neural efficiency, reducing the cognitive effort required for successful navigation (Antonenko et al., 2010; Grabner et al., 2006; Keskin et al., 2020; Lanini-Maggi et al., 2021).

4.4.5 Visual attention predicts spatial knowledge acquisition

Fixation duration is an acknowledged measure of cognitive processes (Holmqvist et al., 2011; Kiefer et al., 2017), and longer fixation on task-relevant information improves experts' memory location for the attended information (Tatler et al., 2005). Therefore, in hypothesis H2, I expected improved spatial learning when experts show higher fixation duration on task-relevant features (i.e., the environment and the landmarks in the environment) and deteriorated spatial learning when they fixate longer on the mobile map display. However, I found only partial support for the influence of visual attention on experts' spatial learning. Specifically, when the expert wayfinders attended longer to the environment and the landmarks in the environment, their spatial learning improved significantly (i.e., lower JRD error), regardless of the landmark visualization style (i.e., abstract 2D or realistic 3D).

These results are not necessarily surprising, as prior work has already demonstrated that increased attention to the environment and task-relevant landmarks in the environment during aided navigation facilitates spatial learning (Brügger et al., 2019; Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018). Furthermore, during active navigation between landmark locations, humans continuously integrate idiothetic information to acquire metric information about the landmark relationships (Chrastil & Warren, 2012, 2013; Etienne & Jeffery, 2004; Montello et al., 2004). The present results suggest that this process is aided by visually attending to the traversed environment and task-relevant landmarks in the environment. Hence, these effects might be stronger in the present study because it involved active motion in an outdoor setting, as opposed to the restricted idiothetic input of previous studies utilizing a desktop or VE setups (Chrastil & Warren, 2012, 2013; De Sanctis et al., 2021; Montello et al., 2004).

Alternatively, previous studies show that when mobile maps aid members of the general population in their navigation quests in unfamiliar environments, the wayfinders must sustain their visual attention toward the traversed environment and task-relevant features for improved spatial learning (Brügger et al., 2019; Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018). Failure to do so, and the resulting divided attention between the navigation aid and the environment, would result in deteriorated spatial learning of the traversed environment (Brügger et al., 2019; Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018). However, in the present study, there was no indication that fixation duration on the mobile map and the landmarks on the mobile map was a predictor of experts' spatial learning. Consequently, due to their level of expertise and experience, the experts in the present study were immune to the adverse effects of divided attention on spatial learning. However, considering the improved spatial learning when attention is guided to the environment and landmarks in the environment, which holds true even in expert populations, suitable navigation aids should not consume too much attention Brügger et al., 2019; Gardony et al., 2015; Hejtmánek et al., 2018.

The results revealed that expert wayfinders' ability to imagine various objects' mental spatial rotations and perspective changes (PTSOT error) predicted their spatial learning (JRD pointing error). These results are in line with Sutton et al.'s (2014) observation that a higher PTSOT error translates to a higher JRD error or reduced learning. While a similar tendency was observed for the experts navigating with abstract 2D landmarks, the results revealed the opposite pattern for those navigating with realistic 3D landmarks (Figure 4.14). Specifically, when experts navigated with realistic 3D landmarks, their spatial learning improved (i.e., lower JRD pointing error) despite a lower baseline survey learning ability (i.e., higher PTSOT error). This suggests that the realistic 3D landmarks facilitated experts' encoding, maintenance, and updating of a mental map during the active exploration of the real-world environment, leading to a higher JRD accuracy despite their lower survey learning ability. This result supports previous research indicating that task performance in experienced and expert groups is also affected by idiosyncratic differences in spatial abilities (Hegarty et al., 2009; Keehner et al., 2004; Lanini-Maggi, 2017; Lanini-Maggi et al., 2021; Maggi et al., 2016).

STUDY II | 5

The scientist only imposes two things, namely truth, and sincerity, imposes them upon himself and upon other scientists.

— **Erwin Schrödinger**
(Nobel Prize–winning Physicist)

This chapter contains parts of the following published research article:

*1. **Kapaj, A.**, Hilton, C., Lanini-Maggi, S., and Fabrikant, S. I. (under review). The influence of landmark visualization style on task performance, visual attention, and spatial learning in a real-world navigation task. Spatial Cognition & Computation.*[1]

*2. **Kapaj**, A., Lin, E., and Lanini-Maggi, S. (2022). The effect of abstract vs. realistic 3D visualization on landmark and route knowledge acquisition. In T. Ishikawa, S. I. Fabrikant, and S. Winter (Eds.), 15th International Conference on Spatial Information Theory (COSIT 2022) (Vol. 240, pp. 15:1-15:8). https://doi.org/10.4230/LIPIcs.COSIT.2022.15.*

In Study I, I investigated the influence of landmark visualization style (abstract 2D footprints vs. realistic 3D buildings) on expert wayfinders' navigation performance, incidental spatial learning, visual attention, and cognitive load, as well as the influence of visual attention as a predictor of spatial learning. The results revealed that the landmark visualization style did not influence experts' navigation performance, incidental spatial learning, or cognitive load during the real-world aided navigation task. On the one hand, the lack of significant differences could be explained by the enhanced spatial abilities, navigation experience, and expertise of the chosen sample group. On the other hand, another possible explanation is that while the experts did not differ with regard to survey knowledge acquisition, they might have differed in landmark and route knowledge. Though not assessed in Study I, these types of knowledge are acquired continuously during navigation tasks (Montello, 1998). Consequently, in Study II, I

[1] Author contributions: AK, SLM, and SF designed the study. AK performed data collection. AK and CH performed data analyses and drafted the manuscript. All authors were involved in revising, editing, and approving the final manuscript.

aimed to further investigate, among other factors, how wayfinders sampled from the general population acquire landmark, route, and survey knowledge of the traversed environment when aided by a mobile map enhanced with landmark information. In the present study, task-relevant landmarks were depicted on the mobile map as either realistic or abstract 3D buildings (see Figure 3.2–B and Section 5.2.3). These landmark visualization styles were based on Elias and Paelke's (2008) realistic to abstract design continuum and Liao et al.'s (2017) design recommendations, which suggest combining realistic 3D landmarks with a 2D basemap for improved navigation. Furthermore, the realistic 3D landmark visualization was informed by the findings of Study I, which revealed that the realistic 3D landmark visualization guided experts' attention to the task-relevant landmarks (see Section 4.3.3) and improved the spatial learning of experts with low survey learning abilities (see Section 4.3.5). In turn, the abstract 3D landmark visualization was based on previous research suggesting that increased realism would adversely affect wayfinders' spatial learning because it requires them to process more visual information (Hegarty et al., 2009; Liao et al., 2017; Plesa & Cartwright, 2008).

5.1 Research question and hypothesis

In the present study, I investigated the influence of landmark visualization styles (i.e., realistic 3D vs. abstract 3D) on the navigation performance, visual attention, spatial learning (i.e., route, landmark, and survey knowledge), and cognitive load of wayfinders sampled from the general population during a real-world aided navigation task. In Study II, I aimed to answer the following research questions (RQ) and associated hypotheses (H), which are derived from the thesis's main research question (see Section 1.2):

> **RQ1**: What are the differences in participants' navigation performance, visual attention, and acquisition of landmark, route, and survey knowledge about the traversed environment during a real-world navigation task aided by a mobile map depicting landmarks as abstract or realistic 3D buildings?

According to previous research, a salient depiction of landmarks on mobile maps supports spatial learning in general populations by guiding their attention to task-relevant features and facilitating the matching of information between the map aid and the physical environment (Chrastil & Warren, 2012, 2013; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009; Yesiltepe et al., 2021). Therefore, I hypothesized the following:

> ***H1***: Participants navigating with realistic 3D landmarks will demonstrate 1) better navigation performance (i.e., fewer navigation errors); 2) longer visual attention to task-relevant features (i.e., the traversed environment and landmarks in the environment); 3) better landmark, route, and survey knowledge acquisition; and 4) lower cognitive load than the participants navigating with abstract 3D landmarks.

> **RQ2**: How does the allocation of visual attention during aided navigation influence participants' acquisition of landmark, route, and survey knowledge?

Based on the finding in Study I that visual attention predicts survey knowledge acquisition (see Section 4.3.5), and on previous research reporting an adverse role of divided attention on wayfinders' spatial learning (Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018), I hypothesized the following:

> ***H2***: Longer visual attention to the environment and to the task-relevant landmarks in the environment – and, conversely, shorter visual attention to the mobile map – will lead to improved landmark, route, and survey knowledge acquisition.

5.2 Methods

5.2.1 Participants

The present study was conducted in English. The participants were recruited through the personal contacts and mailing lists of the Department of Geography at the University of Zurich. The sample size calculation was determined before data collection using a single-predictor multilevel linear regression model (DeBruine & Barr, 2021) with the *simr* R package (Green & MacLeod, 2016) for data simulation in *R* (version 4.2.1; R Core Team, 2022). Using parameters estimated from Study I (i.e., fixed effects beta coefficients and variance of random effects), the model revealed that 40 participants, each completing 20 trials of pointing tasks, would achieve a power of 83% (see Appendix for study preregistration). Consequently, 46 healthy adults comprising 22 females (*M* age = 27.3 years, *range* = 21–46 years) and 24 males (*M* age = 27.8 years, *range* = 22–38 years) took part in the present study (six more than initially calculated to accommodate data loss). When asked about their familiarity with the traversed environment, 10 participants rated themselves as having some familiarity, and the remaining 36 were unfamiliar.

Similar to Study I, the procedures carried out in this study received ethical approval (*No. 19.6.10*) from the University of Zurich Ethics Committee. The participants gave written informed consent before the start of the experiment, and they were informed that they could end their participation in the experiment at any time and without consequences. The participation criteria were normal or corrected to normal vision and no history of physical and psychiatric disorders that could interfere with visual attention and cognitive states during the navigation task. Participants with corrected eyesight could join the study only by wearing contact lenses, as the eyeglasses would impede eye-tracking recordings. All the experimental procedures lasted approximately two hours, and the participants were compensated with 40 Swiss Francs.

5.2.2 Experimental design

To account for idiosyncratic differences in spatial abilities among the participants, in the present study, I utilized a within-subject experimental design (Martin, 2007) with landmark visualization style (i.e., realistic vs. abstract 3D buildings; Figure 3.2–B) as the independent variable. Therefore, the recruited participants were exposed to both independent variable levels during the navigation task. To account for an ordering effect on learning (Martin, 2007), I counterbalanced the landmark visualization style presented to the wayfinders. Specifically, half of the participants were presented with the first five landmarks as realistic 3D buildings and the second five as abstract 3D buildings (Figure 5.1–A), whereas the other half were presented with the reverse landmark visualization order (Figure 5.1–B). Several dependent variables were measured in the present study: wayfinders' navigation performance (i.e., task accuracy), spatial learning (i.e., landmark, route, and survey knowledge), visual attention (i.e., eye-movement recordings throughout the navigation task), and cognitive load (i.e., objective and subjective measurements).

5.2.3 Materials and apparatus

Navigation route

The real-world navigation study presented in Study II was conducted in an urban residential area in Zurich, Switzerland. The learning phase consisted of a predefined route-following navigation task. The predefined route was approximately 1 km long and comprised five right turns, four left turns, and one place where participants continued straight ahead at landmark-equipped intersections (Figure 5.1). Ten buildings located at intersections were selected as task-relevant landmarks and depicted on the mobile map aid as either realistic or abstract 3D buildings. To inform the selection of the depicted landmarks, I conducted a small survey (n = 9) to select one building per intersection to serve as a task-relevant landmark. The sample group consisted of employees (i.e., PhDs, postdocs, and professors) of the Geographic Information Visualization and Analyses research group at the Department of Geography of the University of Zurich. This sample group did not participate in the real-world navigation experiment conducted for this study. Similarly to Nothegger et al. (2004), I provided participants with a sketch map of the intersection, their position approaching the intersection, the turning direction after the intersection, and images of the buildings – as seen from the participants' perspective – indicating the buildings' location at the intersection. The intersections were presented one at a time and in a randomized order. The participants were asked to rate the most prominent building. Put simply, the building they would use when giving directions, or the building that was the easiest to describe (Nothegger et al., 2004).

Mobile map design

During the route-following navigation task in the real world, wayfinders were aided by a mobile map depicting landmarks as realistic or abstract 3D buildings, a predefined route as a blue line, and the destination point as a red flag (see Section 3.3.1 and Section 3.2 for information on the design of 3D landmarks and mobile map aids, respectively). As stated in the experimental design section, the counterbalancing performed to control for ordering effects on learning (Martin, 2007) of landmark visualization style (i.e., the independent variable) resulted in two mobile maps. The two maps differed in the depiction order of landmarks: 1) Figure 5.1–A depicts the first five landmarks as realistic, and the second five as abstract 3D buildings and 2) Figure 5.1–B depicts the landmarks in the reversed order (i.e., the first five landmarks as abstract, and the second five landmarks as realistic 3D buildings). The mobile maps were displayed on a tablet device that participants could freely zoom, pan, rotate, and tilt. Map interactions were recorded and stored in a log file and are mentioned for replicability purposes; however, they will not be part of the present thesis's analysis, which focuses on wayfinders' spatial abilities, spatial learning, and cognitive load. Nevertheless, similarly to Study I, the mobile maps did not show or track wayfinders' location along the predefined navigation route.

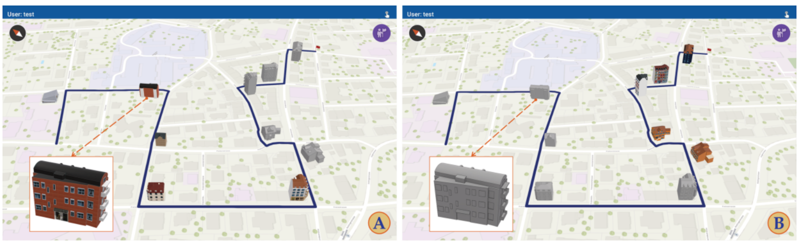

Figure 5.1: Interactive mobile maps depicting the first five landmarks as realistic (A) or abstract (B) 3D buildings. The inset view depicts a zoomed-in landmark in both visualization conditions.

Sensory recordings and questionnaire measures

Mobile eye-tracking (MET) glasses were used to record wayfinders' eye movements during the navigation task. I used the binocular head-mounted *Pupil Invisible* MET glasses from Pupil Labs.[2] Pupil Invisible glasses record participants' eye movements at a 200-Hz sampling rate and do not require gaze calibration (Tonsen et al., 2020). These MET glasses contain a scene camera with 1088 × 1088 resolution and an 82° × 82° field of view, which records at 30 Hz. Depending on weather conditions, I used shaded or clear lenses to prevent participants from squinting. The MET glasses were connected to an accompanying mobile device used for data recording, which participants carried in

[2]Pupil Labs GmbH, Berlin, Germany; https://pupil-labs.com/products/invisible

a backpack. The MET data processing and analyses performed to examine wayfinders' visual attention during the navigation task are detailed in Section 5.2.5.

Electroencephalography (EEG) was used to objectively assess participants' cognitive load during the real-world wayfinding task. I utilized the same EEG device as in Study I (see Section 4.2.5). The EEG data processing steps and planned analyses will be detailed in Section 5.2.5.

The NASA Task Load Index (NASA TLX; Hart & Staveland, 1988) questionnaire was employed to assess the participants' subjective workload during the navigation task. In the present study, I used a computerized version of the NASA TLX two-step evaluation procedure. In the first step, the participants were asked to rate the contribution of each of the six categories (see Section 3.3.2) to their workload. In the second step, the participants were presented with 15 possible pairwise comparisons of the six scales and had to pick the scale of the given pair that contributed the most to their workload. See Section 5.2.5 for the NASA TLX data analysis.

The Questionnaire on Spatial Strategies (QSS; Münzer & Hölscher, 2011) was utilized to collect wayfinders' self-reported spatial abilities (see Section 4.2.3 for more information regarding QSS). The average score of self-reported individual spatial ability was used to investigate whether spatial ability would predict wayfinders' visual attention and spatial learning. I used an online version of the QSS to record additional demographic data such as age, gender, education, profession, mobile map use, familiarity with the study area, and participants' preference concerning the landmark visualization style.

The Perspective Taking and Spatial Orientation Test (PTSOT; Hegarty & Waller, 2004) was utilized to evaluate wayfinders' learning ability for survey knowledge by assessing their ability to mentally rotate and imagine perspective changes for a given set of objects (see Section 4.2.3 for more information regarding PTSOT). Ten PTSOT items across four participants were not answered within the test's five-minute time limit and were assigned to a 90° chance performance score (Friedman et al., 2020; Hegarty & Waller, 2004). Subsequently, the average PTSOT error of one of these participants was higher than the 90° chance performance, indicating that this participant did not understand the task (Friedman et al., 2020; Hegarty & Waller, 2004); the participant was excluded from further PTSOT analyses.

The landmark and route knowledge task was used to assess participants' landmark recognition and associated route directions. The participants were presented with images of 30 buildings in a randomized order; the images were taken from their viewpoint for better recognizability (Christou & Bülthoff, 1999). Based on their location, the buildings were categorized into three landmark types (Cheng et al., 2022; Wunderlich & Gramann, 2021b; Wunderlich et al., 2023), each comprising 10 buildings:

1. **Relevant landmarks** (REL) define buildings positioned at route intersections where a destination-relevant navigation decision was required; these landmarks were depicted on the mobile map as realistic or abstract 3D buildings (Figure 5.1).
2. **Irrelevant landmarks** (IRL) define buildings located along the predefined navigation route where no navigation decision was required (i.e., no changes in moving direction) and were not depicted on the mobile map aid.
3. **Novel landmarks** (IRL) define buildings that were neither along the predefined navigation route nor depicted on the mobile map but had a similar style to those around the navigation route.

The participants were asked if they recognized encountering the 30 buildings during the real-world navigation task and to answer with *"yes"* or *"no"* using an online questionnaire. If *"yes"*, they were asked to identify whether they saw the building *"on the map and in the environment"* or *"only in the environment"* to discern between REL and IRL landmarks, respectively. When the participants classified the buildings as REL landmarks, they were asked to indicate the route direction they took after passing the building, answering with either *"turned right"*, *"turned left"*, or *"went straight"*.

The landmark free reconstruction of order task (Hilton et al., 2021b) was utilized to assess whether the participants could place the 10 REL landmarks in the correct sequence as they were visited during the navigation task. The participants were presented with building image printouts as seen from their perspective during the navigation task. The 10 buildings were color-printed on five sheets of A4 paper with one randomly chosen landmark pair per page. The participants were then instructed to write down the sequence in which they believed they encountered the buildings during the route-following task.

The pointing and distance estimation task (Ishikawa & Montello, 2006) was used to assess the participants' survey knowledge acquisition of the traversed environment during the aided real-world route-following navigation task. The participants were asked to recall the direction and distance of pairs of the 10 REL landmarks belonging to the same visualization condition (i.e., realistic or abstract 3D buildings). Hence, 10 landmark pairs out of the 20 possible permutations (5*4) per visualization condition were randomly chosen for each participant. For instance, I randomly selected one of the following direction and distance estimations for each landmark pair: *"standing at Landmark 1, determine the direction and distance of Landmark 2"* or *"standing at Landmark 2, determine the direction and distance of Landmark 1"*. I used a paper-based version of the task consisting of images and names of two landmarks and a 10-cm radius with the name of one of the landmarks of the pair in the center (see Figure 3.3–A). Specifically, participants were asked, *"Imagine you are standing at building X, facing straight ahead, as when you walked by the building. Please indicate the direction of building Y by drawing a line from the center of the circle and note the beeline distance in meters between building X and Y."*

5.2.4 Experimental procedure

The real-world navigation study was carried out in December 2021 on days with suitable weather conditions. On the day of the experiment, the participants were welcomed in a meeting room close to the study area, where they were asked to read and sign the consent form. After the informed consent procedures, the participants were given instructions and asked to fill out the QSS and demographic questionnaires and the PTSOT task. Upon the completion of these questionnaire measures, the experimenters prepared the EEG device and helped the participants put it on. Next, the participants were equipped with MET glasses. After the EEG and MET data recordings were started, the participants were led to the beginning of the predefined navigation route and shown how to interact with the tablet device, allowing them to become familiar with it. Subsequently, the participants were introduced to the navigation task:

> *You will be navigating in a residential area with the aid of a mobile map. Please walk as you would when exploring a new environment. Your task is to follow the route marked in blue on the mobile map and to find the 10 visualized buildings in the environment. Please raise your hand to indicate you found the building when standing in front of it, and do not wait for confirmation. Continue to the next*

> *building and repeat the same gesture until you reach the tenth building. Once you have found all the buildings, continue to the final destination marked with a red flag on the map. Please wait there for further instructions.*

To control for intentionality in learning (Wenczel et al., 2017), the participants were informed that their newly acquired knowledge of the traversed environment would be tested at the end of the navigation task, without revealing information about the follow-up tests. Furthermore, the participants were shadowed at a safe distance to note their navigation performance – that is, their turning directions and identification of the task-relevant landmarks. If a participant made an error in turning direction, I allowed them to self-correct their decision. If the participant continued in the wrong direction, I called them back to the intersection where the error was made and prompted them to continue. Upon completing the navigation task, I removed the EEG and MET devices and led participants back to the preparation room to complete the follow-up tests. The time from the end of the navigation task to the preparation room was approximately 10 minutes and included a trip with public transport. During this trip, the participants completed the NASA TLX questionnaire to rate their self-perceived navigation task workload. Once back at the preparation room, the participants completed a computerized version of the landmark and route knowledge questionnaire. Then, they completed the paper-based landmark free reconstruction of order and direction and distance estimation tasks. Subsequently, they rated their familiarity with the study area and their preference regarding the landmark visualization style. There were no time constraints for the participants' completion of the follow-up tests, and they were free to correct their answers as often as they wanted before the test was finalized. Finally, the participants were given a debriefing sheet, thanked, and rewarded for their participation.

5.2.5 Data processing and analyses

As stated in Section 5.2.2, the dependent variables measured in the present study were wayfinders' navigation task performance, distribution of visual attention, spatial learning (comprising landmark, route, and survey knowledge), and wayfinders' objective and subjective cognitive load. All the statistical analyses carried out to investigate the influence of landmark visualization style (the independent variable) on the above dependent variables were performed utilizing linear mixed-effect (LME) or generalized mixed-effect (GLME) models using the *lme4* package (Bates et al., 2015). The LME and GLME models were implemented in R (version 4.2.1; R Core Team, 2022) with the significance threshold set at $p < .05$. To identify the LME and GLME models that would reach convergence for each dependent variable, I began with a model containing the dependent variable as a response variable, no fixed effects, and a random effect structure informed by the experimental design (Barr et al., 2013). If the model did not reach convergence, I iteratively reduced the random effects structure by removing first the random slopes and then the random intercepts until the model converged. When more than one model converged, I utilized the Aikake Information Criterion (AIC) to select the model that fit the data best (Field et al., 2012). Subsequently, I centered the continuous variable at the mean value and contrast-coded categorical variables to -0.5 and 0.5. Then, on each best-fitted model selected to analyze the dependent variables, I added the fixed effects (detailed in the following sections together with the data processing steps). The results of the present study were plotted using the *ggplot2* package (Wickham, 2016).

Navigation performance measures

In order to analyze the participants' navigation task performance, I noted their wrong turns at intersections and failures to identify the task-relevant landmarks in the environment. Due to the participants' limited number of navigation errors (see Section 5.3.1) when navigating with realistic or abstract 3D landmarks, I did not perform any statistical comparison of task accuracy between the groups.

Visual attention measures

To analyze wayfinders' allocation of visual attention during the mobile map-aided navigation task, I annotated the fixation data recorded with MET glasses to a corresponding area of interest (AOI). Using the iMotions software,[3] the participants' raw fixation data were manually assigned to one of the following AOIs: 1) the mobile map display (*MAP*); 2) the environment (*ENV*; i.e., environmental features apart from the 10 REL landmarks); and 3) the 10 REL landmarks in the environment (*LmENV*). The annotated raw gaze data with AOI information were parsed into fixations and saccades using the *EYE-EEG*

[3]Copenhagen, Denmark; https://imotions.com/products/imotions-lab

plugin (version 0.99; Dimigen et al., 2011) in the *EEGLAB* toolbox (version 2020.0; Delorme & Makeig, 2004) in MATLAB (R2020b; version 9.9.0). To detect saccadic eye movements, the velocity threshold was set at 6 *SD* above participants' median gaze velocity for at least four consecutive samples in order to suppress noise in the detection procedure (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006). Subsequently, I relied on fixation duration, a widely acknowledged measure of visual information processing (Holmqvist et al., 2011; Kiefer et al., 2017), to analyze wayfinders' visual attention during the aided navigation task. Due to the better data quality of the MET glasses employed in this study compared to Study I, I set a fixation threshold from 150 ms to 2,000 ms (Holmqvist et al., 2011), in contrast to the lower fixation threshold of 100 ms in Study I.

I fitted three separate LME models, differing only in the fixation duration (FD) on each AOI (i.e., MAP, ENV, LmENV) to analyze wayfinders' visual attention behavior during the aided navigation. The selected LME models included the wayfinders' FD on a particular AOI as a response variable and the landmark visualization condition as the main effect. To control for the wayfinders' self-reported spatial abilities (QSS score) and their familiarity with the study area on visual attention allocation, these variables were expressed in the LME models as interaction terms with the experimental condition. The selected LME models included a by-subject random intercept:

$$\textit{FD on ENV} \sim \textit{Condition} * \textit{QSS score} + \textit{Condition} * \textit{Familiarity} + (1|\textit{Subject}) \tag{5.1}$$

$$\textit{FD on MAP} \sim \textit{Condition} * \textit{QSS score} + \textit{Condition} * \textit{Familiarity} + (1|\textit{Subject}) \tag{5.2}$$

$$\textit{FD on LmENV} \sim \textit{Condition} * \textit{QSS score} + \textit{Condition} * \textit{Familiarity} + (1|\textit{Subject}) \tag{5.3}$$

Landmark knowledge measures

The influence of landmark visualization style on wayfinders' landmark knowledge was assessed with the first two questions of the landmark and route knowledge task (see Section 5.2.3) and with the landmark free reconstruction of order task (see Section 5.2.3).

To investigate the wayfinders' recognition of landmarks as measured by the landmark and route knowledge test, I utilized the *psycho* package (Makowski, 2018) in R to perform analyses according to the signal detection theory (SDT; Tanner & Swets, 1954). SDT evaluates participants' ability to discriminate between information and background noise or distractors (Tanner & Swets, 1954). In the context of SDT, participants' correct answers are encoded as a *"hit"* or *"correct rejection"*, while false answers are encoded as a *"miss"* or *"false alarm"*. I used the d prime (d') discriminability index, computed as the difference between the standardized scores of hits and false alarms (d' = *Z[hit] - Z[false alarm]*), to analyze landmark recognition accuracy across the visualization conditions. Additionally, I used criterion location (c) computed as *c = -0.5 * (Z[hit] - Z[false alarm])* to control for participants' response biases against zero (that is, no) bias. I used SDT to run two-fold landmark recognition analyses. First, I analyzed whether participants could distinguish between landmarks that were present in the environment (REL and IRL; see Section 5.2.3) and landmarks that were absent from the environment (NOL; Figure 5.2–A). Second, I analyzed whether participants could distinguish between landmarks present in the environment and depicted on the mobile map (REL) and landmarks that were present in the environment but not depicted (IRL; Figure 5.2–B).

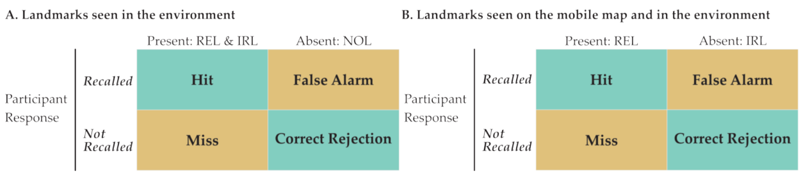

Figure 5.2: Encoding of participants' responses, whether they could recognize the landmarks in the environment (A), and the landmarks visualized on the map (B).

I used LME models on the d' values to analyze wayfinders' recognition accuracy for landmarks seen in the environment and for landmarks visualized on the mobile map across the landmark visualization conditions. Furthermore, I utilized paired t-tests to investigate whether the participants' response biases influenced their answers. The LME models included d' as a response variable, while the condition, QSS score, familiarity, and FD on each AOI were included as fixed effects. The QSS, familiarity, and FD on each AOI were added to the model as interaction terms with the condition in order to control for their influence on wayfinders' recognition of landmarks across visualization styles. The response variable, fixed effects, and interaction terms were fed into the following two models with by-subject random intercepts:

$$\begin{aligned} &\textit{Recognition of environment landmarks} \sim \textit{Condition} * \textit{QSS score} \\ &+ \textit{Condition} * \textit{Familiarity} + \textit{Condition} * \textit{FD on ENV} + \textit{Condition} \\ &* \textit{FD on MAP} + \textit{Condition} * \textit{FD on LmENV} + (1|\textit{Subject}) \end{aligned} \tag{5.4}$$

$$\begin{aligned} &\textit{Recognition of map landmarks} \sim \textit{Condition} * \textit{QSS score} \\ &+ \textit{Condition} * \textit{Familiarity} + \textit{Condition} * \textit{FD on ENV} + \textit{Condition} \\ &* \textit{FD on MAP} + \textit{Condition} * \textit{FD on LmENV} + (1|\textit{Subject}) \end{aligned} \tag{5.5}$$

The other measurement employed to assess wayfinders' landmark knowledge was the landmark free reconstruction of order. In this measure, the participants were asked to note the sequence in which they encountered the landmarks during the navigation task. I encoded the participants' answers as 1 if they placed the landmark in the correct position in the sequence and 0 if the position was wrong. I utilized a GLME with the encoded data; landmark reconstruction of order was the response variable, and the condition, QSS score, familiarity, and FD on each AOI were fixed effects. The QSS score, familiarity, and FD on each AOI were expressed as interaction terms with the condition. The GLME included by-landmark-item and by-subject random intercepts:

$$\begin{aligned} &\textit{Reconstruction of landmarks order} \sim \textit{Condition} * \textit{QSS score} \\ &+ \textit{Condition} * \textit{Familiarity} + \textit{Condition} * \textit{FD on ENV} + \textit{Condition} \\ &* \textit{FD on MAP} + \textit{Condition} * \textit{FD on LmENV} \\ &+ (1|\textit{Landmark item}) + (1|\textit{Subject}) \end{aligned} \tag{5.6}$$

Route knowledge measures

The participants' route knowledge was assessed with the landmark and route knowledge task. Their answers were encoded as 1 for the correct turning direction and 0 for the wrong turning direction. Subsequently, I utilized a GLME model with route direction recognition as the response variable and the condition, QSS score, familiarity, and FD on each AOI as fixed effects. The fixed effects were added as interaction terms with the condition to control for the influence of spatial abilities, familiarity, and visual attention across the landmark visualization styles. The selected GLME model included by-landmark-item and by-subject random intercepts:

$$
\begin{aligned}
&\textit{Recognition of route directions} \sim \textit{Condition} * \textit{QSS score} \\
&+ \textit{Condition} * \textit{Familiarity} + \textit{Condition} * \textit{FD on ENV} + \textit{Condition} \\
&* \textit{FD on MAP} + \textit{Condition} * \textit{FD on LmENV} \\
&+ (1|\textit{Landmark item}) + (1|\textit{Subject})
\end{aligned} \tag{5.7}
$$

Survey knowledge measures

The wayfinders' survey knowledge of the 10 task-relevant landmarks was assessed using the pointing and distance estimation task (see Section 5.2.3). Similar to the JRD task, the pointing task was expressed as absolute angular degree error, calculated as the difference between the estimated direction and actual directions between the reference and target landmarks. The pointing error varies from 0° to 180° indicating high or low survey knowledge acquisition. Meanwhile, the distance between two REL landmarks was expressed as a distance error in meters, calculated as the difference between the estimated and actual distance. The pointing and distance estimation errors were analyzed using LME models, with the error as the response variable and the experimental condition as the main effect. In addition to the fixed effects of QSS score, familiarity, and FD on each AOI, the model also included the PTSOT error as a fixed effect to control for participants' baseline survey learning ability. All the fixed effects were added as interaction terms with the experimental condition to assess the influence of spatial abilities, familiarity, and FD across visualization styles. Since one participant's PTSOT data was excluded because it was higher than the 90° chance performance, the following LME model, which includes by-landmark-item and by-subject random intercepts and a by-condition random slope on the subject's level, was run on the data from the remaining 45 participants:

$$
\begin{aligned}
&\textit{Pointing error} \sim \textit{Condition}^{*}\textit{QSS score} + \textit{Condition}^{*}\textit{PTSOT error} \\
&+ \textit{Condition}^{*}\textit{Familiarity} + \textit{Condition}^{*}\textit{FD on ENV} + \textit{Condition} \\
&{}^{*}\ \textit{FD on MAP} + \textit{Condition}^{*}\textit{FD on LmENV} \\
&+ (1|\textit{Landmark item}) + (1 + \textit{Condition}|\textit{Subject})
\end{aligned} \tag{5.8}
$$

$$
\begin{aligned}
&\textit{Distance error} \sim \textit{Condition}^{*}\textit{QSS score} + \textit{Condition}^{*}\textit{PTSOT error} \\
&+ \textit{Condition}^{*}\textit{Familiarity} + \textit{Condition}^{*}\textit{FD on ENV} + \textit{Condition} \\
&{}^{*}\ \textit{FD on MAP} + \textit{Condition}^{*}\textit{FD on LmENV} \\
&+ (1|\textit{Landmark item}) + (1 + \textit{Condition}|\textit{Subject})
\end{aligned}
\tag{5.9}
$$

Cognitive load measures

EEG recordings were used as an objective assessment of wayfinders' cognitive load during the present route-following navigation task. Due to recording issues, the data of one participant was not recorded. Subsequently, in order to improve the signal-to-noise ratio, the EEG task recordings of the remaining 45 participants were processed using the *BeMoBIL* pipeline (Klug et al., 2022) in the *EEGLAB* toolbox for MATLAB, following the same processing steps as in Study I (see Section 4.2.5). I relied on power spectral analyses to investigate the wayfinders' cognitive load (see Section 3.3.2) on the theta (4–8 Hz) and alpha (8–13 Hz) frequency bands. Three electrodes in the frontal (FC1, FCz, and FC2) and three in the parietal (O1, Oz, and O2) lobes were selected for the respective power spectral analyses of the frontal theta and parietal alpha power. To account for wayfinders' individual power modulations, I utilized the relative theta and alpha power, calculated as the division of the absolute power in the given frequency bands over the absolute power of the entire frequency bandwidth (1–30 Hz):

$$\textit{Relative theta power} = \frac{\textit{Absolute theta power}}{\textit{Absolute (delta + theta + alpha + beta) power}} \times 100 \tag{5.10}$$

$$\textit{Relative alpha power} = \frac{\textit{Absolute alpha power}}{\textit{Absolute (delta + theta + alpha + beta) power}} \times 100 \tag{5.11}$$

The total relative powers for the frontal theta and parietal alpha bands were acquired by averaging the relative power of the frontal (FC1, FCz, and FC2) and parietal (O1, Oz, and O2) electrodes. Before running statistical tests on the wayfinders' relative theta and alpha power, I first checked the data distribution using a Shapiro–Wilk test. The normality test revealed no violations of normality for the relative frontal theta power ($W = 1$, $p = .50$), whereas the parietal alpha power departed significantly from a normal distribution ($W = 1$, $p = .002$). Therefore, a paired t-test was utilized to analyze the normally distributed relative frontal theta power, while a paired Wilcoxon signed-rank test was used to analyze the non-normally distributed relative frontal theta power.

NASA TLX was utilized to assess wayfinders' self-perceived workload during the navigation task. In the present study, I recorded and analyzed the full NASA TLX two-part evaluation procedure. The first part is similar to Study I (see Section 4.2.5), where participants rated each scale's contribution to their workload from 0 (low load) to 100 (high load). In the second part, when presented with the 15 possible pairwise comparisons of the six scales, the participants had to pick the member of the pair that contributed the most to their workload. The number of times each scale was selected could vary from 0 (not relevant) to 5 (the most relevant scale; Hart & Staveland, 1988). Dividing the number of times each scale was selected by 15 (i.e., the total number of pairwise comparisons) produces a weight for that scale. When the scale's weight is multiplied by the participants' raw rating of that scale's contribution to their workload, it gives the scale's adjusted rating for the participants' workload. Summing the adjusted rating of the six scales generates an overall rating for each participant. Since NASA TLX was not used to capture the wayfinders' workload when navigating with realistic or abstract 3D landmarks, it will be used only for an overview of the participants' workload during the navigation task, regardless of the landmark visualization style.

5.3 Results

5.3.1 Navigation performance

All 46 wayfinders in the study completed the navigation task with only a few navigation errors. For instance, there were only two failures to identify two task-relevant landmarks, one per visualization condition; these errors were committed by two participants. In addition, a total of eight wrong turns at destination-relevant intersections were committed by five participants. Due to the limited number of failures to identify the task-relevant landmarks and turning errors out of the total 460 possible errors – that is, 10 landmarks and intersections times 46 participants – we did not conduct any statistical analyses. However, it is obvious that the navigation performance of participants using the mobile map depicting landmarks as realistic or abstract 3D buildings was very high.

5.3.2 Visual attention

In this section, I will report the results concerning the participants' distribution of visual attention on the *ENV*, *MAP*, and *LmENV* AOIs during the navigation task (see Table 5.1). The LME model (see Equation 5.1) revealed that the wayfinders' distribution of visual attention on the ENV AOI was influenced by the landmark visualization style (see Table 5.1–A). Specifically, when wayfinders navigated with realistic 3D landmarks, their FD on the environment was significantly longer (β = 7.28, p < .001) compared to navigating with abstract 3D landmarks (see Figure 5.3–A). The LME model also revealed that wayfinders' QSS score significantly predicted their distribution of visual attention on the ENV AOI (β = -7.15, p = .03); the wayfinders' FD on the ENV AOI decreased by 7.15 ms with an incremental increase in their self-reported spatial abilities (Figure 5.3–B). Furthermore, the QSS score interacted significantly with the visualization condition (β = -3.89, p = .01). In particular, when wayfinders navigated with realistic 3D landmarks, their FD on the ENV AOI decreased by 3.89 ms with an increase in their spatial abilities. The model revealed that wayfinders' overall familiarity with the study area was not a significant predictor of visual attention on the ENV AOI. However, familiar participants' FD on the environment was significantly longer when they navigated with the realistic 3D landmarks (β = 4.62, p = .04; Figure 5.3–C).

Table 5.1: Fixed effects parameter estimation for wayfinders' fixation duration [ms] on the three study AOIs.

	A. ENV AOI			*B. MAP AOI*			*C. LmENV AOI*		
	β	*CI*	p	β	*CI*	p	β	*CI*	p
Intercept	442.3	431.4 – 453.2	**<.001**	445.0	431.3 – 458.8	**<.001**	425.6	411.2 – 439.9	**<.001**
Main effects									
Condition [Realistic]	7.28	2.83 – 11.72	**<.001**	-2.41	-8.56 – 3.74	.44	-0.16	-8.77 – 8.44	.97
QSS score	-7.15	-13.77 – -1.54	**.03**	-6.35	-14.68 – 1.98	.14	-3.40	-12.26 – 5.45	.45
Familiarity [Familiar]	-3.70	-14.60 – 7.20	.51	-7.61	-21.40 – 6.17	.28	-10.31	-24.67 – 4.04	.16
Two-way interactions									
Condition [Realistic] * QSS score	-3.89	-6.69 – -1.08	**.01**	-2.20	-5.77 – 1.37	.23	-2.27	-7.80 – 3.26	.42
Condition [Real.] * Familiarity [Fam.]	4.62	0.18 – 9.06	**.04**	-5.29	-11.42 – 0.85	.09	-3.41	-12.00 – 5.19	.44

The LME models showed that wayfinders' visual attention to the *MAP* (Equation 5.2) and *LmENV* (Equation 5.3) AOIs was not significantly influenced by the landmark visualization style, QSS score, or familiarity with the study area. Additionally, the model revealed that the interactions of condition with wayfinders' QSS score and familiarity were also not significant predictors of fixation duration (see Table 5.1–B and C).

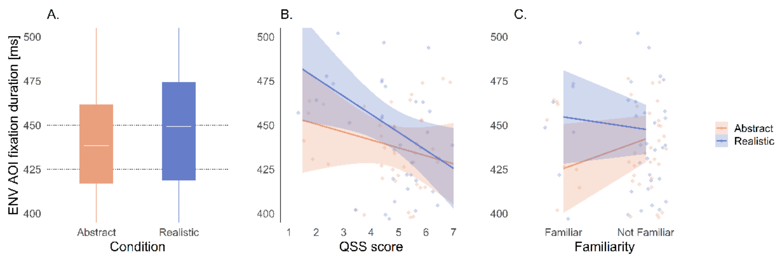

Figure 5.3: Average fixation duration on the ENV AOI (A), influence of the QSS score (B), and familiarity with the study area (C) across conditions. *Note: Dots indicate average data, and shaded areas indicate 95% confidence intervals.*

5.3.3 Landmark knowledge

I investigated the participants' landmark knowledge acquisition by utilizing LME models to analyze the d' values for the participants' accuracy in recognizing landmarks seen in the environment (Equation 5.4) and on the mobile map (Equation 5.5). Additionally, as part of the participants' acquired landmark knowledge, I investigated their recognition accuracy for landmark reconstruction of order using a GLME model (Equation 5.6). The results of the landmark knowledge models are shown in Table 5.2. The LME model results revealed that the recognition of landmarks seen in the environment was not predicted by the condition, nor by any other fixed effects or their two-way interactions (see Table 5.2–A).

Table 5.2: Fixed effects parameter estimation for wayfinders' recognition of landmarks in the environment (A), on the map (B), and landmark reconstruction of order (C).

	A. Environment landmarks			*B. Map landmarks*			*C. Landmarks order*		
	β	*CI*	*p*	β	*CI*	*p*	*Odds ratios*	*CI*	*p*
Intercept	1.31	1.14 – 1.48	**<.001**	1.81	1.58 – 2.04	**<.001**	1.28	0.41 – 4.02	.67
Main effects									
Condition [Realistic]	0.10	-0.05 – 0.25	.20	0.17	0.02 – 0.32	**.03**	1.26	0.89 – 1.78	.20
QSS score	0.08	-0.02 – 0.18	.11	0.15	0.01 – 0.29	**.03**	1.66	1.15 – 2.40	**.01**
Familiarity [Familiar]	0.16	-0.01 – 0.33	.07	0.19	-0.04 – 0.42	.10	1.77	0.97 – 3.24	.06
FD on ENV	<-0.00	-0.01 – <0.00	.19	<-0.00	-0.01 – <0.00	.57	1.00	0.99 – 1.02	.67
FD on MAP	<-0.00	-0.01 – <0.00	.27	<0.00	<-0.00 – <0.00	.98	1.00	0.99 – 1.01	.39
FD on LmENV	<0.00	<-0.00 – <0.00	.22	<0.00	<-0.00 – <0.00	.32	1.00	0.99 – 1.01	.66
Two-way interactions									
Condition [Real.] * QSS score	-0.05	-0.14 – 0.04	.28	-0.06	-0.15 – 0.03	.20	0.68	0.54 – 0.85	**<.001**
Condition [Real.] * Familiarity [Fam.]	0.10	-0.05 – 0.25	.20	0.05	-0.11 – 0.20	.55	1.00	0.70 – 1.42	1.00
Condition [Real.] * FD on ENV	<-0.00	-0.01 – <0.00	.61	<-0.00	-0.01 – <0.00	.21	1.01	0.99 – 1.02	.33
Condition [Real.] * FD on MAP	<-0.00	-0.01 – <0.00	.24	<-0.00	-0.01 – <0.00	.60	0.99	0.98 – 1.00	.23
Condition [Real.] * FD on LmENV	<-0.00	<-0.00 – <0.00	.85	<0.00	<0.00 – 0.01	**.03**	1.00	0.99 – 1.01	.56

The LME model (Equation 5.5) results revealed that visualization style (Table 5.2–B) significantly predicted wayfinders' recognition of landmarks depicted on the mobile map (β = 0.17, p = .03). Specifically, wayfinders' d' value for recognizing landmarks depicted on the mobile map improved by 0.17 points when they navigated with realistic 3D landmarks (Figure 5.4–A). In addition, the results revealed that wayfinders' QSS score significantly predicted (β = 0.15, p = .03) their recognition of landmarks depicted on the mobile map. This indicates that higher spatial abilities (i.e., higher QSS score) correspond with higher accuracy in recognizing landmarks visualized on the mobile map (Figure 5.4–B) regardless of the visualization style, as reflected by the lack of significant interaction between the QSS score and the condition (β = -0.06, p = .20). Furthermore, the model revealed a significant interaction between the landmark visualization style and FD on the LmENV AOI (β < 0.00, p = .03). Specifically, when participants navigated with realistic 3D landmarks and had a longer FD on the landmarks in the environment (LmENV AOI), their recognition of landmarks depicted on the mobile map improved significantly compared to navigation with abstract 3D landmarks (Figure 5.4–C).

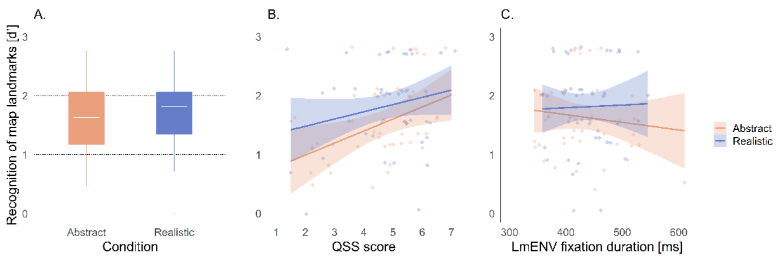

Figure 5.4: Recognition of landmarks seen on the mobile map display (A), the influence of the QSS score (B) and fixation duration on the LmENV AOI (C) across the landmark visualization styles. *Note: Dots indicate individual data points, and shaded areas indicate 95% confidence intervals.*

In addition to the above LME models, I performed paired t-tests in criterion location c (see Section 5.2.5) to control for participants' response biases in recognizing landmarks seen in the environment and on the mobile map against the non-bias value (zero). The paired t-test revealed that participants' response bias for the recognition of landmarks in the environment was higher than zero when navigating with both realistic (M = 0.17, t(45) = 3, p = .009) and abstract (M = 0.19, t(45) = 3, p = .007) 3D landmarks. Similarly, the paired t-test revealed the same pattern for the recognition of landmarks on the mobile map across the realistic (M = 0.29, t(45) = 5, p < .001) and abstract (M = 0.35, t(45) = 6, p < .001) conditions. The results for response bias indicate that participants were more likely to respond that they did not recognize the landmarks in the environment and on the mobile map display. Further paired t-tests were conducted to compare participants' response bias across the landmark visualization styles; these tests revealed that the differences in response bias were not significant between conditions for the recognition of landmarks in the environment ($t(45) = 0.3$, $p = .80$) and on the mobile map ($t(45) = 0.9$, $p = .40$).

The final measure utilized to assess participants' landmark knowledge was the landmark free reconstruction of order task (see Section 5.2.3). The GLME model (see Equation 5.6) revealed that landmark visualization condition (Figure 5.5–A), familiarity, FD on AOIs, and these variables' interactions with the condition were not significant predictors of wayfinders' accuracy for the reconstruction of landmarks sequence (see Table 5.2–C). However, the GLME model revealed that the wayfinders' spatial abilities (QSS) score significantly predicted their reconstruction of the landmark sequence (*odds ratio* = 1.66, p = .01), which means that an increase in spatial abilities would be reflected in higher accuracy for the landmark reconstruction of order (see Figure 5.5–B). The model also revealed a significant interaction of the realistic condition with the QSS score (*odds ratio* = 0.68, $p < .001$). As seen from Figure 5.5–B, this indicates that when participants with low spatial abilities – that is, low QSS score – navigated with realistic landmarks, their reconstruction of the landmarks' sequence improved. Furthermore, the significant interaction indicates that participants with higher self-reported spatial abilities exhibited small differences in landmark sequence memory across the landmark visualization styles (Figure 5.5–B).

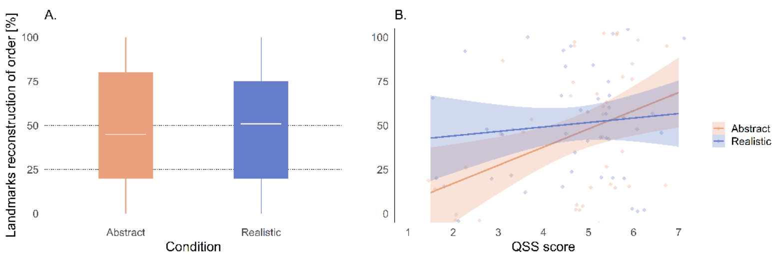

Figure 5.5: Reconstruction of landmark order by condition (A) and the influence of the QSS score (B) across conditions. *Note: Dots indicate individual data points, and shaded areas indicate 95% confidence intervals.*

5.3.4 Route knowledge

The participants' memory of destination-relevant turning directions was assessed with the landmark and route knowledge task (see Section 5.2.3). The GLME model (Equation 5.7) result outcomes, including odds ratios, CIs, and *p*-values, are reported in Table 5.3.

Table 5.3: Fixed effects parameter estimation for the recall of route directions.

	Route direction recall		
	Odds ratios	*CI*	*p*
Intercept	1.51	0.77 – 2.98	.23
Main effects			
Condition [Realistic]	1.24	0.95 – 1.62	.12
QSS score	1.43	1.19 – 1.71	**<.001**
Familiarity [Familiar]	1.30	0.97 – 1.75	.08
FD on ENV	1.00	0.99 – 1.01	.43
FD on MAP	1.00	0.99 – 1.01	.71
FD on LmENV	1.00	1.00 – 1.01	.21
Two-way interactions			
Condition [Realistic] * QSS score	0.89	0.76 – 1.05	.16
Condition [Realistic] * Familiarity [Familiar]	1.02	0.78 – 1.34	.90
Condition [Realistic] * FD on ENV	1.01	1.00 – 1.01	.14
Condition [Realistic] * FD on MAP	0.99	0.99 – 1.00	**.02**
Condition [Realistic] * FD on LmENV	1.00	1.00 – 1.01	.82

The model revealed that landmark visualization style (Figure 5.6–A), familiarity, and FD on each AOI were not significant predictors of wayfinders' memory of the landmarks' associated turning directions. Furthermore, the model shows that the realistic 3D landmark visualization style did not significantly interact with wayfinders' spatial abilities (QSS score), familiarity, or FD on the ENV and LmENV AOIs. However, the results revealed that wayfinders' QSS score significantly predicted their memory of route directions (*odds ratio* = 1.43, $p < .001$). This indicates that higher self-reported spatial abilities corresponded to higher recall of the landmarks' associated turning directions among the wayfinders (Figure 5.6–B), regardless of the landmark visualization style. Also, the model results show that wayfinders' recall of route directions was significantly higher when they navigated with the realistic 3D landmarks and exhibited shorter fixations on the MAP AOI (*odds ratio* = 0.99, $p = .02$). In contrast, when they fixated longer on the mobile map, wayfinders' recall of route directions decreased (Figure 5.6–C).

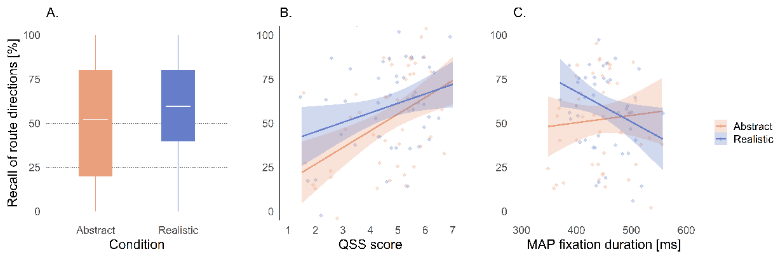

Figure 5.6: Recall of route directions for each condition (A), the influence of the QSS score (B), and fixation duration on the MAP AOI (C) across conditions. *Note: Dots indicate individual data points, and shaded areas indicate 95% confidence intervals.*

5.3.5 Survey knowledge

The participants' survey knowledge of the 10 task-relevant landmarks was assessed with a pointing and distance estimation task (Section 5.2.3). The results of the LME models shown in Equations 5.8 and 5.9 are reported in Table 5.4–A and B, including the models' estimates, CIs, and *p*-values.

Table 5.4: Fixed effects parameter estimation for wayfinders' survey knowledge.

	A. Pointing error			*B. Distance error*		
	β	*CI*	*p*	β	*CI*	*p*
Intercept	43.51	36.27 – 50.75	**<.001**	107.22	82.99 – 131.44	**<.001**
Main effects						
Condition [Realistic]	-0.42	-4.76 – 3.92	.85	4.50	-2.17 – 11.16	.19
QSS score	-2.56	-6.51 – 1.38	.20	-0.32	-8.65 – 8.02	.94
PTSOT error	0.33	-0.12 – 0.79	.15	0.87	-0.08 – 1.83	.07
Familiarity [Familiar]	-5.11	-11.57 – 1.34	.12	11.13	-2.47 – 24.74	.11
FD on ENV	-0.08	-0.24 – 0.07	.29	0.08	-0.18 – 0.33	.55
FD on MAP	0.06	-0.06 – 0.18	.35	-0.12	-0.33 – 0.08	.25
FD on LmENV	0.04	-0.05 – 0.13	.42	0.14	-0.02 – 0.30	.08
Two-way interactions						
Condition [Realistic] * QSS score	2.82	0.15 – 5.48	**.04**	2.27	-1.85 – 6.38	.28
Condition [Realistic] * PTSOT error	0.12	-0.18 – 0.43	.43	0.07	-0.39 – 0.54	.76
Condition [Realistic] * Familiarity [Familiar]	1.39	3.04 – 5.82	.54	5.47	-1.42 – 12.36	.12
Condition [Realistic] * FD on ENV	-0.15	-0.30 – 0.00	.06	-0.06	-0.31 – 0.18	.61
Condition [Realistic] * FD on MAP	0.13	0.01 – 0.25	**.03**	0.06	-0.13 – 0.25	.53
Condition [Realistic] * FD on LmENV	0.03	-0.06 – 0.12	.57	0.08	-0.07 – 0.23	.28

The results revealed that the wayfinders' pointing and distance errors were not significantly predicted by the landmark visualization style, QSS score, PTSOT error, familiarity with the study area, or their FD on the three study AOIs. In the case of the participants' distance estimation error, the results revealed no significant interactions between the landmark visualization style and the other fixed effects (Table 5.4–B). However, the results showed that the wayfinders' pointing error was significantly influenced by the interaction of the landmark visualization style with several other fixed effects. Specifically, the pointing error was influenced by the landmark visualization style's interaction with the QSS score (β = 2.82, p = .04). This indicates that the pointing error of participants with low spatial abilities improved when they navigated with realistic 3D landmarks compared to abstract 3D landmarks. However, the differences in pointing error performance diminished for participants with higher spatial abilities, regardless of the landmark visualization style (Figure 5.7–A). Similarly, the results revealed (Table 5.4–A) a significant interaction between the landmark visualization style and the FD on the MAP AOI (β = 0.13, p = .03), as well as a marginally significant interaction of the condition with the FD on the ENV AOI (β = -0.15, p = .06). For instance, when participants navigated with realistic 3D landmarks and exhibited shorter FD on the MAP AOI, their pointing error improved by 0.13° compared to when they navigated with abstract 3D landmarks (Figure 5.7–B). In contrast, when participants navigated with realistic 3D landmarks and exhibited longer FD on the ENV AOI, their pointing error decreased by 0.15° (Figure 5.7–C).

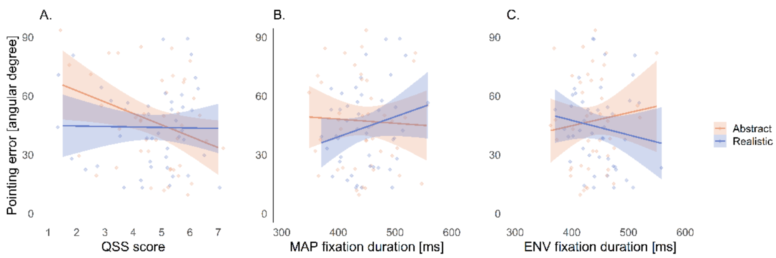

Figure 5.7: The influence of QSS score (A) and fixation duration for the MAP (B) and ENV (C) AOIs on wayfinders' pointing error across conditions. *Note: Dots indicate individual data points, and shaded areas indicate 95% confidence intervals.*

5.3.6 Cognitive load

EEG results

To understand the influence of landmark visualization style on cognitive load, I plotted topographic scalp density maps of all EEG channels. These maps show the scalp distribution of power over the theta (4–8 Hz) and alpha (8–13 Hz) frequency bands. A visual inspection of Figure 5.8 reveals that wayfinders exhibit a higher spectral power on the parietal lobe compared to the frontal lobe across the theta (Figure 5.8–A) and alpha (Figure 5.8–B) frequency bands. Higher spectral power in the parietal lobe is indicative of visual information processing (Bullier, 2001; Xu, 2018). However, there appear to be no differences across conditions in the parietal lobe, revealing no fluctuations in spectral power when wayfinders process visual stimuli depicting landmarks as realistic or abstract 3D buildings.

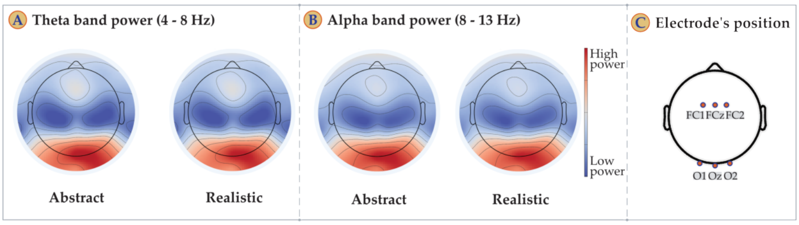

Figure 5.8: Topographic scalp maps reveal a pronounced power spectral density of the parietal lobe in the theta (A) and alpha (B) frequency bands. Panel (C) shows the selected electrodes position in the frontal and parietal lobes.

Further visual inspection of Figure 5.8 does not reveal an increased frontal theta power or decreased parietal alpha power across the landmark visualization styles, which would be indicative of cognitively demanding tasks (Gevins & Smith, 2003; Klimesch, 1999). The lack of visual patterns is confirmed by the non-significant results of the employed paired t-test on the relative frontal theta power ($t(44)$ = -0.6, p = .50, r = .09) and paired Wilcoxon signed-rank test on the relative parietal alpha power (V = 578, p = .50, r = .1) when wayfinders navigated with landmarks depicted in either style.

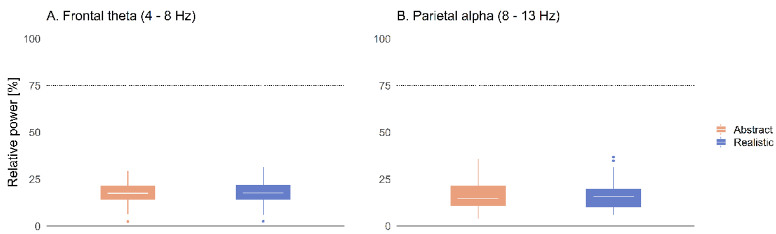

Figure 5.9: Relative frontal theta (A) and parietal alpha (B) power do not differ across landmark visualization styles. *Note: White bars indicate means in panel A and medians in panel B, and dots indicate outliers.*

NASA TLX results

The NASA TLX was utilized to assess the wayfinders' self-perceived workload during the route-following navigation task, regardless of the landmark depiction style on the mobile map aid. The NASA TLX results (see Section 5.2.5 for more information on the scoring procedure) revealed that wayfinders reported a relatively low overall workload of 23.1 out of 100 during the navigation task, aligning with the lack of observed differences in the EEG results. Figure 5.10 shows the participants' self-perceived navigation task workload across the six scales. The highest self-rated scale was *Effort* (27.28 out of 100), and the lowest was *Frustration* (9.67 out of 100). The participants reported that the *Performance* scale was the most important scale (3.93 out of 5) in contributing to the navigation task workload, while the *Frustration* scale was the least important (0.63 out of 5; see Figure 5.10).

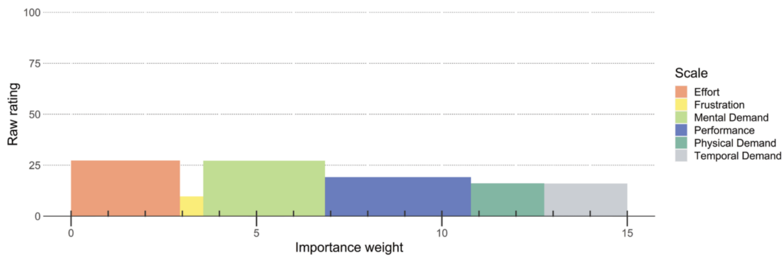

Figure 5.10: Wayfinders' navigation task workload across the NASA TLX scales. The bar heights represent the magnitude of the scale, and the bar widths represent the scale's importance for the workload (i.e., the wider the bar, the greater the importance). *Note: The performance scale is recorded in the reverse direction, which means that low values indicate better task performance.*

5.4 Discussion

In the present study, I investigated how the visualization of landmarks as realistic or abstract 3D buildings on mobile map aids influences wayfinders' navigation task performance, allocation of visual attention, spatial learning, and cognitive load (RQ1). Accordingly, I hypothesized (H1) that when aided by the mobile map depicting landmarks as realistic 3D buildings, wayfinders would demonstrate improved navigation performance, longer visual attention to task-relevant features, enhanced spatial learning performance, and mitigated cognitive load. I also investigated whether wayfinders' distribution of visual attention during the aided navigation task would predict their spatial knowledge acquisition (RQ2). Specifically, I hypothesized (H2) that wayfinders' spatial learning would improve when their visual attention was guided more toward the task-relevant features, such as the environment and landmarks in the environment, and less toward the mobile map aid. The results revealed mixed support for the present study's hypotheses, as detailed in the following discussion sections.

5.4.1 Navigation task unaffected by landmark visualization

Contradicting hypothesis (H1.1), the results revealed no differences in the number of wrong turns or failures to identify the task-relevant landmarks when wayfinders were aided by the mobile map depicting landmarks as realistic or abstract 3D buildings. In general, wayfinders' navigation performance was at a ceiling level; thus, the lack of differences is likely because enriching the mobile map aids with 3D landmarks – regardless of the visualization style (realistic vs. abstract) – provided the necessary spatial information to enhance wayfinders' visual matching between the aid and the environment, leading to the successful completion of the navigation task (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Thrash et al., 2019; Willis et al., 2009). Additionally, the route-following navigation task was not particularly difficult, considering that a 1-km route is not unusually long; this limited the chances for disorientation and map-reading errors.

Following the completion of the navigation task, the wayfinders were asked to rate which landmark visualization style they preferred. In response, 82.6% reported that they favored realistic 3D landmarks, 8.7% favored abstract 3D landmarks, and the remaining 8.7% were neutral in their preferences. The wayfinders' navigation performance and landmark visualization preference results align with previous studies reporting that while users prefer realistic 3D visualizations, their performance does not necessarily improve with them (Hegarty et al., 2009; Kray et al., 2003; Liao et al., 2017; Oulasvirta et al., 2009). Then again, while wayfinders' navigation performance did not improve with the present cartographic design choices concerning task-relevant landmarks, it is reassuring that the additional visual realism in the preferred realistic 3D landmark visualization did not adversely impact task efficiency, which was a risk emphasized in previous studies where all the buildings were shown in realistic 3D style (Dillemuth, 2005; Liao et al., 2017; Plesa & Cartwright, 2008). Overall, the high navigation task performance in the present study reinforces the call to enrich mobile maps with task-relevant landmark information.

5.4.2 Landmark visualization modulates visual attention

The fixation duration results provided limited support for the hypothesis (H1.2) that the realistic 3D landmark visualization would modulate wayfinders' visual attention across the environment, the mobile map display, and the task-relevant landmarks. Contrary to the hypothesis, the results revealed no influence of the landmark visualization style on wayfinders' visual attention to the mobile map or the task-relevant landmarks. However, in line with the stated hypothesis, the results revealed that wayfinders exhibited longer visual attention to the environment when navigating with realistic 3D landmarks.

The results revealed that the visual attention of wayfinders navigating with realistic 3D landmarks was influenced by their familiarity with the study area. Therefore, in follow-up analyses, I further investigated the influence of landmark visualization style and familiarity on wayfinders' fixation duration on the environment. To this end, I split the data based on familiarity and re-ran the Equation 5.1 for each group. The results revealed that the landmark visualization condition modulated wayfinders' visual attention in the environment only for familiar (β = 11.35, p < .001) but not unfamiliar (β = 2.71, p = .21) participants. Interestingly, wayfinders who reported some familiarity with the study area exhibited longer average fixation duration in the environment when navigating with landmarks depicted as realistic 3D buildings. Even though it was not the intention of the present study to investigate the role of familiarity, I tested 10 participants who had some familiarity with the area; this sample size reflected difficulties in assessing the wayfinders' familiarity with the study area without first exposing them to the area as well as difficulties in reaching the a priori-defined sample size. Therefore, I controlled for the familiarity factor in all the LME and GLME models, and the results revealed no other effects of familiarity. Familiarity's influence on fixation duration suggests that realistic 3D landmarks might be particularly beneficial in guiding visual attention to the environment for wayfinders who already have some familiarity with and expectations about the environment and landmarks. Indeed, a recent large-scale study reported that people exhibit better navigation abilities in environments whose general architectural features are similar to their hometowns (Coutrot et al., 2022). Considering the small sample size of the 10 participants familiar with the study area, I cannot draw definitive conclusions about the role of familiarity in designing mobile map aids. However, the topic represents an interesting question for future research.

The results revealed that wayfinders' self-reported spatial abilities influenced their visual attention to the environment. Specifically, wayfinders with lower spatial abilities exhibited longer average fixation duration on the environment when aided by the mobile map depicting landmarks as realistic 3D models. These participants' longer fixation durations can be attributed to deeper learning intentions and higher engagement with the navigation task (Albert & Tullis, 2013; Liao et al., 2019; Wenczel et al., 2017) or the participants' own interest in the task (Goldberg & Kotval, 1999). Hence, the hypothesis that realistic 3D landmarks would guide users' attention to the environment is supported for wayfinders with lower spatial abilities. These results are not surprising given that this group demands more support than wayfinders with higher spatial abilities, who can modulate their attention more independently (Hegarty et al., 2006; Ishikawa, 2022; Montello, 1998). Previous findings have shown that low-spatial-ability wayfinders depend on mobile maps to facilitate their aided navigation tasks; as a result, they become predisposed to these aids' adverse effects on spatial learning (Dahmani & Bohbot, 2020; Ishikawa, 2019; Ruginski et al., 2019) due to their divided attention and higher attention to the map aids (Brügger et al., 2019; Hejtmánek et al., 2018). However, in the present study, low-spatial-ability wayfinders' attention was guided to the environment when aided by a mobile map supplemented with realistic 3D landmarks. The effect of this phenomenon on their spatial learning will be discussed next.

5.4.3 Spatial learning affected by landmark visualization

The results revealed mixed support for hypothesis H1.3 – that wayfinders' spatial learning across the landmark, route, and survey knowledge components would improve when navigating with realistic 3D landmarks. The wayfinders showed similar performance across both landmark visualization styles for recognizing landmarks that they had seen in the environment and for route direction recall. In support of the hypothesis, the results revealed that when wayfinders navigated with realistic 3D landmarks, their recognition of landmarks as being depicted on the mobile map improved compared to when navigating with abstract 3D landmarks. However, a visual inspection of Figure 5.4–C suggests that this result may have been driven by a single data point. Consequently, I removed this data point and re-ran the model in Equation 5.5, which resulted in a marginally significant effect ($\beta = 0.14$, $p = .07$) of landmark visualization style on the recognition of map landmarks. Although the significant result with the full dataset and the marginally significant result with the outlier excluded were in line with the stated hypothesis, I did not interpret it as a meaningful effect.

As landmark and route knowledge acquisition constitute the foundations of environmental spatial representation (Montello, 1998; Siegel & White, 1975), these results lend weight to previous findings that wayfinding performance does not necessarily benefit from increased realism (Hegarty et al., 2009; Kray et al., 2003; Liao et al., 2017; Plesa & Cartwright, 2008; Wilkening & Fabrikant, 2011). This argumentation also extends to wayfinders' poor distance estimation performance compared to the other spatial knowledge acquisition measures, which indicates that the wayfinders might have required more than a single route exposure to build adequate distance knowledge between the task-relevant landmarks (Hilton et al., 2021a; Ishikawa & Montello, 2006). Nevertheless, the insufficient distance estimation performance does not necessarily translate to poor spatial learning of the traversed environment, as the wayfinders performed well on the landmark sequence reconstruction and pointing tasks. Specifically, the results revealed that the realistic 3D landmark visualization style improved the performance of landmark sequence reconstruction and pointing estimation between the task-relevant landmarks for wayfinders with self-reported low spatial abilities. The low-spatial-ability participants' improved performance for landmark sequence and spatial configurational knowledge is likely in conjunction with their aforementioned modulations in visual attention (see Section 5.4.2), which are consistent with increased visual processing of environmental features.

On the one hand, the lack of differences in landmark recognition and route recall can be explained by the fact that depicting landmarks as 3D models on the mobile map aid, regardless of the realistic or abstract style, could have provided the necessary visual information to augment the acquisition of spatial knowledge about the traversed environment (Chrastil & Warren, 2012; Elias & Paelke, 2008; Liao et al., 2017; Willis et al., 2009). On the other hand, participants with lower spatial abilities demonstrated improved spatial learning, which is not necessarily achieved on the first exposure to an environment (Hilton et al., 2021a; Ishikawa & Montello, 2006). The influence of spatial ability in almost all the spatial learning models aligns with previous findings highlighting the importance of individual differences in spatial learning performance during navigation tasks (Hegarty et al., 2006; Ishikawa, 2022; Newcombe et al., 2022). However, the results concerning the interaction of condition with spatial knowledge acquisition contradict previous findings that added realism inhibits performance, especially for low-spatial-ability users (Hegarty et al., 2009; Wilkening & Fabrikant, 2011). Nevertheless, these results confirm previous work reporting that high-spatial-ability users are less affected by the display visualization style (Hegarty et al., 2009; Lanini-Maggi et al., 2021; Wilkening & Fabrikant, 2013). Taken together, the results highlight the importance of tailoring the design of mobile map aids in accordance with the abilities of the targeted user population (Griffin & Fabrikant, 2012; Griffin et al., 2017; Montello et al., 2018).

5.4.4 Visual attention predicts spatial knowledge acquisition

The results revealed partial support for hypothesis H2 – that the distribution of wayfinders' visual attention to the environment, task-relevant landmarks, and mobile map display would influence their spatial learning performance. The results did not indicate a direct relationship between fixation duration for any of the three study AOIs and performance on landmark, route, and survey knowledge acquisition. Nevertheless, the results revealed a relationship between landmark visualization style and fixation duration on the MAP AOI and wayfinders' recall of route directions and pointing estimation between task-relevant landmarks. Specifically, a shorter fixation on the mobile map aid was reflected in improved route recall and landmark configurational knowledge when participants navigated with realistic 3D landmarks. The advantages of the realistic 3D landmark visualization style for route and survey knowledge diminished when participants' fixation durations on the map were longer. Additionally, the results revealed that wayfinders' recognition accuracy of landmarks seen on the mobile map improved when they navigated with realistic landmarks and had a longer fixation duration on the task-relevant landmarks (LmENV AOI). However, this improvement was too small to be meaningful, and it was driven by a single data point (see Table 5.2–B and Figure 5.4–C). Furthermore, a longer fixation duration in the ENV AOI for the realistic landmarks group was associated with a marginally significant improvement in accuracy for the pointing task. Although the influence of fixation duration on the LmENV and ENV AOIs aligns with the stated hypothesis, they are not interpreted as meaningful outcomes.

In view of the previous empirical findings concerning the role of wayfinders' guided and divided attention in spatial learning (Brügger et al., 2019; Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018), the present study results are not necessarily unexpected. Indeed, the results reported here align with the lab-based study of Hejtmánek et al. (2018), who found that wayfinders' spatial learning deteriorated when they spent more time looking at the GPS-like map aid rather than the virtual environment. Considering that reduced visual attention to the mobile map was hypothesized as an improving factor in wayfinders' spatial learning, the present study suggests that depicting landmarks as realistic 3D models provides a promising visualization style for extracting relevant mobile map features more quickly during aided navigation.

5.4.5 Cognitive load unaffected by landmark visualization

The results contradict hypothesis H1.4, which expected that wayfinders' cognitive load would be lower when navigating with realistic 3D compared to abstract 3D landmarks. The EEG results revealed no differences in wayfinders' cognitive load during the navigation task, regardless of the landmark visualization style. The EEG results align with previous studies revealing that the cognitive load of wayfinders sampled from the general population did not differ when solving spatial tasks with various levels of difficulty using static maps (Keskin et al., 2020) and animated displays (Lanini-Maggi, 2017; Lanini-Maggi et al., 2021). The lack of differences between the landmark visualization styles can be explained by the fact that depicting landmarks as 3D models provided the necessary visual information to match the spatial information between the map and the environment and encode it, reducing the cognitive load. Another possible explanation is that the visual differences between the realistic and abstract 3D landmarks are too subtle to affect the users' cognitive states during the navigation task. This interpretation is supported by the lack of differences between conditions on wayfinders' parietal spectral power (see Figure 5.8), which is indicative of visual information processing

(Bullier, 2001; Colby, Goldberg, et al., 1999; Xu, 2018). An alternative explanation is that the navigation task was not sufficiently challenging to impose a high cognitive demand on the wayfinders, as reflected by their low self-reported NASA TLX workload.

General Discussion 6

> *Before the results of a measurement can be used, it must be interpreted – nature's answer must be understood properly.*
>
> — **Max Planck**
> (Nobel Prize–winning Physicist)

The main goal of the present thesis was to examine the potential benefits of landmark visualization styles on mobile maps for effective navigation, guided visual attention, enhanced spatial learning, and reduced cognitive load by examining various user groups during route-following navigation tasks in real-world environments and in various use contexts. Furthermore, I assessed the accuracy with which wayfinders form a spatial representation of the environment considering their individual and group differences in spatial abilities, familiarity with the study area, and gaze behavior during these tasks. In the context of the related work (Chapter 2), I will critically discuss the main outcomes presented in Chapters 4 and 5 and address some limitations of this thesis's research approach. The present chapter is organized according to the main research question already presented in Section 1.2 and included here as a reminder:

> How can we saliently visualize landmarks on mobile maps to improve wayfinders' navigation performance, direct their visual attention to task-relevant features, and support their spatial learning of the traversed environment while mitigating the wayfinders' task-related cognitive load?

6.1 Equal navigation performance across landmark depiction styles, use contexts, and user groups

Previous research has delivered mixed evidence concerning the relationship between the levels of realism and dimensionality for visualizing landmarks on mobile maps and the navigation performance of various user groups in various navigation contexts (Dillemuth, 2005; Hegarty et al., 2009; Kray et al., 2003; Liao et al., 2017; Oulasvirta et al., 2009; Plesa & Cartwright, 2008). This thesis demonstrates that regardless of the employed landmark visualization style (i.e., abstract 2D vs. realistic 3D in Study I and abstract 3D vs. realistic 3D in Study II), the navigation task performance was at a ceiling level across use contexts (i.e., emergency and general wayfinding tasks) and user groups (i.e., experts and novices). The navigation performance of Study I is in line with previous work, demonstrating that increased realism does not harm the performance of expert populations (Hegarty et al., 2009). In contrast, the findings of Study II contradict previous research suggesting that increased realism will harm the performance of users sampled from the general population (Dillemuth, 2005; Hegarty et al., 2009; Plesa & Cartwright, 2008). However, the navigation performance of participants in Study II aligns with previous research demonstrating that while wayfinders prefer realistic-looking visualizations, they do not necessarily perform better with them (Hegarty et al., 2009; Kray et al., 2003; Liao et al., 2017; Oulasvirta et al., 2009; Plesa & Cartwright, 2008). This is known as the "naive realism" effect (Smallman & John, 2005). Reassuringly, the results also demonstrated that adding more visual information to the preferred landmark visualization style did not impair navigation performance.

One explanation for the lack of differences in navigation performance is that, in general, enhancing mobile maps with landmark information (regardless of the visualization style) already facilitates wayfinders' self-localization and locomotion, as well as the visual matching process between the mobile map and the environment, because landmarks serve as anchors. These effects may lead to a successful navigation task regardless of visualization style. This aligns with previous literature on spatial navigation and cognition recommending the enrichment of mobile map-aided pedestrian navigation with landmark information (Chrastil & Warren, 2012, 2013; Kiefer et al., 2014; Raubal & Winter, 2002; Richter & Winter, 2014; Thrash et al., 2019; Willis et al., 2009). Another possible explanation is that the navigation tasks were not particularly challenging for either an experienced user group, such as the expert wayfinders (Study I), or the general population (Study II). Equipping mobile maps with saliently displayed landmark information at decision points (Lovelace et al., 1999; Yesiltepe et al., 2021) and asking participants to identify these task-relevant landmarks may already have contributed to improved navigation efficiency, regardless of the landmark visualization style (Franke & Schweikart, 2017; Liao et al., 2017), navigation use contexts, and user groups with different experience levels (Fabrikant, 2022; Griffin & Fabrikant, 2012; Griffin et al., 2017).

6.2 Landmark depiction style modulates visual attention across use contexts and user groups

In contrast to navigation performance, the present thesis revealed that wayfinders' visual attention behavior during the aided navigation tasks was modulated by the landmark visualization style on the mobile map. Specifically, the experts in Study I had to scan a wider area on the mobile map around the depicted route and landmarks when they navigated with abstract 2D building footprints (see Figure 4.7–A). In contrast, when the landmarks on the map were depicted as realistic 3D buildings, the distribution of the experts' visual attention was cued toward task-relevant landmarks (see Figure 4.7–B). The wider dispersion of experts' attention on the mobile map can be explained by the fact that depicting landmarks with reduced visual properties drove wayfinders to pay more attention to the mobile map's other spatial features, as there is a mismatch between the spatial information presented on the map and the information experienced directly in the environment (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009). The analyses of visual behavior (see Figure 4.8 and Figure 4.9) supported this interpretation by revealing that wayfinders had to scan wider areas on the map to gather the necessary task-relevant spatial information (Keil et al., 2020; Koletsis et al., 2017). The experts' attention to realistic 3D landmarks aligns with previous work finding that when landmarks are depicted as perceptually salient features on maps, wayfinders' visual attention is cued to these task-relevant landmarks (Richter & Winter, 2014; Wenczel et al., 2017; Yesiltepe et al., 2021). The visual search literature offers one possible explanation for this finding: realistic landmarks on mobile maps may serve as bottom-up, stimulus-driven guidance and attract users' attention due to their visually enhanced properties (Wolfe & Horowitz, 2017; Wolfe & Horowitz, 2004).

The interpretation of bottom-up perceptual guidance driven by the saliency of landmark stimuli conflicts with the lack of differences in visual attention to the mobile map observed among the wayfinders in Study II. This lack of differences in visual attention can be explained by the fact that enhancing map aids with 3D landmark information provided the bottom-up saliency (Wolfe & Horowitz, 2017; Wolfe & Horowitz, 2004) necessary to guide users' visual attention regardless of the landmarks' visualization style. Another possible interpretation is the fact that wayfinders were instructed to locate these landmarks in the environment, which may have primed them to consider both landmark visualization styles equally important to the task. The lack of visual attention differences across the realistic and abstract 3D visualization styles aligns with Elias and Paelke's (2008) design recommendations to depict task-relevant buildings as realistic 3D models, 3D drawings, or at least 3D sketches for facilitated recognizability. These recommendations contrast with the design solutions of current mobile maps, which omit landmarks or depict them as 2D footprints in a similar style to other buildings (Grabler et al., 2008).

Interestingly, the results revealed an influence of familiarity with the study area on visual attention to the environment among wayfinders sampled from the general population. Specifically, wayfinders familiar with the study area demonstrated increased visual attention to the environment when navigating with realistic 3D landmarks. One explanation for this finding is that depicting landmarks as realistic 3D buildings enabled the wayfinders to gather spatial information from the map aid without effort. Furthermore, these depictions may have directed their visual attention toward the environment to search for the task-relevant landmarks in order to match the spatial information between the mobile map and the environment (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009). Another possible explanation is that environmental knowledge guides wayfinders' attention towards cognitively salient landmarks (Caduff & Timpf, 2008) by modulating their top-down visual attention (Wolfe & Horowitz, 2017; Wolfe & Horowitz, 2004). For instance, wayfinders' visual attention is guided to familiar objects that have similar properties to previously known environmental objects. This finding aligns with previous research showing that wayfinders' familiarity with a study area's general architecture and street layout can facilitate navigation (Coutrot et al., 2022) and with findings about how users acquire spatial knowledge (Montello, 1998; Siegel & White, 1975). While the collected data from Study II does not allow me to make strong conclusions regarding the influence of familiarity, this raises an important future research question.

Another interesting finding of the present thesis is that individual spatial abilities influenced wayfinders' visual attention allocation. Specifically, in Study II, wayfinders with low spatial abilities produced longer fixations on the environment when they navigated with realistic 3D landmarks. This finding agrees with previous empirical evidence that wayfinders with low spatial abilities generally require more navigation assistance (Hegarty et al., 2006; Ishikawa, 2022, 2018) – and, specifically, more assistance in modulating visual attention to task-relevant features – compared to wayfinders with higher spatial ability, who can modulate their attention independently of the task and in the presence of extraneous information (Lanini-Maggi, 2017; Lanini-Maggi et al., 2021; Maggi et al., 2016; Ooms et al., 2014). Contrary to previous research demonstrating that low-spatial-ability wayfinders rely more on mobile map aids which, in turn, further degrade their spatial learning capabilities (Dahmani & Bohbot, 2020; Ishikawa, 2019; Ruginski et al., 2019), the visual attention of wayfinders with low spatial abilities in the present thesis was guided towards the traversed environment. Longer visual attention to the environment, as in the case of this thesis, indicates higher task engagement and more profound learning intentions (Albert & Tullis, 2013; Liao et al., 2019; Wenczel et al., 2017). As a result, attention can affect survey knowledge acquisition (Hejtmánek et al., 2018), which will be discussed next.

6.3 The roles of landmark visualization style, spatial abilities, and visual attention in learning

The present thesis results revealed that wayfinders' acquisition of spatial knowledge about the traversed environment was not directly influenced by the landmark visualization style utilized on the mobile map. Specifically, the spatial learning performance of the experts in Study I and wayfinders in Study II was similar across the chosen landmark visualization styles. The lack of differences between experts in Study I can be attributed to their enhanced navigation expertise and experience (Maguire et al., 2006; Sutton et al., 2014; Woollett & Maguire, 2011; Woollett et al., 2009). This experience may have made the experts' spatial learning less likely to suffer when navigating with reduced visual landmark encoding on the map, as was the case when landmarks were depicted as abstract 2D building footprints. Moreover, the experts were trained and habituated to this map style. The role of expertise of wayfinders in Study I is supported by their low pointing error of 36.9° which aligns with the results of expert pilots reporting an error of 44.23° (Sutton et al., 2014). While this low pointing error was achieved after only one route exposure, the expert pilots in Sutton et al.'s (2014) VR study were exposed to some landmarks more than once.

An alternative explanation for the lack of differences in spatial learning is the lack of statistical power stemming from the small sample size of the expert wayfinders participating in Study I. Therefore, given this sample size, I conducted a post-hoc power analysis to determine the effect size that could have been detected on the utilized spatial learning tests. Given the variance of experts' answers and utilizing the same statistical tests, the experiment was powered at 80% to detect a 26° difference in pointing error. This is not a small difference, as Craig et al. (2016) observed approximately 20° improvements by allowing participants sampled from the general population to rest between the learning and testing phases. Furthermore, a power analysis revealed that I would have needed to recruit 84 expert wayfinders to achieve an 80% power for pointing errors of the size shown by the assessed expert sample. Unfortunately, this was impossible considering the experimental time frame, the limited availability of navigation experts, and the logistical effort needed to achieve such a sample. Indeed, these limitations are why there is limited prior research on expert navigation. Therefore, the results of Study I can serve as an initial indicator of spatial learning performance for future hypotheses and studies with larger samples.

The results of Study II, conducted with an adequate sample size of wayfinders sampled from the general population, revealed the same lack of differences in spatial learning performance across the chosen landmark visualization styles. Similarly to the experts in Study I, the wayfinders in Study II also revealed a rather high pointing accuracy, with an error of 45.7° after only one route exposure. This pointing error is much lower than the pointing error of other studies, which vary from 55–75° on the first exposure to the environment (Cheng et al., 2022; Credé et al., 2020; Huffman & Ekstrom, 2019). The lack of differences in spatial knowledge across the user groups (experts and novices) and use contexts (emergency and general navigation tasks) can be explained by the fact that enhancing mobile maps with perceptually salient landmarks improved the wayfinders' spatial learning regardless of the depicted landmarks' dimensionality (2D vs. 3D) and abstraction (abstract vs. realistic) levels in the landmark visualization styles. This argumentation aligns with previous research suggesting that mobile maps enhanced with salient landmark information facilitate wayfinders' spatial learning of the environment through the active encoding of the landmarks' spatial configuration (Chrastil & Warren, 2012; Thrash et al., 2019; Willis et al., 2009).

The spatial learning performance of experts in Study I assessed only their survey knowledge acquisition about the environment; the study did not evaluate their landmark and route knowledge learning, which constitute the foundations of spatial learning (Montello, 1998; Siegel & White, 1975). Therefore, it may have been possible to detect an influence of landmark visualization style on the experts' landmark and route knowledge acquisition had they been assessed. One way to minimize this limitation in future work would be to consider landmark and route knowledge assessments, thus achieving a more nuanced analysis of experts' spatial learning during aided navigation tasks (Hegarty et al., 2006). However, the results of Study II revealed no influence of landmark visualization styles on wayfinders' landmark and route knowledge. Therefore, the very good survey knowledge performance of the expert wayfinders, the fact that the JRD task assesses the configurational knowledge between the task-relevant landmarks, and the lack of landmark and route knowledge differences among the Study II wayfinders suggest that the outcomes may have been similar for the experts in Study I had these types of knowledge been assessed. One explanation for the lack of differences in wayfinders' landmark, route, and survey knowledge performance is that increased dimensionality and realism of landmarks' visualization style, though preferred by wayfinders, do not necessarily translate to better spatial learning performance in the traversed environment (Hegarty et al., 2009; Kray et al., 2003; Liao et al., 2017; Plesa & Cartwright, 2008). This argument also extends to the limited distance knowledge acquisition between the task-relevant landmarks of the Study I and Study II wayfinders after only one route exposure. This poor performance can be explained by the fact that there must be more than one route exposure to build adequate distance knowledge between task-relevant landmarks (Hilton et al., 2021a; Ishikawa & Montello, 2006).

While the landmark visualization styles did not directly influence wayfinders' spatial learning as hypothesized, the present thesis revealed that the spatial learning of wayfinders across both studies was influenced by an interaction of their self-reported spatial abilities and the landmark visualization styles. Specifically, when wayfinders with low spatial abilities navigated with landmarks depicted as realistic 3D buildings, they demonstrated improved survey knowledge acquisition in Study I and improved landmark sequence recall and survey knowledge acquisition in Study II. These results are consistent with previous research highlighting the importance of individual differences in spatial learning performance during navigation tasks (Hegarty et al., 2018; Hegarty et al., 2006; Ishikawa, 2022; Ishikawa & Montello, 2006; Newcombe, 2018; Newcombe et al., 2022), even in expert populations such as pilots (Sutton et al., 2014), athletes (Meneghetti et al., 2022), taxi and bus drivers (Maguire et al., 2006), and surgeons (Keehner et al., 2004). For instance, Sutton et al. (2014) found that expert pilots with a lower baseline survey learning ability demonstrated reduced spatial knowledge acquisition. These findings point out that even expert populations are prone to idiosyncratic differences in spatial abilities (Hegarty et al., 2009; Keehner et al., 2004; Lanini-Maggi et al., 2021; Maggi et al., 2016; Sutton et al., 2014).

The improved survey knowledge of low-spatial-ability wayfinders can be explained by the fact that this group needs more assistance in encoding and matching the spatial information seen on the map and experienced directly in the environment (Hegarty et al., 2006; Ishikawa, 2022; Montello, 1998). The realistic 3D depiction of landmarks likely facilitates the visual matching between the information sources and spatial learning (Chrastil & Warren, 2012; Kiefer et al., 2014; Richter & Winter, 2014; Willis et al., 2009). These results contradict previous work showing that increased realism can be detrimental for low-spatial-ability users (Hegarty et al., 2009; Wilkening & Fabrikant, 2011). However, the results of Studies I and II regarding high-spatial-ability wayfinders support previous claims that these users demonstrate improved performance regardless of the display visualization styles (Hegarty et al., 2009; Lanini-Maggi et al., 2021; Wilkening & Fabrikant, 2013).

Another interesting finding of the present thesis is that the allocation of visual attention influences spatial learning during the aided navigation tasks across the tested landmark visualization designs, user groups, and navigation use contexts. Specifically, the results in Study I revealed that when the expert wayfinders focused their attention on the environment and the landmarks in it, their acquisition of spatial knowledge about the traversed environment improved, regardless of the 2D or 3D landmark visualization style on the mobile map. Meanwhile, the Study II results revealed that when wayfinders navigated with realistic 3D landmarks and focused for a shorter time on the mobile map, their route and survey knowledge of the traversed environment improved. On the other hand, when wayfinders' visual attention to the mobile map increased at the expense of reduced attention to the environment, the spatial learning of wayfinders navigating with realistic 3D landmarks deteriorated. This is because by fixating longer on the mobile map, wayfinders could not extract more meaningful spatial information from the map and thus became fully guided by the technology (Hejtmánek et al., 2018). This finding aligns with previous evidence that for improved spatial learning during aided navigation, wayfinders' visual attention should be guided and sustained toward the traversed environment and landmarks and away from the mobile map aid (Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018). The improved spatial learning performance when wayfinders paid more attention to the environment and environmental features such as landmarks can be explained by the improved encoding of these features, which leads, in turn, to improved spatial learning (Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018). Conversely, the deteriorated spatial learning performance when wayfinders focused longer on the mobile map can be explained by the fact that unbalanced and divided attention between the mobile map and the environment hinders the formation of spatial representations (Gardony et al., 2013; Gardony et al., 2015; Hejtmánek et al., 2018).

6.4 Cognitive load unaffected across landmark depiction style, use contexts, and user groups

The EEG results of the present thesis revealed that wayfinders' objective cognitive load during map-aided navigation is not affected by the different landmark design choices utilized in various navigation use contexts and user groups. While wayfinders' cognitive load did not increase with the abstract landmarks or decrease with the realistic landmarks, as hypothesized, it is reassuring that adding more details to the realistic landmarks did not induce higher cognitive load; previous work has suggested that this may occur due to the increased amount of visual information that must be processed (Liao et al., 2017). Even though there were no indications of induced or mitigated cognitive load across the tested landmark visualization styles, the increased power in the wayfinders' parietal lobes (see Figure 4.10 and Figure 5.8) aligns with previous research suggesting visual information processing by wayfinders during the map-aided navigation tasks (Bullier, 2001; Colby, Goldberg, et al., 1999; Xu, 2018). Furthermore, the increased parietal power in the theta frequency band across both studies follows prior evidence that theta power oscillations in the parietal region are associated with attention and sensorimotor information encoding during the active exploration of the environment (Chrastil et al., 2022; Ekstrom et al., 2005). The lack of cognitive load differences across Studies I and II aligns with previous work assessing the cognitive load of novice and expert wayfinders during spatial tasks with static (Keskin et al., 2020) and animated displays (Lanini-Maggi, 2017; Lanini-Maggi et al., 2021). Meanwhile, the lack of differences in cognitive load across the landmark visualization styles can be explained by the fact that, due to the landmarks' increased saliency compared to other spatial features, enhancing the mobile maps with landmark information guided users' bottom-up attention to these task-relevant features (Wolfe & Horowitz, 2017); this, in turn, made the navigation task easier to solve. The absence of a challenging navigation task is also supported by the wayfinders' self-reported low workload during the navigation tasks in both studies (see Figure 4.12 and Figure 5.10 for the NASA TLX results).

The lack of differences in wayfinders' cognitive load when aided by mobile maps depicting landmarks in various visualization styles can also be explained by the methodological and analytical challenges of the EEG data. A methodological limitation of both studies is the failure to obtain and control for the wayfinders' baseline power before the navigation phase. I performed power spectral density analyses averaged throughout the entire experimental duration, which may have covered mental load fluctuations when wayfinders attended to the environment, landmarks, or the mobile map. Chrastil et al.'s (2022) findings suggest that analyzing cognitive load at decision points where a destination-relevant navigation decision is required rather than during continuous locomotion through the environment provides deeper insights into wayfinders' cognitive states. To overcome these limitations, future investigations of cognitive load during map-aided navigation should obtain wayfinders' baseline power in a resting state prior to navigation. In addition, studies should synchronize eye-tracking and EEG data to perform event-related potential analyses that are time-locked to particular events (Luck, 2014), such as when a navigation decision is required or when participants are attending to the environment or the mobile map.

CONCLUSION 7

I have always been fascinated by maps and cartography. A map tells you where you have been, where you are, and where you are going – in a sense, it is three tenses in one.

— **Peter Greenaway**
(Film Director)

7.1 Main findings

In this thesis, I conducted two map-aided navigation studies to investigate how various visualization styles of landmarks on mobile maps influence wayfinders' navigation performance, spatial learning, visual attention, and cognitive load. These studies represent the first empirical investigations carried out in highly ecologically valid, real-world environments to explore the interactions across employed landmark visualization styles, user groups, and use contexts (see Figure 1.1). The main findings of both studies are summarized below:

1. The realistic 3D landmark visualization style modulates navigators' gaze behavior in various ways, dependent on the wayfinders' background: a) experts' attention is cued to the task-relevant landmarks on the mobile map and b) the attention of wayfinders with low spatial abilities and wayfinders familiar with the study area is cued to the traversed environment.

2. The interplay between landmark visualization styles, spatial abilities, and gaze behavior influences spatial learning in the following ways: a) experts' spatial learning improves when their attention is guided toward the environment and environmental landmarks and when realistic 3D landmarks assist experts with low spatial abilities; b) the

spatial learning of navigators from the general population improves when they navigate with realistic 3D landmarks and focus less attention on the map; learning also improves when realistic 3D landmarks assist navigators with low spatial abilities.

3. While wayfinders prefer realistic 3D landmarks, their high navigation accuracy and low cognitive load are unaffected by the visualization style across user groups and navigation contexts.

Taken together, the present real-world empirical findings demonstrate that landmark visualization style modulates wayfinders' visual attention, which, in turn, predicts their spatial learning performance. Furthermore, the findings highlight the importance of spatial abilities as predictors of spatial knowledge acquisition, even in expert user groups. In conclusion, these empirical findings provide new insights with important implications for designing future mobile map aids that support navigation performance, guide users' visual attention toward task-relevant landmarks, and facilitate spatial encoding and formations of spatial learning – especially for wayfinders with varying spatial abilities – while keeping wayfinders' navigation related cognitive load low.

7.2 Design recommendations

From the empirical findings of this thesis, we can draw design recommendations for future human-, context-, and task-adaptive mobile map aids that go beyond the historical "one fits all" norm of static, 2D paper maps. These design recommendations focus on depictions of landmarks on mobile maps that will direct users' visual attention to task-relevant environmental features. In doing so, such depictions will improve spatial knowledge acquisition during assisted navigation, especially for wayfinders with low spatial abilities. Furthermore, these design recommendations will mitigate wayfinders' navigation-related cognitive load without compromising their performance. However, the question of how mobile map aids should graphically communicate landmarks to the users for improved spatial learning arises.

7.2.1 Landmark visualization

The present empirical results show that landmarks in the environment should be communicated on navigation aids as perceptually salient, realistic-looking 3D buildings. This visualization style guides the bottom-up visual attention of navigators who are unfamiliar with the environment to the saliently depicted landmarks, while guiding the top-down visual attention of familiar navigators. This effect occurs because the landmarks stand out from other spatial information depicted in 2D due to their enhanced visual saliency. Guiding attention to the realistic landmarks facilitates wayfinders' visual matching process between the spatial information presented on the mobile map and experienced directly from the environment. This, in turn, improves navigators' orientation and self-localization, leading to less time spent looking at the mobile map and thus alleviating the negative influence of divided attention in acquiring landmark, route, and survey knowledge.

> ***Future mobile map aids should depict landmarks as perceptually salient 3D map features to direct wayfinders' visual attention away from the map and towards the environment for increased spatial learning.***

7.2.2 User groups

While Elias and Paelke (2008) suggest a graphical continuum for depicting landmarks on mobile maps, several questions remain open. Should we communicate landmarks in the same style given the role of individual and group differences in spatial skills in acquiring spatial knowledge? Which users benefit the most from an enhanced graphical depiction of landmarks on mobile maps? The present studies show that acquiring spatial knowledge about a traversed environment is challenging, especially for users with low spatial abilities. The results of Study I showed that even expert wayfinders – similarly to the wayfinders sampled from a general population in Study II – are affected by the influence of spatial abilities in their spatial learning performance. The findings across both real-world studies demonstrate that visualizing landmarks as 3D buildings with higher fidelity improved the acquisition of spatial knowledge about the traversed environment for wayfinders with low spatial abilities. Moreover, the benefit of a realistic depiction of landmarks diminishes in wayfinders with higher spatial abilities across both studies, whose spatial learning performance improves regardless of the landmark visualization style. These findings highlight the importance of tailored design choices that consider user groups and their specific characteristics.

> ***Future mobile map aids should depict landmarks as realistic 3D features to prioritize the needs of user groups with low spatial abilities for improved spatial learning performance.***

7.2.3 Use contexts

During which tasks and use contexts is it important to guide wayfinders' attention away from the mobile map and toward task-relevant landmarks and other environmental features for improved spatial learning? In short, the answer is all map-aided navigation tasks, from specific and stressful tasks in an emergency scenario to tasks related to the everyday locomotion of humans in space. This is because the habitual use of and over-reliance on navigation aids can negatively impact wayfinders' short- and long-term spatial skills and spatial learning (Dahmani & Bohbot, 2020; Ishikawa, 2019; Parush et al., 2007). However, the consequences of deteriorated spatial learning can be critical for some tasks and use contexts. For instance, if a military unit deployed as first aid responders in an unfamiliar area during a civil emergency is hindered in their spatial knowledge of the environment, this can lead to severe consequences. The results of Study I revealed that when experts' attention is guided toward the environment and landmarks in the environment, and when experts with low spatial abilities navigate with realistic landmarks, their spatial learning improves.

> ***Future mobile map aids should focus on realistic 3D depictions of landmarks to direct experts' attention away from the mobile map and towards the unfamiliar environment, thus improving spatial learning during aided navigation, especially for experts with low spatial skills.***

7.3 Contributions

The findings and design recommendations of the present thesis provide three important contributions to the research fields of spatial navigation and cognition, cartography, and GIScience. First, the thesis contributes to research on spatial navigation and cognition by providing further insights into humans' navigation behavior and spatial knowledge acquisition during aided navigation tasks. In particular, the thesis contributes further insights and extends the role of landmarks as objects that facilitate wayfinders' formation of spatial representations (Montello, 1998; Montello, 2005; Richter & Winter, 2014; Siegel & White, 1975). Furthermore, the empirical findings contribute additional insights into the role of individual differences in spatial abilities, as well as the role of visual attention allocation in map-aided spatial navigation (Gardony et al., 2015; Hejtmánek et al., 2018; Ishikawa, 2022; Newcombe et al., 2022).

Second, the methodological approach adopted for this thesis contributes highly ecologically valid insights, emphasizing the empirical study of navigation in the real world. In-situ investigations of human navigation behavior during active exploration of the environment provide important insights into the influence of bodily motion cues on spatial knowledge acquisition (Chrastil & Warren, 2012; Montello et al., 2004). In addition, the implementation of EEG in the present thesis provides a methodological contribution to direct investigations of the influence of various map designs on users' cognitive load. These findings contribute valuable insights for geography, cartography, GIScience, psychology, and spatial navigation and cognition related to aided navigation by mobile maps in natural settings.

Third and finally, the findings and design recommendations presented in this thesis make practical contributions to the future design of mobile maps as navigation aids. These contributions are important for cartographers and industry practitioners working on encoding and designing spatial information on mobile maps and providing mapping services for wayfinding. In particular, future mobile map aids should communicate landmarks to users to guide their attention away from the display and back to the environment and task-relevant landmarks, thus counteracting the negative influence that the overreliance on mobile maps has on spatial learning. Improved spatial learning of the traversed environment can be achieved if the design of landmarks on mobile maps is informed by individuals' spatial skills, and especially if the needs of less skilled users are accommodated.

7.4 Outlook

The findings and limitations of the present thesis give rise to many open questions to be addressed by similar future research. Regarding the landmark visualization style, I focused only on a graphical depiction of local landmarks placed at street intersections where a navigation decision was required. In Study I, the landmarks were depicted as abstract 2D building footprints or realistic 3D buildings, whereas in Study II they were depicted as abstract or realistic 3D buildings. Therefore, I utilized only three of the six landmark visualization styles on the abstraction continuum for the graphical depiction of landmarks on mobile maps proposed by Elias and Paelke (2008). Concerning the landmark design of Study I, future work should further disentangle the influence of graphical abstraction and the dimensionality of landmarks on expert wayfinders' navigation performance, visual attention, spatial learning, and cognitive load. Furthermore, future work should consider other graphical representation styles for depicting local and global landmarks on map aids. Such work could include landmarks located not only at intersections but also along the route and those that are simultaneously visible to wayfinders in order to assess their benefits for spatial learning (Credé et al., 2020).

In both studies, I used an interactive mobile map with which users could freely interact. The landmark visualization style may have influenced how users interacted with the map aid. This is especially true for the expert wayfinders of Study I who navigated with the realistic 3D landmarks, as they are trained and primarily rely on abstract 2D maps for decision-making in real-world emergency scenarios (Wilkening & Fabrikant, 2013). Therefore, the wayfinders' interactions with the mobile map constitute interesting future research directions, as I did not record the interactions in Study I and could not analyze wayfinders' interactions with the map in Study II due to time constraints. Furthermore, I utilized an emergency navigation task for the expert wayfinders and a general navigation task for the wayfinders sampled from the general population. Hence, it would be interesting for future research to investigate the influence of landmark visualization styles on navigation efficiency and spatial learning when novice wayfinders are required to navigate in an emergency scenario. In addition, the emergency scenario of Study I may have induced higher stress in the expert wayfinders, which may have influenced their spatial learning. Stressful situations could have deep ramifications for military emergency respondents, who are exposed to stronger affective situations during emotionally laden contexts; such situations require solid navigational skills to complete the navigation tasks (Gardony et al., 2011). Hence, future work should employ stress-related standardized questionnaire measures (Lanini-Maggi et al., 2021) coupled with physiological measures such as electrodermal and electromyography activities (Credé et al., 2019, 2020) to investigate the effect of affective states on wayfinders' navigation performance and spatial learning, regardless of expertise.

Technological advancements in recent decades have transformed mobile map applications into ubiquitous navigation tools that a large and diverse variety of user groups employ in everyday use contexts (Bartling et al., 2022; Bartling et al., 2021). The empirical findings of the present thesis support the call for adaptive design changes in mobile map applications (Reichenbacher, 2001, 2003) that focus on depicting landmarks to accommodate the needs of various user groups in different use contexts (Fabrikant, 2022; Griffin et al., 2017). Therefore, future research on map adaptation should further investigate how to select and visualize landmarks on mobile maps considering their visual, structural, and cognitive saliency (Caduff & Timpf, 2008; Raubal & Winter, 2002; Sorrows & Hirtle, 1999) for the efficient visual processing of depicted relevant information (Swienty et al., 2008) and enhanced spatial learning (Richter & Winter, 2014) across users with individual spatial abilities (Hegarty et al., 2006; Ishikawa, 2022; Newcombe et al., 2022) and across use contexts (Fabrikant, 2022; Griffin et al., 2017).

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Appendix

The questionnaire measures, the collected empirical data across both studies and the statistical analysis scripts supporting the findings of this thesis are available online at the Open Science Framework open-access repository: https://doi.org/10.17605/osf.io/ambju.