Dissertation

Please Follow the Signs

Considering Existing Navigational Aids in Indoor Navigation Services

Ausgeführt zum Zwecke der Erlangung des akademischen Grades einer

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von

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Matrikelnummer: 01129622

Wien, am 22. Juni 2023 ……………………..

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A thesis submitted in fulfilment of the academic degree of

Doctor of Natural Sciences (Dr. rer. nat.)

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Department of Geodesy and Geoinformation

Research Unit Cartography

Research conducted at TU Wien

Faculty of Mathematics and Geoinformation

by

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Vienna, June 22, 2023 ……………………..

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I hereby declare that I have written this Doctoral Thesis independently, that I have completely specified the utilized sources and resources and that I have definitely marked all parts of the work - including tables, maps and figures - which belong to other works or to the internet, literally or extracted, by referencing the source as borrowed.

Vienna, 22nd June, 2023

Wangshu Wang

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Kurzfassung

Die Navigation in großen öffentlichen Gebäuden stellt für Menschen eine besondere Herausforderung dar. Aus diesem Grund wurden externe Darstellungen der Umgebung entwickelt, wie beispielsweise Navigationshilfen wie Schilder und Grundrisse sowie mobile Navigationsdienste. Diese wurden konzipiert, um die Orientierung in Gebäuden zu erleichtern und die Wahrnehmung zu entlasten. Derzeit arbeiten diese Systeme unabhängig voneinander. Untersuchungen deuten darauf hin, dass bestehende Navigationshilfen, die auf kodierten räumlichen Beziehungen basieren, als semantische Orientierungspunkte dienen können und das Erlernen von räumlichem Wissen erleichtern, während mobile Navigationsdienste das räumliche Lernen beeinträchtigen.

Diese Dissertation befasst sich mit den Herausforderungen der Navigation in Innenräumen und des räumlichen Lernens, indem bestehende Navigationshilfen in Navigationsdienste integriert werden. Um das Navigationsverhalten von Menschen in Innenräumen und die Einflussfaktoren an Entscheidungspunkten besser zu verstehen, wurde ein exploratives Experiment mit menschlichen Teilnehmern durchgeführt. Die Ergebnisse dieses Experiments liefern einen systematischen Überblick über die Taktiken zur Entscheidungsfindung bei der innerräumlichen Navigation. Zudem tragen sie zur Weiterentwicklung der bestehenden Orientierungstheorie bei und bieten praktische Informationen für das Architekturdesign, das Gebäudemanagement und das Design von Navigationssystemen in Innenräumen.

Basierend auf diesen Erkenntnissen wurde ein vollständig automatisiertes algorithmisches Framework namens ISIGNS (Indoor Sign InteGrated Navigation System) vorgeschlagen, um bestehende Navigationshilfen in Indoor-Navigationsdienste zu integrieren, wobei der Fokus auf Schildern und ihrer Semantik liegt. Die Implementierung von ISIGNS ist äußerst anwendbar, da sie lediglich einen Navigationsgraphen und einen Zeichendatensatz erfordert, der aus den meisten räumlichen Datenbanken für Innenräume abgeleitet werden kann. In einem In-situ-Experiment, bei dem ISIGNS mit menschlichen Teilnehmern evaluiert wurde, zeigte sich das Potenzial, das Navigationserlebnis zu bereichern und die Benutzerfreundlichkeit zu verbessern. Darüber hinaus konnte der vorgeschlagene Ansatz das räumliche Lernen der Teilnehmer signifikant verbessern, insbesondere hinsichtlich des Erwerbs von Wissen über Orientierungspunkte und des Überblicks über eine räumliche Umgebung. Durch die explizite Einbeziehung der Semantik von Schildern lenkt ISIGNS die Aufmerksamkeit auf die Umgebung und nutzt die semantische Natur von Schildern, was zu einer verbesserten räumlichen Wissensbildung führt.

Insgesamt trägt diese Dissertation zu unserem Verständnis des menschlichen Orientierungsverhaltens bei der innerräumlichen Navigation bei. Sie untersucht die Faktoren, die die Entscheidungsfindung beeinflussen, und liefert wichtige Erkenntnisse über die Auswirkungen verschiedener Umweltinformationsquellen auf den Erwerb räumlichen Wissens. Der vorgeschlagene ISIGNS-Rahmen stellt eine äußerst wirksame Lösung dar, um bestehende Navigationshilfen in Indoor-Navigationsdienste zu integrieren. Dadurch wird nicht nur das Navigationserlebnis verbessert, sondern auch das räumliche Lernen gefördert.

Abstract

Navigating through large-scale public buildings presents unique challenges for individuals. Therefore, external representations of the environment, such as existing navigational aids (signs and floor plans) and mobile navigation services, have been designed to assist indoor wayfinding and offload cognition. Currently, these systems operate independently. Studies indicate that existing navigational aids, with their encoded spatial relations, can serve as semantic landmarks and facilitate spatial knowledge acquisition, whereas mobile navigation services impair spatial learning.

This dissertation aims to address the challenges of indoor wayfinding and spatial learning, by integrating existing navigational aids into navigation services. An explorative experiment involving human participants was conducted to clarify indoor human wayfinding behaviour and its influencing factors at decision points. The results provided a systematic overview of indoor wayfinding decision-making tactics, enriching the existing wayfinding theory and practically informing architecture design, building management, and indoor navigation system design.

Building upon these insights, a fully automated computational framework named ISIGNS (Indoor Sign InteGrated Navigation System) was proposed to integrate existing navigational aids into indoor navigation services, focusing on signs and their semantics. Implementing ISIGNS requires only a navigation graph and a sign dataset, which can be derived from most indoor spatial databases, making it highly applicable. An in-situ experiment evaluating ISIGNS with human participants demonstrated its potential for enriching navigation experiences and improving usability. Moreover, the proposed approach significantly enhanced human spatial learning, particularly in acquiring landmark and survey knowledge. By explicitly incorporating sign semantics, ISIGNS encourages attention allocation to the environment and leverages the semantic nature of signs, leading to improved spatial knowledge acquisition.

Overall, this dissertation contributes to our understanding of indoor human wayfinding behaviour, sheds light on the factors influencing decision-making, and provides insights into the effects of different environmental information sources on spatial knowledge acquisition. The proposed ISIGNS framework introduces an effective solution for integrating existing navigational aids into indoor navigation services, enhancing navigation experiences, and promoting spatial learning.

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Chapter 1

Introduction

1.1 Motivation

Imagine you are on a train journey to visit your friends, with a 20-minute transfer at a major railway station. While getting off the train, you consider buying flowers for them. The news of the recently launched indoor navigation system at the station comes into your mind, and you download the app to locate a flower shop. The app shows one on underground level one, only a 50-meter walk with two level changes.

As you follow the app's instructions, you frequently stop and seek confirmation that you are on the correct path amidst the flow of people. Along the way, you also encounter several signs and information screens. You wonder why the navigation app does not display them, which can be helpful. After successfully buying the flowers, you want to go to the platform for the connecting train. You realise that you have not checked the platform number yet, so you cannot enquire about a route from the app. Now, with time ticking, will you be able to find the platform information and eventually reach the right platform?

Wayfinding is the process in which people try to orient and navigate themselves in an environment, aiming to find their way from an origin to a destination and recognise it when reached (Golledge, 1999). During wayfinding, people make decisions by coordinating their cognitive maps, the environment, and its external representations (Ishikawa, 2020). It can be challenging in indoor environments, especially in large-scale public buildings such as museums, universities, hospitals, shopping malls and transportation hubs, due to the segregated nature of indoor spaces in terms of their physical, functional, and social structures (Richter, 2017). Wayfinding difficulties can lead people to frustration, particularly when individuals are searching for specific locations within a limited timeframe, a situation commonly encountered in daily life.

To offload cognition and ease indoor wayfinding, external representations of the environment, such as existing navigational aids (signs and floor plans), are designed and placed in almost all public buildings (Arthur & Passini, 1992). With technological development, public service sectors such as the Frankfurt Airport (Figure 1.1A) (infsoft, 2015) and the Austrian Federal

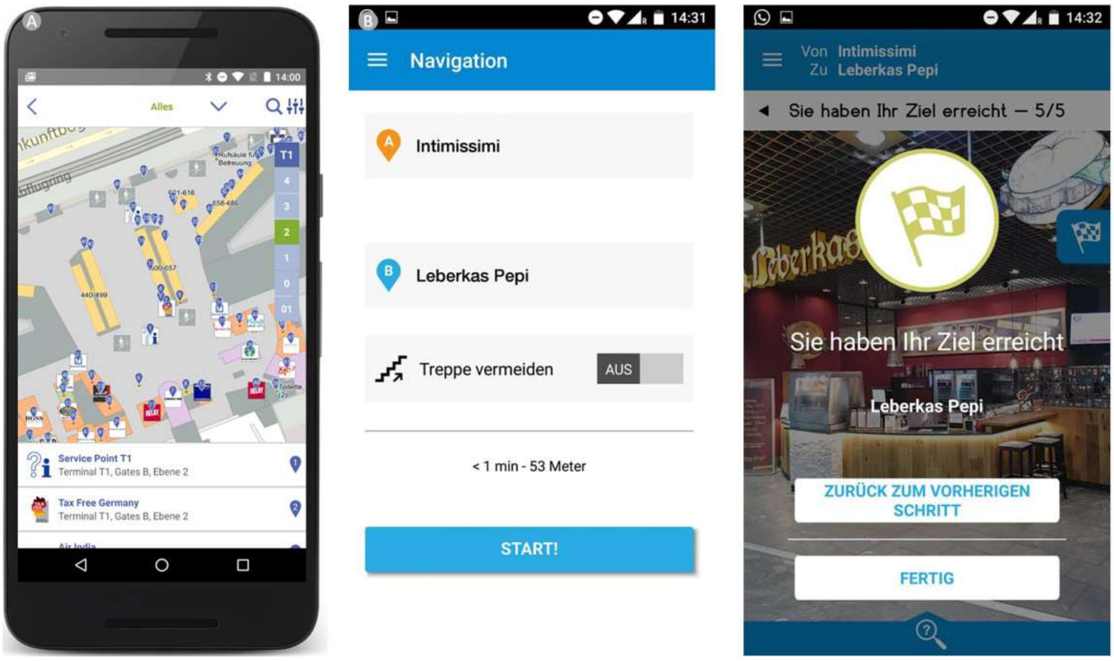

Figure 1.1 - Indoor navigation apps provided by public service sectors. (A) Indoor navigation app for the Frankfurt Airport (infsoft, 2015). (B) Indoor navigation app for Vienna Central Station (Kotrba, 2018).

Railways (Figure 1.1B) (Kotrba, 2018) have begun to offer indoor mobile navigation services. In fact, the scenario we have asked you to imagine was the actual user experience at Vienna Central Station. Some users reported feeling confused while using the mobile navigation service and wandering in the area, as depicted by their trajectories in Figure 1.2B (Fian & Hauger, 2021). In contrast, the trajectories of participants who did not rely on the indoor navigation system are illustrated in Figure 1.2A (Fian & Hauger, 2021). Surprisingly, participants using the official indoor navigation app from the Austrian Federal Railways displayed more diverse trajectories and made more frequent stops than those without mobile navigation services. They shared their confusion while using the navigation system amidst a bustling environment filled with analogue navigational aids, other sources of information, and people, leading them to seek reassurance along the way. Consequently, they suggested to researchers a combination of the mobile navigation service with existing navigational aids (Fian & Hauger, 2021; Wang et al., 2019).

Navigators in environments like railway stations, with an abundance of available information, often face information overload (Arthur & Passini, 1992; Mandel, 2013; Zhang & Park, 2021). To alleviate the cognitive system from information overload, individuals instinctively block information processing, which results in confusion (Arthur & Passini, 1992). At such a moment, if relevant information is presented appropriately, it can facilitate wayfinding, as our experience in using relevant existing navigational aids. This expectation extends to mobile navigation services. However, when both are provided, more information and an additional

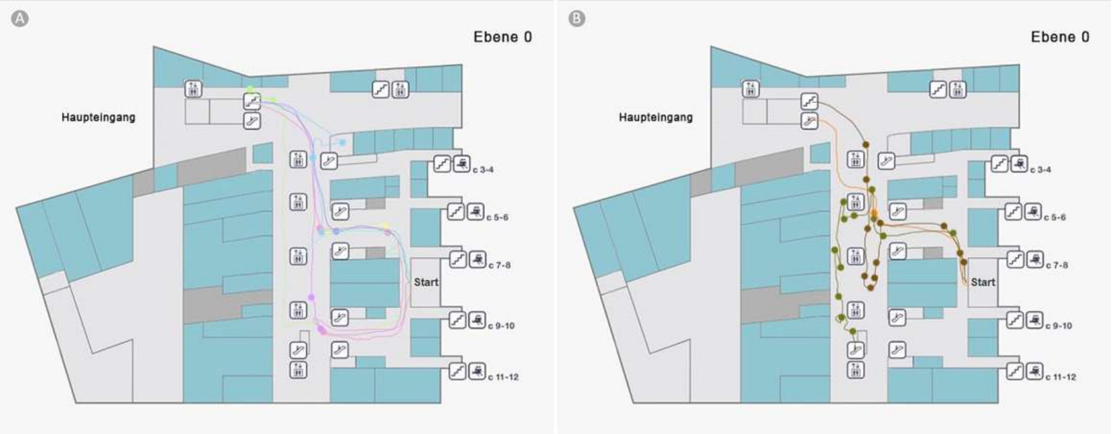

Figure 1.2 - Example trajectories of participants not using the indoor navigation system (A), compared to using the indoor navigation system (B) (Fian & Hauger, 2021).

communication source are added to the navigator's cognitive system. Literature has raised concerns that constant information overload may lead to an inability to concentrate, i.e., a state termed continuous partial attention (Rose, 2010), which by itself causes inefficiency and hampers knowledge acquisition (Bawden & Robinson, 2020). Processing redundant information places an extraneous cognitive load on individuals, further straining the limited processing capacity of their working memory, thereby limiting their ability to learn as wayfinders (Sweller et al., 2011). These confusions also diminish the overall user experience, as Fian and Hauger (2021) observed. This leaves us pondering one question: why do we offer separate navigation systems—existing navigational aids in the environment and mobile navigation services—and train people to ignore their surroundings?

Although not every indoor environment is as information-rich as railway stations, current indoor navigation systems still fall short in supporting navigators, especially regarding user experience and spatial learning. Conventional navigation systems often rely on metric-based turn-by-turn instructions, which are not the most natural and intuitive for humans to comprehend (Denis, 1997; Fellner et al., 2017). In addition, concerns have been raised about their negative impact on spatial learning (Aporta & Higgs, 2005), primarily due to passive decision-making (Bakdash et al., 2008; Brügger et al., 2019; Parush et al., 2007) and a lack of attention to the environment (Burnett & Lee, 2005; Fenech et al., 2010; Gardony et al., 2013; Gardony et al., 2015; Ruginski et al., 2019; Willis et al., 2009). Empirical studies have verified these concerns in short-term spatial knowledge acquisition (Brügger et al., 2019; Burnett & Lee, 2005; Fenech et al., 2010; Gardony et al., 2013; Ishikawa et al., 2008; Münzer et al., 2006; Parush et al., 2007; Ruginski et al., 2019) as well as long-term spatial ability (Dahmani & Bohbot, 2020; Ishikawa, 2018). While these studies were mainly conducted outdoors, which differs from indoor space in terms of environmental affordance (e.g., enclosure, dimensionality, traversal, line of sight, and type of landmarks) (J. Chen & Clarke, 2020; Kray et al., 2013), similar tendencies have also been observed indoors (Nyonyo, 2022). Spatial cognition and ability are crucial not only for wayfinding, but also for spatial reasoning and various fundamental cognitive processes (Bellmund et al., 2018; Epstein et al., 2017; D. R. Montello & Raubal, 2013). Therefore, indoor navigation systems should also consider facilitating spatial learning in addition to supporting the navigation process.

To mitigate the negative impact on spatial learning, researchers have suggested redirecting users' attention from navigation services to relevant environmental features (Chrastil & Warren, 2012; Fenech et al., 2010; Ishikawa, 2020). Outdoors, a best practice is to include landmarks in route instructions parenGramann et al., 2017; Wunderlich and Gramann, 2018, 2021, because landmarks are prominent environmental features (Raubal & Winter, 2002; Sorrows & Hirtle, 1999) and frequently mentioned in human route descriptions (Denis, 1997).

Identifying and incorporating landmarks into indoor navigation services remains challenging, and their influence on spatial learning requires further exploration. As an initial attempt, research in mixed reality has demonstrated the benefits of spatial learning by overlaying semantic landmarks in navigation services (B. Liu et al., 2021). Existing navigational aids inherently serve as semantic landmarks. As previously suggested by users, integrating these existing navigational aids into navigation services can allow the two separate systems to operate in tandem. This approach would help avoid confusion and foster system-environment mutual confirmation, ultimately leading to improved performance and a more satisfying user experience. Furthermore, guiding navigators' attention to existing navigational aids would encourage them to attend to the environment, potentially benefiting spatial learning.

1.2 Research challenges

This study aims to meet the challenges of indoor wayfinding and spatial learning, by integrating existing navigational aids into navigation services. The following research challenges are involved:

Research Challenge 1: Understanding the indoor wayfinding mechanism at decision points. To provide user-centred navigation services, it is crucial to comprehensively understand individuals' information needs during indoor wayfinding. Previous research has examined indoor wayfinding strategies at the general planning level (Hölscher et al., 2006) and the factors influencing decision-making (Passini, 1984b). Yet, wayfinders encounter decision points en route, where they must evaluate the information at hand and decide on the next move. These are the places where people face wayfinding difficulties and confusion, where incongruence may occur (Best, 1970). Therefore, we must establish a systematic overview of the decision-making and reasoning processes at decision points. This involves exploring the factors influencing wayfinders' decision-making at decision points in the absence of mobile navigation services, and investigating the factors that affect the selection and utilisation of existing navigational aids. Moreover, indoor wayfinding behaviour is influenced by buildings' physical and functional characteristics, such as layout, signage, landmarks, and environmental cues (Hirtle & Bahm, 2015). The impact of building characteristics on decision-making and the choices of navigational aids remains to be analysed.

Research Challenge 2: Integrating Existing Navigational Aids into Indoor Navigation Services.

Two key considerations need to be addressed. First, it is necessary to identify suitable existing navigational aids that are meaningful and practical to integrate. This requires exploring the utilisation of existing navigational aids and identifying the features wayfinders use to describe indoor environments. Second, the methodological approach for incorporating these aids needs to be determined. This involves modelling the suitable existing navigational aids and their semantics into an indoor spatial model, developing a suitable semantic-aware routing algorithm, and effectively communicating the route information.

Research Challenge 3: Understanding how the sources of environmental information influence the levels of spatial knowledge. The way individuals learn about the environment, either through direct experience or external representations of the environment, significantly affects the levels and structure of their spatial knowledge (Ishikawa, 2020; Thorndyke & Hayes-Roth, 1982; Van Der Kuil et al., 2020). During locomotion, various senses are engaged to acquire landmark, route, and survey knowledge. The level of direct experience directly impacts the levels and structure of spatial knowledge acquired (D. R. Montello, 1998; Siegel & White, 1975). Previous studies have explored how existing navigational aids affect the structure of the acquired spatial knowledge and highlight the negative impact of mobile navigation systems on spatial knowledge acquisition. For instance, compared to direct experience, maps or floor plans are considered to facilitate metric information and survey knowledge more than others (Thorndyke & Hayes-Roth, 1982). Signs and floor plans, as the main types of existing navigational aids, are considered to encode distinct types of spatial information, thereby influencing spatial learning differently (Hölscher et al., 2007). However, how different mobile navigation systems affect the levels and structure of spatial knowledge remains an open question (Ruginski et al., 2022). An empirical understanding of how different sources of environmental information influence spatial learning can provide valuable insights for the future design of human-oriented navigation systems that promote spatial learning.

1.3 Research questions

To address the challenges mentioned above, we identify the following research questions:

RQ 1. What factors influence navigators' decision-making at decision points, and how are the selection and utilisation of existing navigational aids affected?

RQ 2. How do we integrate existing navigational aids into indoor navigation services?

RQ 3. Compared with conventional mobile navigation services, how do navigators' wayfinding performance, spatial learning, and user experience differ when navigating with the integrated indoor navigation service?

The research questions are intended to address the research challenges and guide our study step-by-step, not aiming for a one-to-one alignment. Research Challenge 3 is reflected in **RQ 1** and **RQ 3**. Since **RQ 2** and **RQ 3** build upon the initial exploration from **RQ 1**, the formulation of these questions will be refined and become more specific as the research progresses.

Guided by the research questions, this study will allow us to gain insights into the decision-making process of indoor human wayfinding and the factors that influence it (**RQ 1**). These insights will form the foundation for a computational framework for integrating existing navigational aids into indoor navigation systems (**RQ 2**). The evaluation and analysis of this framework will benefit our understanding of how mobile navigation systems influence wayfinding performance, spatial knowledge acquisition, and user experience (**RQ 3**).

Theoretically, this dissertation will contribute to the human indoor wayfinding theory and the cognitive mechanism underlying mobile navigation systems and spatial learning. Practically, it will advise architecture and building wayfinding system design and indoor navigation system development. At the same time, it will provide a practical computational framework for modelling indoor semantic features and integrating them into navigation services.

1.4 Research scope

Indoor navigation systems usually consist of positioning, spatial data models, route planning and route communication components (Section 2.3). The computational framework in this dissertation considers the spatial data models, route planning and route communication, in terms of the feasibility of automatically integrating existing navigational aids, while not focusing primarily on computational efficiency or other related considerations. Indoor positioning falls beyond the scope of this dissertation.

While route information can be communicated through different modalities (Section 2.3.3), we focus on generating textual route instructions. In the evaluation, this dissertation intentionally compares the content of textual route instructions while keeping the visual presentation consistent across both systems. We acknowledge the importance of the visual representation of navigation guidance and the timing of route instructions in influencing wayfinding performance, spatial learning, and user experience, yet they remain for future research.

1.5 Dissertation organisation

The dissertation is organised into seven chapters, each addressing a specific aspect of the research topic. The following is an overview of the structure and content of each chapter:

Chapter 1 introduces the background and motivation of the research topic and states the research challenges and questions.

Chapter 2 sketches the background and related literature of the research topic, including the indoor environment, human indoor wayfinding, spatial cognition and spatial learning, and indoor navigation systems. In this chapter, we elaborate on fundamental theories and concepts, and identify research gaps.

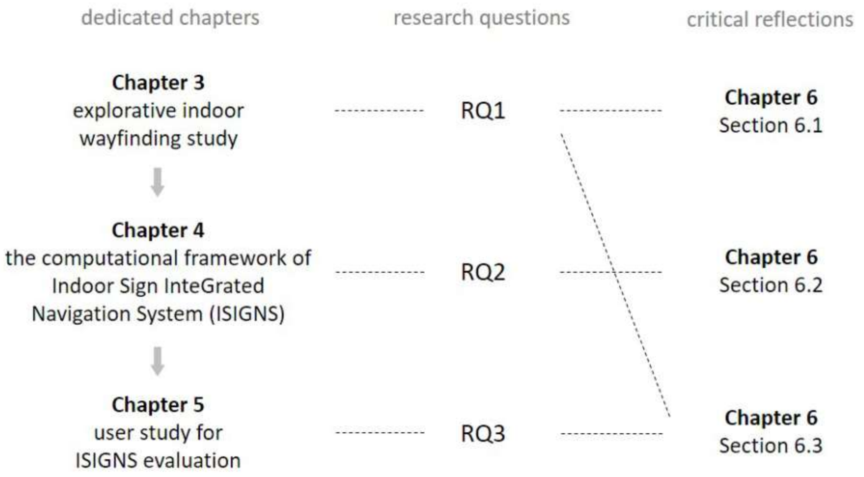

Figure 1.3 - The connection between research questions and chapters.

Chapter 3 details an explorative indoor wayfinding study. This empirical study clarifies human indoor wayfinding tactics at decision points and the relevance of existing indoor navigational aids. This chapter focuses on **RQ 1** (Figure 1.3).

Chapter 4 addresses **RQ 2** (Figure 1.3) by proposing the Indoor Sign InteGrated Navigation System (ISIGNS). It presents the overall workflow of ISIGNS and elaborates on the data modelling, routing, and route instructions generation. A proof-of-concept is developed and evaluated to showcase the process and its feasibility.

Chapter 5 comprises an empirical experiment comparing the proposed ISIGNS with the conventional navigation system using metric-based turn-by-turn instructions. It aims to evaluate the performance and user experience of ISIGNS and test whether it prompts spatial learning. This chapter addresses **RQ 3** (Figure 1.3).

Chapter 6 discusses the main contributions of this dissertation and their potential implications. Additionally, we critically reflect on the limitations of our study and suggest directions for future research avenues (Figure 1.3). This chapter ends with a summary of the key recommendations for indoor navigation service providers.

Chapter 7 summarises the main findings of this dissertation and relates them to the research questions. It finalises the dissertation with concluding remarks.

1.6 Related publications

Some sections of this dissertation contain parts from related publications. They are listed below:

Wang, W., Huang, H., & Gartner, G. (2021). Can indoor navigation service incorporating signs support spatial learning?. Abstr. Int. Cartogr. Assoc., 3, 312. https://doi.org/10.5194/

ica-abs-3-312-2021

Wang, W., Huang, H., Lyu, H., & Gartner, G. (2019). Incorporating directional signs into indoor navigation systems. Abstr. Int. Cartogr. Assoc., 1, 394. https://doi.org/10.5194/ica-abs-1-394-2019,2019

Wang, W., & Gartner, G. (2018). Integrating Existing Indoor Navigational Aids into Data Modelling and Route Planning. In P. Kiefer, H. Huang, N. Van de Weghe, & M. Raubal (Eds.), Adjunct Proceedings of the 14th International Conference on Location Based Services (pp. 147-151). Zurich: ETH Zurich. https://doi.org/10.3929/ethz-b-000225607

Wang, W., Huang, H., Gartner, G. (2018). Considering Existing Indoor Navigational Aids in Navigation Services. In P. Fogliaroni, A. Ballatore, & E. Clementini (Eds.), Proceedings of Workshops and Posters at the 13th International Conference on Spatial Information Theory (COSIT 2017). Lecture Notes in Geoinformation and Cartography (pp. 179-189). Cham: Springer. https://doi.org/10.1007/978-3-319-63946-8_33

Chapter 2

Background and related work

2.1 Indoor navigation

Navigation is the act of planning the route ("wayfinding") and moving through the environment ("locomotion") to reach a destination by entities (D. R. Montello, 2005). These entities can be organisms or intelligent machines. In this dissertation, we narrow it down to human beings.

Locomotion refers to the process of coordinating one's body to move in the immediate environment (D. R. Montello, 2005). During this process, we engage our senses (vision, hearing, touch, and vestibular and kinesthetic senses) to interact with the proximal surroundings.

One major sensory mode is vision, which allows sighted people to visually scan and perceive their surroundings. Visual perception is fast and functions in both proximal and distal surroundings (Arthur & Passini, 1992). Hearing is not typically used as a primary sense for locomotion in humans. However, humans can still take auditory cues to become aware of their surroundings while moving. For example, people walking in a railway station may use their hearing to detect the train approaching. The sense of touch is essential for detecting obstacles and surfaces during movement and providing feedback about the body's position and direction. Touch is vital for people with visual impairment, in both cases of using a white cane to sense the environment and using tactile maps.

According to Ittelson's environmental perception theory (Ittelson, 1978), body-based perceptions (vestibular and kinesthetic senses) play an important role in distinguishing people from observers to explorers of the environment. The vestibular system, located in the inner ear, helps maintain balance and control body posture during movement. It detects the head position and direction changes and sends signals to the muscles and joints to adjust accordingly. Then, the kinesthetic sensory receptors located in the muscles, tendons, and joints provide information about the body's position and movement, which is used to coordinate and control locomotion. When people actively explore the environment, the body-based perceptions construct and update spatial information, thus contributing to spatial learning (Klatzky et al., 1998).

Through locomotion, people perceive information from different locations in the environment and integrate them into a configurational representation (Ishikawa, 2020). This configurational representation is known as the cognitive map, which we will elaborate on in Section 2.2.1. It is the cognitive map that helps people to find their way in the environment.

Wayfinding is the process in which people try to orient themselves and navigate in an environment, aiming to find their way from an origin to a destination and to recognise this destination when it is reached (Golledge, 1999). It involves planning and continuous decision-making during the course, like which route to take at various decision points. To make informed decisions, people need to consult spatial knowledge, which is a combination of the “knowledge in the head” and the “knowledge in the world”. Coined by Norman (Norman, 2013, p. 75), “knowledge in the head” is what we have learned and stored in the memory, which can be both declarative and procedural knowledge, while “knowledge in the world” refers to external information. When people are exposed to an unfamiliar environment, the primary information source to support wayfinding is external, which can be the environment as well as any external representations of the environment, i.e., navigational aids.

We attempt to sketch navigation theoretically as two separate components, but in reality, most navigating acts involve both. People start by planning their route to their destination. When they locomote, they perceive information from the environment and subsequently update their cognitive maps. This may, in turn, affect their decisions along the way. To summarise, navigation is an interaction between human beings and the environment. On the one hand, the environment “affords” human beings with its layout and composition; on the other hand, human beings “pick up” spatial information depending on their previous experience and make navigation decisions (J. J. Gibson, 2014; Ishikawa, 2020).

In the following sections, we focus on the indoor environment and unfold the theory and related work on human indoor wayfinding.

2.1.1 The indoor environment and wayfinding

In this section, we introduce the indoor environment from a wayfinding point of view, i.e., how the characteristics of and environmental features in the indoor space affect human wayfinding.

Indoor refers to “of or relating to the interior of a building” (Merriam-Webster, n.d. Definition 1). Cartographers extended this definition by incorporating further characteristics of the indoor space, like “enclosed”, “bounded”, and “human activities” (Worboys, 2011; Yan et al., 2018; Yang & Worboys, 2011; Zlatanova & Isikdag, 2015). In this dissertation, we consider the indoor environment as the enclosed interior of a built environment that allows human movement.

The indoor environment differs from the outdoor environment in some key properties that affect human navigation (Table 2.1) (J. Chen & Clarke, 2020; Kray et al., 2013). For simplicity, we compare the indoor with the outdoor environment, while acknowledging the intermediate spaces between indoors and outdoors that have their own features, classified as transitional spaces (Kray et al., 2013) or quasi spaces (Yan et al., 2018). Many researchers

Table 2.1 - Comparison of the outdoor and indoor environment

Properties	Outdoor	Indoor
Enclosure	unenclosed	usually fully enclosed
Dimensionality	often 2D	usually 3D
Access	often unrestricted	usually regulated by architectural features (e.g., doors)
Traversal	often free movement	usually constrained by architectural features (e.g., corridors, doors, etc.)
Line of sight	often unobstructed	usually limited
Landmarks	global and local	mainly local

considered indoor space smaller and fully enclosed by physical constraints, as opposed to the generally larger and unbounded outdoor space (Worboys, 2011; Zlatanova & Isikdag, 2015). Another fundamental property is dimensionality. Most outdoor environments are considered two-dimensional, while most indoor environments have more than one level, therefore regarded as three-dimensional. This increasing dimensionality makes the indoor environment more complex and cognitively more demanding for navigators (Kray et al., 2013).

The built nature of indoor spaces introduces regulated access (often through gates and doors) and constrained traversal, whereas people can move freely outdoors (Kray et al., 2013). Constrained by architectural features (e.g., doors, corridors, staircases, etc.), the physical access to a certain part of the building is restricted. People cannot go through locked doors and must use a staircase or an elevator to change floor levels. People in a wheelchair or with a stroller can only change floors with an elevator. Hence, they may need to detour to reach a destination. Besides, additional physical access restrictions may apply in some functional regions, subject to the groups of users (e.g., staff members and visitors) (Richter, 2017).

Not only physical access but also visual access is limited indoors. Global landmarks are powerful tools for people to localise themselves and stay oriented when navigating outdoors. However, the limited visual access indoors discontinues the line of sight and can hardly allow access to global landmarks (Basiri et al., 2017; Giudice et al., 2010; Giudice et al., 2019). As the environmental features are often similar in the same building, only relying on local landmarks increases the uncertainty of indoor navigation.

Weisman (1981) characterised four main environmental variables influencing wayfinding, including types of signage, visual access of a setting, architectural differentiation, and the overall plan configuration. Except for the signage, the space syntax theory can describe the other environmental variables (Hillier & Hanson, 1984). Using space syntax analysis, e.g., the visibility graph analysis, researchers have discovered problems with local visibility at architectural hotspots reflected by the step depth (Hölscher et al., 2012). Complex layout, captured by connectivity and integration of space, was also responsible for the indoor wayfinding difficulties (Hölscher et al., 2012; Li & Klippel, 2012).

The characteristics mentioned above of the indoor environment contribute to a greater navigation complexity. To overcome these difficulties, navigational aids have since long been designed to represent spatial information and assist wayfinding. In addition to floor plans and signs placed in the environment, indoor navigational aids can also be equipped on mobile devices with various functions. This dissertation distinguishes the former as existing navigational aids (signs and floor plans) and the latter as navigation services[1]. We introduce the existing indoor navigational aids in the next section and detail the indoor navigation service in Section 2.3.

2.1.1.1 Existing indoor navigational aids

Architects attempt to create public buildings and plan the interior space with intuitive layouts that follow a logical flow to ease wayfinding. However, due to the nature of the built environment, wayfinding design is not only handled by the design of the building. To communicate environmental information and aid wayfinding, navigational aids come into play. Most public buildings offer signs to guide users and indicate semantic information. In addition, floor plans are sometimes available for an overall understanding of the space.

Signs

The sign system contributes to a wayfinding narrative of public space, with each sign conveying a unique message. This message is related to the functional information expressed by the sign. Normally, there are four major functions that define the sign types accordingly (Arthur & Passini, 1992; D. Gibson, 2009; Passini, 1984b).

1. An Orientation sign provides an overview of various points of interest within a specific area, which can be the entire building, a floor, a section, or a wing. This sign typically includes symbols or labels indicating important locations such as rooms, stairwells, exits, etc. Figure 2.1A shows a directory of a building wing. Orientation signs are usually located at significant circulation points, such as main entrances, lobbies, and stairwells.
2. A Directional sign points to specific areas and indicates the direction of travel once the navigator enters the circulatory system of the building. These signs typically include information such as room numbers and floor levels, as well as arrows and other symbols to indicate the direction of travel (Figure 2.1B). Directional signs can be found in various formats, including freestanding, wall-mounted, and overhead ceiling-mounted signs. These signs are usually located at decision points and are designed to be easily readable, with clear and concise information. This is the most common type of sign used for wayfinding, which provides sequential point-to-point information.
3. An identification sign provides information about a specific location, space, or object, and is used to help identify and locate it. These signs typically include the name or designation of the space or object, along with any other relevant information, such

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[1] We acknowledge that floor plans can also be portable, either paper printed or digitally displayed on a mobile device as a static plan. To distinguish them from mobile navigation services, this dissertation considers them as part of the environment.

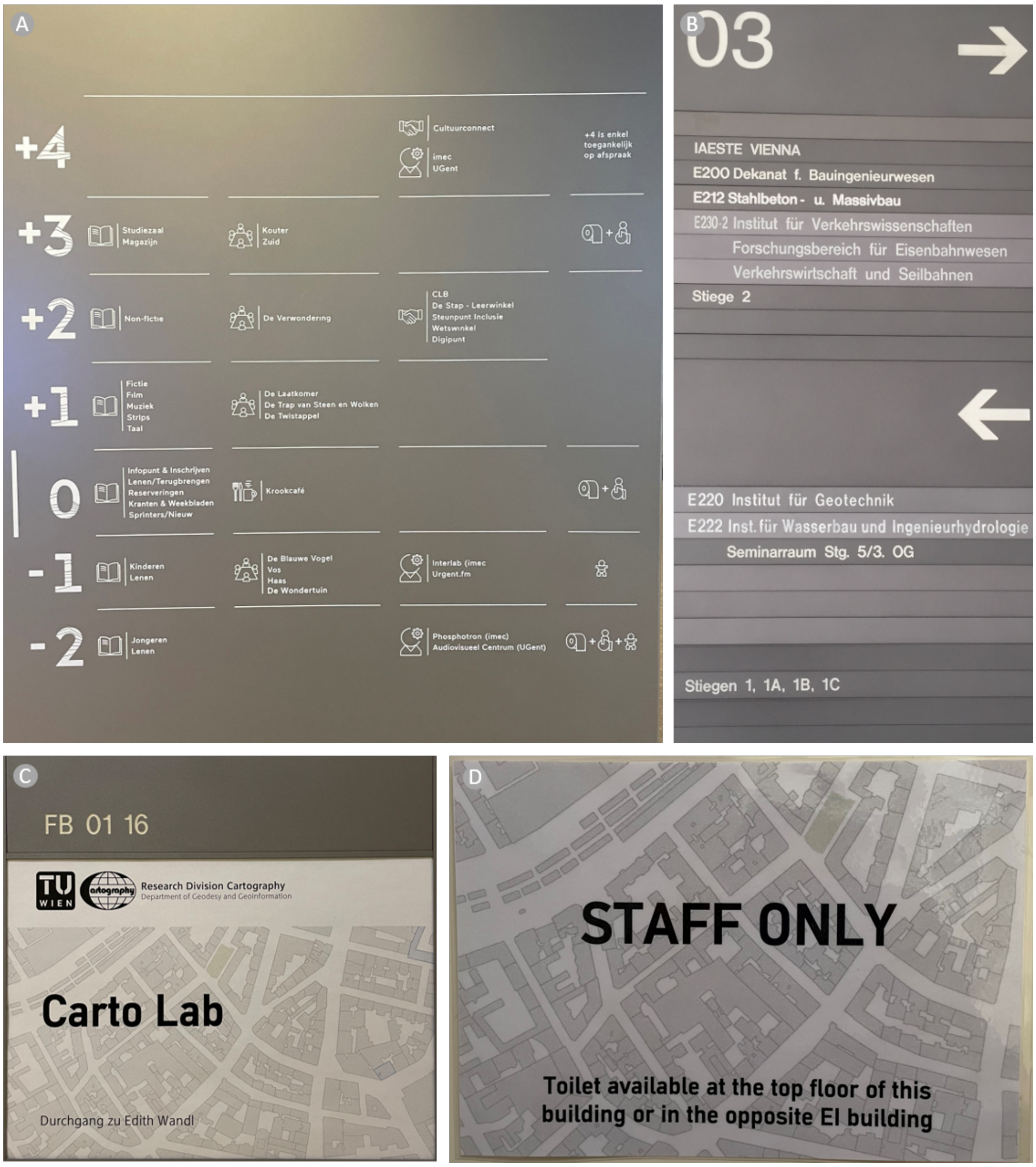


Figure 2.1 - Examples of different types of signs: (A) an orientation sign; (B) a directional sign; (C) an identification sign; (D) a regulatory sign.

as its function (Figure 2.1C). They are usually smaller in size than orientation signs and are often incorporated into the design of the space or feature they identify. The purpose of an identification sign is to provide specific and accurate information that helps people identify the location they are looking for. The sign should be noticeable, easy to read and understand, and placed in a visible location.

4. A regulatory sign is used to convey information about regulations or rules that must be followed in a specific area. They are used to inform people of actions or behaviours that are required or prohibited, such as safety precautions. These signs typically include symbols, pictograms or short text messages (Figure 2.1D). Regulatory signs are usually used in areas where there is a need to control or direct people's behaviour and are designed to be easily readable and understood by the intended audience.

Orientation, directional, and identification signs are essential for wayfinding in complex buildings. A typical wayfinding scenario in a facility well-equipped with signs can be described as follows. Navigators to reach a destination in a building. Once they enter, the orientation sign at the entrance informs them which area their destination is located and how to get there. They then continue to the target area. Depending on the size of the target area, either an orientation or a directional sign awaits them for the direction to the destination. Along the way to the destination, they may encounter several decision points, where they have to decide which outgoing options to take. At least directional signs are available at all these decision points to guide them to their destination. When they finally arrive, an identification sign indicates the end of the journey.

By analysing the space, the potential users, and the typical wayfinding scenarios, designers plan with possible sign locations and the content on the signs. Signs should be placed at entrances, circulation pathways, and decision points for wayfinding purposes. The content on the signs should be clear and concise, with the sign system being continuous and consistent. Graphic designers should also take care of the overall design aesthetic, legibility, and accessibility of the signs. The designing and implementing of a sign system is suggested to be iterative, involving multiple rounds of evaluating and refining the design before final implementation (D. Gibson, 2009; van Uffelen, 2020). However, the reality can be different. The possible multi-functionality of a building and the diverse needs of user groups, can lead to ambiguity and confusion (Wang et al., 2019). Researchers attempt to refine sign design guidelines for specific building types, such as hospitals (Greenroyd et al., 2017; Rodrigues et al., 2019), libraries (Li & Klippel, 2012; Luca & Narayan, 2016; Mandel, 2016), and transport hubs (Sun et al., 2021). A lack of communication between several contributors to the sign system and multiple channels of wayfinding information can also contribute to confusion (Li & Klippel, 2012). To meet these challenges, a possible solution can be synchronising other wayfinding support systems with the sign system.

Floor plans

A floor plan is a diagrammatic representation of the layout of an indoor space (Gärling et al., 1983; Meilinger et al., 2006). It covers the information on an orientation sign, i.e., an overview

Figure 2.2 - Examples of floor plans: (A) a “YOU ARE HERE” floor plan marked with the viewer’s current location; (B) a floor plan combined with an orientation sign.

of the entire building or a floor. In addition, it provides a clear visual representation of the layout and organisation of the space. To assist localisation, wall-mounted floor plans often indicate the current location as a dot with the information "YOU ARE HERE" (Figure 2.2A). As a result, they are also called you-are-here maps or YAH maps (C. H. Chen et al., 2009; Levinew et al., 1984). Floor plans are usually located at similar locations with orientation signs and are often combined (Figure 2.2B).

Compared with signs, especially directional signs, wayfinders need more time to comprehend floor plans (Butler et al., 1993). To use a floor plan, wayfinders start with matching the environment with the floor plan. Then they need to find their current location and the destination on the floor plan, and draft possible connections. Based on their preferred criteria, they select one route. Further, they ought to switch from the allocentric reference framework suggested by the floor plan to the egocentric one to translate the chosen route into one in reality (Shelton & McNamara, 2004). After memorising all the route segments, they follow the route. Wayfinders may forget some route segments during the following route because of the high cognitive load (Hölscher et al., 2009). Consequently, they have to verify the information along the way. Similar to maps in the outdoor environment, misaligned floor plans add additional cognitive effort to wayfinders (Levine, 1982; Levinew et al., 1984; Rossano & Warren, 1989).

2.1.2 Human indoor wayfinding

Wayfinding is the planning and continuous decision-making process. In this section, we start with the overall planning and decision-making, and then look into how environmental features influence individual decisions. We end with the group and individual differences of human beings and their impact on wayfinding behaviours.

2.1.2.1 Decision-making in indoor wayfinding

"Wayfinding" was first introduced into literature by Kevin Lynch. In his book The Image of the City, he introduced the term "legibility" and argued that environmental legibility is fundamental to wayfinding (Lynch, 1960). He identified essential elements of a city, namely paths, edges, districts, nodes and landmarks, which influence how we form the city "image". Although his study mainly focused on the urban environment, these terms (e.g., wayfinding, environmental legibility, etc.) and the research methods (e.g., analysing sketch maps and verbal protocols) are used by subsequent researchers in wayfinding studies in any environment.

In the following decades, environmental psychologists bridged geography and psychology to understand human-environment relation and looked into the human information processing of wayfinding (Stea & Downs, 1973). Kaplan (1973) proposed a four-phase human information processing: perception, prediction, evaluation, and action. In the first phase, human beings perceive the environment to know where they are and the primary environmental characteristics. Then they predict possible future situations based on the current condition. After evaluating the possible future situations and what each alternative may lead to, they can think of possible actions. The last three phases together comprise the decision-making process.

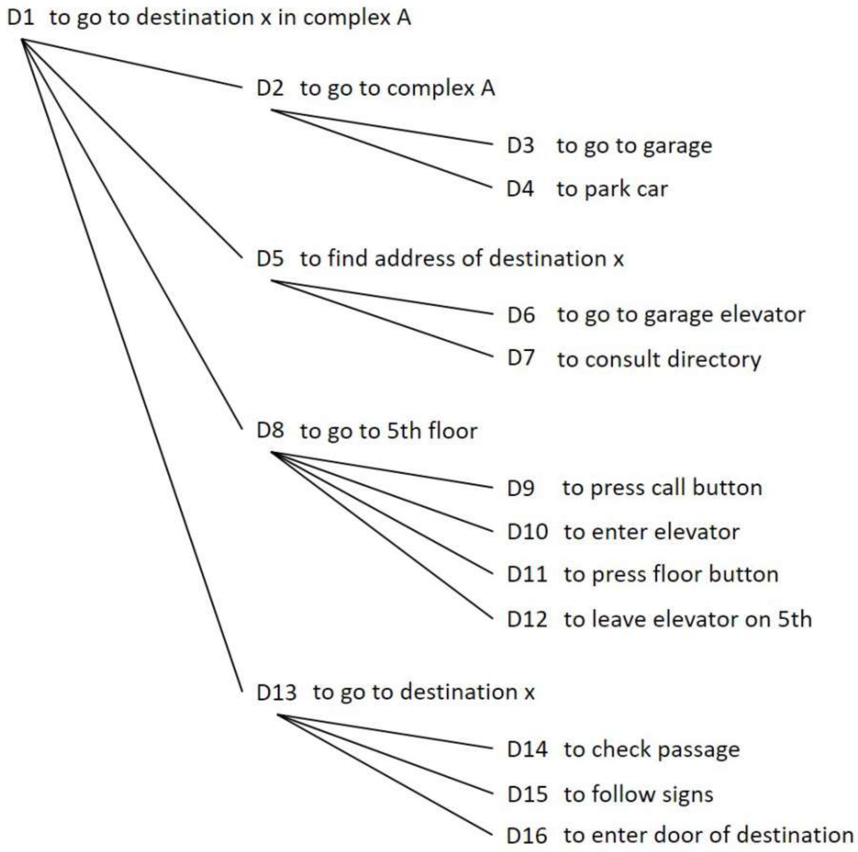


Figure 2.3 - An example decision plan illustrating Passini's decision-making hierarchy (redrawn from Arthur and Passini, 1992, p. 30).

Building upon Kaplan's decision-making theory and the conceptual framework of action plans (Gärling et al., 1984; Russell & Ward, 1982), Passini introduced wayfinding decision-making into the indoor environment. He conducted a series of experiments to understand the relationship between the indoor environment and human wayfinding and proposed a hierarchical decision plan for indoor wayfinding (Passini, 1981; Passini, 1984a, 1984b). Indoor wayfinding was considered as a series of spatial problem-solving that includes different levels of decision-making and decision execution. Depending on whether a decision is directly executable, he distinguished them into two types and named the non-directly executable decisions as tasks. One can then divide a task into subtasks, eventually into a hierarchical structure composed of directly executable decisions. Figure 2.3 illustrates such an example decision plan. The wayfinding process is then taken as forming a decision plan that decomposes a wayfinding task into executable decisions, and matching the perceived information with the expected information at the time of decision execution. The decision is executed if the perceived information is successfully matched with the expected. Otherwise, one revises the decision plan according to the new information.

Passini identified two possible task situations by looking at wayfinding as a task-generating activity. In the first situation, people employ an access strategy when relevant environmental information is available to help with decision-making. This strategy is further categorised into three tactics depending on the types of available information. If people rely only on sensory information, i.e., information perceived directly from the immediate environment, they use the direct access tactic. If people also consult their memory information, i.e., environmental information of this setting or similar setting in memory, they are using an indirect access tactic. If people need to consciously reason about and infer from all information they have at the moment, they are using inference tactics. As the reliability of the information source decreases among the aforementioned tactics, so as the reliability of the tactics. The reliability and efficiency are further declining when no relevant information is available. In such task situations, people employ the search strategy, which can be systematic or random. This is usually where people have wayfinding difficulties and get lost.

From an architectural background, Passini's indoor wayfinding research aimed at informing architecture design and spatial planning (Arthur & Passini, 1992). The decision diagram of potential wayfinding tasks guides the design of possible spatial organisations. The proposed strategies and tactics instruct the building managers and graphic designers on where to provide crucial sensory information (e.g., signs and floor plans) and how to improve their design. Worth noting is that the "decision" in this framework is considered as "the choice of a behavioural action" (Passini, 1984a, p. 211). What he coded as a decision is a choice of an intended or actual behavioural action. This decision is not necessarily tied to a decision point (i.e., a location where people have at least two outgoing options).

To be distinguished from Passini's decision-making strategy, which refers to the approach people choose based on the available information in any decision situation, is the wayfinding strategy, which represents the mechanisms and heuristics applied during route planning (Hölscher et al., 2006; Hund & Minarik, 2006; Lawton, 1996; Wiener et al., 2004). Deriving from outdoor wayfinding strategies, e.g., region-based strategy (Wiener et al., 2004), least-angle strategy (Hochmair & Frank, 2000), with consideration of the three-dimensional structure indoors, Hölscher et al. (2006) proposed three indoor wayfinding strategies.

1. The central point strategy: people refer to a known location of the building to help with orientation and route planning. Although named as the central point, this known location is not necessarily at the centre of the building but instead as a reference point.
2. The direction strategy: people first plan their route towards the destination's horizontal location, then consider the level difference.
3. The floor strategy: people plan their route towards the vertical location, that is, the destination's floor level first, then consider the horizontal difference.

These wayfinding strategies correspond to the higher levels of Passini's decision plan, which deal with the general planning of indoor wayfinding. These studies provided valuable architectural design suggestions to ease human wayfinding. However, for existing buildings, compared with reforming their architecture, it is more practical to improve their existing navigational aids and to provide mobile navigation services. It is, therefore, crucial to understand wayfinding decision-making at a local level, which is how people decide at each decision point en route.

2.1.2.2 Environmental features and decision-making

At a finer level, wayfinders continue to make decisions as the journey goes on, and they encounter decision points along the way. Following similar definitions from Butler et al. (1993) and M. O'Neill (1991), we define a decision point as a location where people have at least two outgoing options. Early research by Best (1970) identified decision points as the places where people often get lost. Janzen (2006) confirmed the importance of decision points in wayfinding with memory tests. M. O'Neill (1991) and M. J. O'Neill (1991) further investigated the impact of decision point complexity on indoor wayfinding, which was measured by the number of possible paths at decision points. His findings suggested that the wayfinding accuracy decreases as the decision point complexity increases. Even the presence of signage could not compensate for the complexity of decision points.

Not only the decision point complexity affects wayfinding behaviour, but also the environmental features, like illumination and corridor width. Taylor and Socov (1974) varied the illuminating conditions on different paths and found that participants chose the brighter one. The preference towards a more illuminated path was further enhanced by increasing the illumination ratio between the paths. Bell et al. (2005), Hidayetoglu et al. (2012), and Hughes et al. (2020) further confirmed this finding with empirical studies. In a virtual environment, Vilar et al. (2012) verified the influence of the illumination as well as the corridor width. They concluded that people preferred wider corridors, and this preference maximised at a 150 cm width difference between the corridors. When combining the illumination and corridor width, almost all participants in the experiment chose the brighter and wider side. Further studies endorsed people's preference towards the wider corridor, because people perceived it as safer (Sun & de Vries, 2013; Zhang & Park, 2021).

When the existing navigational aids were available at decision points and taken into consideration, Vilar et al. (2014) found a greater reliance on signs over the aforementioned environmental features. Butler et al. (1993) and Hölscher et al. (2007) noticed a preference towards signs over floor plans.

Besides environmental features, researchers also observed certain behaviour patterns associated with the environment to affect choices at decision points. At T-type intersections, indoor wayfinding behaviour studies discovered and validated a right-turn tendency over decades (Bitgood, 2006; Taylor & Socov, 1974; Whyte, 1980; Zhang & Park, 2021). People also tend to follow the inertia to choose the straight path and the central corridor (Bitgood, 2006).

2.1.2.3 Group and individual differences in indoor wayfinding

What influences human indoor wayfinding behaviour is not only the perceived physical environment but also group and individual differences, such as age, gender, cultural background, familiarity with the environment, and individual spatial ability.

People who differ in age perceive environmental features diversely. Research suggests that elderly people tend to choose more salient environmental features than younger adults (Davis et al., 2008; Lee & Kline, 2011). A gender difference is noticed in the use of wayfinding strategies. Studies indicate that females employ more landmark-related strategies than males (Cherney et al., 2008; Choi et al., 2006; Merrill et al., 2016). People from different cultural backgrounds also appear to have difficulties understanding the indoor wayfinding system designed in another culture (Hashim et al., 2014; Joy Lo et al., 2016). Moreover, navigators familiar with the environment choose different indoor wayfinding strategies than unfamiliar visitors, leading to particular wayfinding behaviours (Hölscher et al., 2006; Li & Klippel, 2014).

Some people enjoy exploring new places and can easily find their way. Others are not confident in wayfinding and very often get lost. People differ in their spatial ability and spatial preference. Individual differences in distinct components of spatial ability (mental rotation, spatial perspective-taking, sense of direction, etc.) also contribute to specific aspects of indoor wayfinding differently (Kuliga et al., 2019).

2.2 Spatial cognition and spatial learning

According to Hart and Moore (1973, p. 248), spatial cognition is "the knowledge and internal or cognitive representation of the structure, entities and relations of space; in other words, the internalised reflection and reconstruction of space and thought". In a broader sense, it includes the mental processes associated with perceiving, processing, and using spatial information (Ishikawa, 2020; D. R. Montello & Raubal, 2013). It is crucial in activities such as wayfinding, spatial reasoning and problem-solving. Additionally, spatial cognition deals with acquiring and using spatial knowledge from various sources such as direct experience, iconic spatial representations (e.g., maps, drawings, and diagrams), and non-iconic form (language) (D. R. Montello & Raubal, 2013). Hence, it is essential to investigate such cognitive representation and its formation.

2.2.1 Cognitive maps and cognitive mapping

The term "Cognitive maps" was coined by (Tolman, 1948) in his well-known research with rats in a maze. He concluded from a series of experiments that rats had built a map-like representation of the space through direct experience, and humans would behave similarly, by analogy. He also argued that creating such a representation was not merely a response to stimulus, which is the fundamental view of behaviourism (Skinner, 1985), but through latent learning. This means it is initiated by an internal mind, a belief held by cognitive scientists (Chomsky, 1959). The word "map" can be confusing as it may imply a map-like representation, as pointed out by Hart and Moore (1973). However, we can hardly find an accurate map in our mind, but rather pieces of spatial knowledge connected to form a configurational representation (Downs & Stea, 1973; Ishikawa, 2020; Piaget, 1976). The term and its alternatives were a topic for research exchange in cognitive psychology for decades (Kitchin, 1994). A comprehensive discussion of the terms and their usage is beyond the scope of this dissertation. We agree with an inclusive understanding of cognitive maps that they refer to spatial representations in one's mind. Correspondingly, cognitive mapping is the process of constantly acquiring, storing, and updating spatial knowledge (Downs & Stea, 1973; Ishikawa, 2020).

Regarding cognitive mapping, we must distinguish between ontogenesis and microgenesis. Ontogenesis is the individual development from infancy to adulthood, as Piaget's spatial development theory concerns. He stated that children's understanding of space and spatial relationships develops in stages, from topological to projective relations to general and mixed metrics, as they grow and interact with their environment (Piaget, 1976). Piaget's theory emphasises the importance of children's experiences with their environment and interaction in space in forming their cognitive maps.

Spatial microgenesis refers to the development over a short period, which deals with the case when one becomes familiar with a new place. A classical theory of microgenetic development of spatial knowledge was proposed by (Siegel & White, 1975). They succeeded in Shemyakin's idea that cognitive mapping consecutively proceeds from landmark recognition to path integration and eventually to a relational understanding of space (Shemyakin, 1962). They further elaborated it into a model with three stages.

The first stage starts with the development of landmark knowledge, where humans identify and memorise distinct objects prominent in the environment, and scenes, which are perceptual events associated with specific locations (Siegel & White, 1975). Landmarks are salient and identifiable features that serve as reference points for wayfinders to localise themselves and reach their destinations (Sorrows & Hirtle, 1999). They are categorised into visual, semantic (or cognitive), and structural landmarks based on their distinct characteristics (Raubal & Winter, 2002; Sorrows & Hirtle, 1999). Visual landmarks stand out in the environment because of their visual traits. Semantic or cognitive landmarks distinguish themselves from their surroundings due to the meaning they bear. The meaning can be related to their significance in culture, the individual connotation people associate with them, or the explicit message they intend to deliver (e.g., the message on a sign). Finally, structural landmarks are distinct by reason of their unique position in the structure of the environment (Sorrows & Hirtle, 1999).

As human exposure to the environment continues, connections begin to develop between landmarks. This is the second stage of acquiring route knowledge. Route knowledge concerns the sequences of landmarks and associated actions (Siegel & White, 1975). It guides people from one location to another and is considered "procedural knowledge" (Golledge, 1999). Worth noting is that it involves only the sequences or procedures, not the relationships between landmarks.

In the final stage, human spatial knowledge progresses from topological to metric. Clusters of landmarks and routes start forming in the human mind. Based on the metric properties within and across clusters, a general "coordinated frame of reference" is eventually developed, producing survey knowledge (Siegel & White, 1975). Survey knowledge is the integration of landmark and route knowledge.

This stagelike framework suggests a lack of metric information at the early stages of cognitive mapping, whereas empirical studies sometimes reveal otherwise (Klatzky et al., 1990; Loomis et al., 1993). Montello challenged this framework by proposing a continuous framework: “There is no stage in which only pure landmark or pure route knowledge exists: Metric configurational knowledge begins to be acquired on the first exposure” (D. R. Montello, 1998, p. 146). Although the two frameworks differ in how spatial knowledge is acquired, in terms of whether it is a discrete or continuous process, they agree on the content in cognitive mapping: landmark, route, and survey knowledge.

Briefly mentioned in Section 2.1, people perceive information through locomotion and integrate them into a configurational representation. Direct experience in the environment enables humans to form representations of spaces by coordinating and internalising actions (Lhuillier et al., 2021). Through engagement with the environment, human spatial knowledge increases quantitatively, which contributes to spatial learning. While quantitative changes accumulate, qualitative transitions occur in levels from sensorimotor, preoperational, concrete operational, and eventually to the formal operational level. Our spatial knowledge, in turn, becomes more refined, abstract, and complex (Hart & Moore, 1973; Piaget, 1976).

In addition to direct experience, people build their cognitive maps through external representations of the environment, such as maps (Ishikawa, 2020). Compared with direct experience, the knowledge acquired from external representations alone is believed to differ in structure (Van Der Kuil et al., 2020). Thorndyke and Hayes-Roth (1982) conducted an indoor study to compare the spatial knowledge acquired from maps and direct experience. They recruited participants working in the building for different time lengths and naive participants who had to learn the building structure from floor plans. Spatial knowledge assessment tasks unveiled different patterns in the accuracy of distinct types of spatial knowledge. Direct experience promotes the acquisition of route knowledge, while maps enhance configurational learning of the environment, thus benefiting the survey knowledge acquisition. Further research suggests that in a complex indoor environment, direct experience alone is not sufficient for spatial knowledge acquisition (Moeser, 1988). Combining direct experience and maps can engage more sensory modalities, thus enriching spatial learning (Stea & Downs, 1973; Van Der Kuil et al., 2020).

Another kind of external representation of the environment, mobile navigation services, are essential to our daily lives nowadays. Opposed to maps, which facilitate spatial knowledge acquisition, they are considered to affect spatial learning differently.

2.2.2 The impact of mobile navigation services on spatial cognition

With the development of positioning technologies, mobile navigation services have been designed to assist navigation and have become prevalent. While mobile technologies have many advantages, their use also has detrimental effects on our spatial cognition and behaviour.

Doubts first arose from ethnographic researchers five years after the selective availability of Global Positioning Systems (GPS) was discontinued in 2000. Aporta and Higgs (2005) reported their ethnographic work on the impact of using GPS on Inuit wayfinding. They noted that using GPS led to further consumption of the technology and less engagement with the environment, which resulted in an observed decay of people's navigation ability in the Igloolik region. The modified spatial behaviour and the declined spatial ability raised immediate safety concerns, as the fallibility of technologies (e.g., batteries fail and ephemeral features change) can be fatal in such ferocious environments.

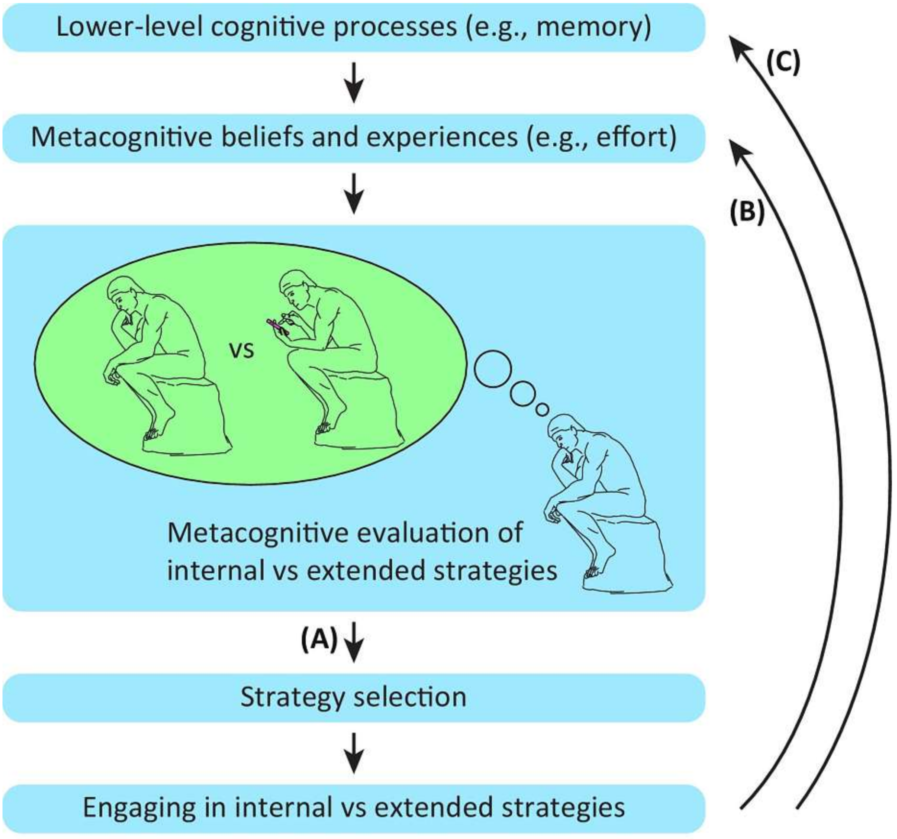
Since then, empirical research has shown evidence that a high degree of reliance on navigation services negatively affects spatial learning (Brügger et al., 2019; Burnett & Lee, 2005; Fenech et al., 2010; Gardony et al., 2013; Hejtmánek et al., 2018; Ishikawa et al., 2008; Münzer et al., 2006; Parush et al., 2007; Ruginski et al., 2019). One shared explanation is that navigation services attract navigators' attention from the environment to the tool, which causes inattention blindness and reduced situational awareness (Burnett & Lee, 2005; Fenech et al., 2010; Gardony et al., 2013; Gardony et al., 2015; Willis et al., 2009). Thus, navigators fail to attend to and encode landmarks or scenes along the travelled environment, which results in decreased spatial knowledge acquisition (Ruginski et al., 2019). A lack of mental effort (Parush et al., 2007) and passive decision-making (Bakdash et al., 2008; Brügger et al., 2019) also account for the insufficiency of spatial learning.

The reliance on navigation services and the reduced spatial knowledge acquisition trigger biased metacognitive evaluations of human mental capacities and the capacities of the extended mind (Risko & Gilbert, 2016) (Figure 2.4). In this case, we evaluate our internal spatial knowledge and navigation services when navigating. A decrease in our internal spatial knowledge after relying on navigation services will encourage us to believe that navigation services are more reliable. Consequently, we are more likely to choose to rely on navigation services in the future. It then enters into a self-reinforcing circle that drifts us away from depending on our internal spatial abilities to navigation services. Much worse than that, it will likely reduce both our spatial abilities and metacognitive confidence in them.

Empirical research has confirmed the long-term negative effect on human spatial cognition (Dahmani & Bohbot, 2020; Ishikawa, 2018) within two decades of mobile navigation services entering our daily life. The alarming future described by Aporta and Higgs (2005) has already come. Although most populations are less likely to endanger themselves when their smartphone batteries fail, compared to the Inuit people, spatial cognition and spatial learning are still crucial for human cognition and behaviour beyond the spatial domain (Epstein et al., 2017; Gramann et al., 2017; Ishikawa, 2018). These changes involve neural mechanisms that underpin spatial learning and are also deployed in many other cognitive processes, so deterioration of spatial cognition may have extensive impacts (Bellmund et al., 2018; Epstein et al., 2017). Rather than being determined by technologies, it is high time to think about technologies that enable spatial learning.

2.2.3 How could mobile navigation services facilitate spatial learning?

In response to the reduced spatial knowledge acquisition caused by current commercial navigation systems, researchers have recommended various potential solutions. One recommendation is to balance between system automation and user engagement, i.e. to engage users to decide



Trends in Cognitive Sciences

Figure 2.4 - A metacognitive model of cognitive offloading (from Risko and Gilbert, 2016, p. 684).

on their own routes rather than following the path proposed by the system (Brügger et al., 2019; Huang et al., 2021; Thrash et al., 2019; Willis et al., 2009). However, Ishikawa (2020) pointed out that active decision-making should be implemented cautiously with consideration of the use context. In a free exploration situation, like being a tourist to a new city, prompting active decision-making could improve spatial learning with a satisfied user experience. This may not be the best choice for a goal-directed user, especially when time is limited.

In addition to the level of automation, several researchers suggest guiding navigators' attention from the navigation services to the environment (Ishikawa, 2020; Waters & Winter, 2011). Allocating human attention to relevant environmental features facilitates the encoding of place–action associations and spatial relations of places, thus improving spatial knowledge acquisition (Chrastil & Warren, 2012; Gärling et al., 1986). Waters and Winter (2011) suggested including landmarks in route instructions, because they are prominent environmental features. Additionally, human route descriptions often refer to landmarks (Denis, 1997). Including landmarks in navigation instructions can, therefore, reduce the system-user gap, i.e., the gap between the information presented by information systems and that processed by the human cognition system (Norman, 2013; Raubal, 2009). Users need to bridge the gap before they can solve the same problem. The narrower the gap, the easier humans comprehend (Norman, 2013). Although Waters and Winter (2011) evaluation of online route videos did not uphold their hypotheses, studies in virtual environments supported that adding landmarks to navigation instructions prompts spatial learning (Gramann et al., 2017; Wunderlich & Gramann, 2018). This finding stays consistent in real-world studies (Wunderlich & Gramann, 2021).

The previous research focused on the outdoor environment, while identifying and integrating indoor landmarks is yet more challenging. Although various methods have been proposed to extract (Ohm et al., 2014; Viaene et al., 2014; Z. Zhou et al., 2021) and incorporate (Fellner et al., 2017) indoor landmarks, it is still unclear that integrate which kind of indoor landmarks could retain spatial knowledge acquisition. B. Liu et al. (2021) empirically tested that overlaying semantic landmarks with mixed reality (MR) devices could assist spatial learning in the indoor environment. Although MR devices are gaining popularity in indoor navigation (Çöltekin et al., 2020; L. Liu et al., 2019), they are still far from daily use. Furthermore, researchers have already raised concerns about the impact of using MR devices on people's social behaviour in everyday life, such as reducing our social engagement (Göbel, 2021) and impairing our ability to distinguish between real and virtual objects at a fundamental cognitive level (Çöltekin et al., 2020). Hence, there is a need to explore a method that integrates semantic landmarks, such as existing navigational aids, into indoor navigation services that are compatible with conventional devices. Additionally, the impact of this integration on spatial learning is yet to be explored.

2.3 Indoor navigation systems

Indoor navigation systems usually comprise several components: positioning, space modelling, route planning and route communication (Fallah et al., 2013; Huang & Gartner, 2009; L. Liu et al., 2021). In recent years, indoor positioning technologies have developed rapidly, with advancements in sensor accuracy and sensor fusion technologies, e.g., Kalman filter, particle filter, and Bayesian networks (El-Sheimy & Li, 2021). These developments, coupled with the decreasing cost of sensors, have made indoor navigation systems more accessible than ever before. However, while positioning plays a crucial role in enabling navigation systems, this section will focus primarily on the other components of indoor navigation systems, namely indoor spatial models, route planning, and route communication.

2.3.1 Indoor spatial models

Indoor models can be broadly categorised into two main types: semantic and spatial models (Worboys, 2011). Semantic models are often formal models representing the conceptual formation of indoor spaces, e.g., a navigation ontology proposed by Yang and Worboys (2011). Spatial models can be further distinguished into geometrical, topological (or sometimes addressed as symbolic-based), and hybrid models (Afyouni et al., 2012; Worboys, 2011).

Geometrical models represent indoor spaces using metric or coordinate-based representations (Afyouni et al., 2012). These models excel at providing accurate location, direction, and distance information (e.g., Park et al., 2020), making them suitable for positioning applications. In contrast, topological models focus on the connectivity and reachability between entities, representing the location of entities semantically while preserving topological relationships (Afyouni et al., 2012; Worboys, 2011). They are suitable for navigation and wayfinding applications (e.g., L. Liu et al., 2019), although they may not provide as much accuracy or detail as geometrical models.

Hybrid models combine geometrical and topological representations to take advantage of both strengths. They provide accurate location and distance information while representing complex relationships between entities, offering more flexibility and scalability than pure geometric models, while retaining some abstract benefits of symbolic models (Afyouni et al., 2012; Worboys, 2011). As a result, hybrid models are suitable for a wide range of applications, including positioning, navigation, and building management. Several approaches to constructing hybrid models have been proposed in the literature. For instance, Nagel (2014) proposed the multilayered space-event model (MLSEM), which combines different spatial models to represent indoor space with multiple layers and connections between them. Another example is the annotated hierarchical graph model (AH-graph), which represents indoor space as graphs at various abstract levels and includes annotations of the nodes and edges (Fernandez & Gonzalez, 2001).

While hybrid models offer a promising solution to indoor space modelling, some researchers argue that the foundational data structure to support navigation is the graph (Yang & Worboys, 2015; Zhou, 2022). The graph model provides a natural way to represent indoor space as a network of interconnected spaces and features, with nodes representing spaces and edges representing connections and travel paths between them (Yang & Worboys, 2015). To incorporate the geometry, topology, and basic semantics of indoor spaces, Yang and Worboys (2015) proposed a graph model that combines these aspects to create a comprehensive representation of indoor space specifically designed for navigation.

The graph model proposed by Yang and Worboys (2015) divides nodes into several types to capture different aspects of indoor space, including junction nodes, turning nodes, room nodes, portal nodes, landmark nodes, stairwell nodes, elevator nodes, terminal nodes, and midpath nodes. Junction nodes, created based on topological connectivity, represent the intersections of paths where decisions must be made. Turning nodes represent deviations in angles along a route, which are determined by geometry. Derived from semantics, room nodes represent enclosed spaces, while portal nodes represent connections between spaces. Landmark nodes represent notable features within an area. Stairwell and elevator nodes represent vertical connections between different levels of a building. The last two types of nodes are related to corridors, with terminal nodes representing physical dead ends and midpath nodes representing points along long corridors.

Edges are generated based on the types of nodes, connecting rooms to corridors through portal nodes and connecting nodes in complex spaces. Intra-level connections can be enabled in multi-level indoor spaces by connecting related stairwell and elevator nodes. Through this approach, the graph model provides a comprehensive representation of indoor space that combines geometrical, topological, and semantic information (Yang & Worboys, 2015). In a case study of a university building, they demonstrated the effectiveness of this navigation graph model, laying the foundation for incorporating further semantics, such as existing navigational aids, into navigation graphs.

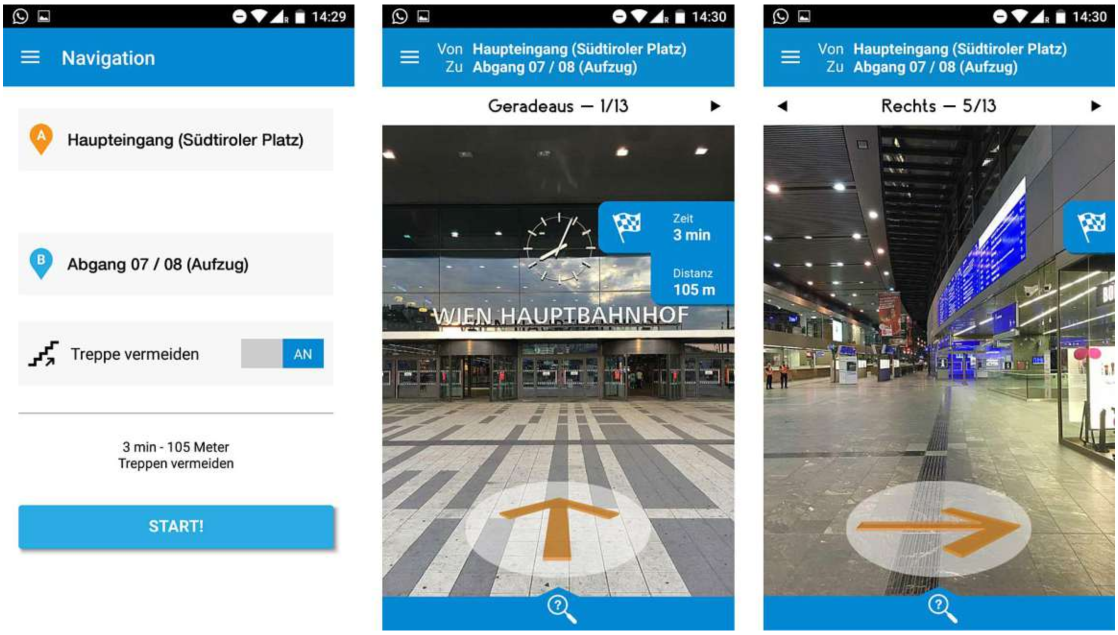
Building Information Modeling (BIM) is a rapidly emerging technology in architecture, engineering, and facility management that involves creating and managing information about a building throughout its lifecycle (Heaton et al., 2019; L. Liu et al., 2021). With the maturation of BIM technology, it has been widely adopted in the construction industry in recent years (Heaton et al., 2019). BIM data, such as the open BIM standard, the Industry Foundation Classes (IFC), contains detailed semantic information that can be used for indoor navigation (L. Liu et al., 2021). Although originally designed for construction and maintenance purposes, some semantic information, such as building signage systems, can be utilised to enrich navigation models. The potential adoption of BIM in new and existing buildings as they transition to smart buildings allows us to access such semantic information and integrate them into navigation graphs.

2.3.2 Indoor route planning

Outdoor routing algorithms have been extensively studied. Apart from the shortest path, various factors are also considered, such as the least turns (Jiang & Liu, 2011; Y. Zhou et al., 2014), multimodal options for transportation (Brands et al., 2014; L. Liu & Meng, 2009), and landmarks (Caduff & Timpf, 2005). Researchers have also paid attention to people's cognitive aspects, including feelings and emotions towards places (Huang et al., 2014) and spatial knowledge acquisition (Huang et al., 2021).

In contrast, indoor routing algorithms have been less diverse, often adapting well-established outdoor navigation algorithms for indoor use, such as Dijkstra's algorithm (Xu et al., 2015), the A* algorithm (Xiong et al., 2015), and the least risk algorithm (Vanclooster et al., 2013). However, the unique characteristics of indoor environments and distinct landmarks pose challenges requiring dedicated attention. The routing algorithms developed for indoor space are mainly in connection with data models, focusing on physical constraints. For instance, Karimi and Ghafourian (2010) proposed an algorithm considering the different requirements of people with physical, cognitive, or sensory impairments. They matched them with physical constraints in different indoor areas to calculate suitable routes. Y. Zhou et al. (2018) considered path complexity reflected by the number of turns, the crowded degree of a place, and blockages of certain areas in their algorithm. Other indoor routing criteria involve specific keywords for visiting certain shops along a route (Feng et al., 2020).

Similar to outdoor routing, landmarks are also considered indoors, although focusing primarily on path complexity. For instance, Viaene et al. (2018) proposed a landmark-based indoor routing algorithm formed by minimal actions linked to landmarks to reduce path complexity. However, promoting spatial learning and engagement with the environment remains untouched. A noticeable gap exists between the extensive research conducted on outdoor routing algorithms



Von Haupteingang (Südtiroler Platz)
Zu Abgang 07 / 08 (Aufzug)

Haupteingang (Südtiroler Platz)

Abgang 07 / 08 (Aufzug)

Treppe vermeiden: AN

3 min - 105 Meter
Treppen vermeiden

Geradeaus — 1/13

Zeit 3 min

Distanz 105 m

Rechts — 5/13

Figure 2.5 - An indoor navigation app using augmented reality (Kotrba, 2018).

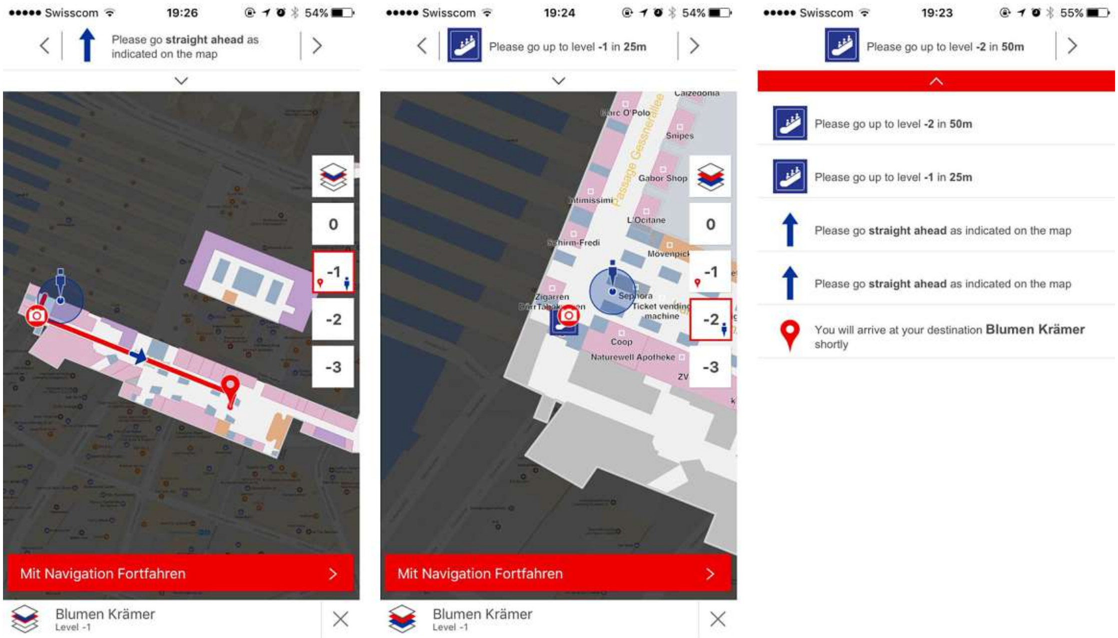
and the relatively limited exploration of their indoor counterparts. As highlighted by L. Liu et al. (2019), indoor routing heavily relies on the semantics and properties of indoor spaces. Bridging this gap by developing algorithms that account for the specific characteristics of indoor environments, including integrating existing navigational aids and their semantics, may contribute to prompting indoor spatial learning.

2.3.3 Indoor route communication

Indoor route communication, also known as route guidance, involves the indoor navigation system interacting with users to provide route-related information (Fallah et al., 2013). This interaction primarily occurs through three senses: vision, hearing, and touch.

The visual display is the most commonly used method of communication in indoor navigation systems (Fallah et al., 2013). User interfaces often utilise maps (e.g., Arikawa et al., 2007; Nossum, 2011), photos (Chang et al., 2008), 3D simulations (Lertlakkhanakul et al., 2009), augmented reality (AR) (L. Liu et al., 2021; Rehman & Cao, 2017) (Figure 2.5), and text to guide users (Figure 2.6). Each of these methods has its advantages and disadvantages. For example, photos and 3D simulations allow for the efficient transmission of a large amount of information, which can be particularly beneficial for individuals with cognitive disabilities as they can directly relate the screen visuals to their surroundings (Fallah et al., 2013). However, they require significant resources from the device, e.g., storage capacity and network connection. At the same time, interpreting such an amount of information requires cognitive resources, like attention and time, which suggests a high cognitive load (Ohm et al., 2015).

AR navigation systems overlay digital information onto the real-world view (Figure 2.5),



Please go **straight ahead** as indicated on the map

Please go up to level **-1** in **25m**

Please go up to level **-2** in **50m**

Please go up to level **-2** in **50m**

Please go up to level **-1** in **25m**

Please go **straight ahead** as indicated on the map

Please go **straight ahead** as indicated on the map

You will arrive at your destination **Blumen Krämer** shortly

Figure 2.6 - An indoor navigation app using floor plans and text (own screenshots).

providing real-time visual cues and directions, which enhances situational awareness and contextual information (L. Liu et al., 2021; Rehman & Cao, 2017). However, their effectiveness relies heavily on sensor accuracy, camera quality, and computational power, which may introduce inaccuracies or delays in providing directions. While AR is designed to improve situational awareness (Woodward & Ruiz, 2022), users may become overly focused on virtual elements, potentially compromising their awareness of the actual surroundings and raising safety concerns (Çöltekin et al., 2020).

As an alternative, simple text directions can be displayed, which is less resource-intensive but provides less detailed information, which may be less accurate (Fallah et al., 2013). They are seldom used alone but combined with other visual display types (Figure 2.6). To compare these guidance types, De Cock et al. (2019) conducted an online survey, mixed and matched these types to find out user preference. Their results suggested that combining textual route instructions with other forms were usually preferred by users.

Audio guidance offers another form of route instructions, typically delivered through recorded directions (Loomis et al., 1994) or speech synthesis (D'Atri et al., 2007; Hub et al., 2003). Compared to visual display, audio guidance is considered safer and less cognitively demanding, as it requires less attention and can be hands-free for users. It also benefits visually impaired individuals (Ahmetovic et al., 2016; Sato et al., 2017).

Both visual text display and audio guidance are derived from route instructions. The most common form is turn-by-turn instructions (De Cock et al., 2019). They include actions, directions, landmarks, and metric information, to guide navigators through two fundamental processes: reaching a decision point and deciding on the next move there (Klippel, 2003;

Richter & Klippel, 2005). Compared to metric-based turn-by-turn instructions, landmark-based ones are considered more intuitive and supportive for spatial learning outdoors (see Section 2.2.3). Drawing on the category-based method proposed by Duckham et al. (2010) to integrate outdoor landmarks into route instructions, Fellner et al. (2017) incorporated indoor-specific characteristics and proposed an approach for generating indoor landmark-based route instructions. This method involves initially establishing a set of criteria for selecting indoor landmarks. These landmarks are then integrated into route instructions by associating them with decision points related actions and directions.

Haptic-based navigation systems utilise touch and do not rely on vision or hearing. Therefore, it is especially suitable for people with vision or hearing difficulties. These systems, such as haptic gloves (Amemiya et al., 2004), vibrotactors on a waist belt (Heuten et al., 2008), or haptic feedback in a backpack (Ertan et al., 1998), provide navigation information through tactile feedback. Changes in vibration frequency or intensity indicate directions. However, haptic information is less intuitive than visual or audio cues, requiring user training and heightened concentration. Overall, indoor route communication encompasses various modalities, each with advantages and considerations regarding resource requirements, user preference, and accessibility for individuals with sensory impairments. As the bridge between visual and audio guidance, route instructions form the primary foundation for conveying route directions.

2.4 Summary

As an integral part of our daily life, navigation consists of two components: locomotion and wayfinding (D. R. Montello, 2005). When we locomote, we engage our senses (vision, hearing, touch, and vestibular and kinesthetic senses) to interact with the environment (Arthur & Passini, 1992; Ittelson, 1978; Klatzky et al., 1998). During this process, we pick up environmental information and gradually develop our internal spatial representations (J. J. Gibson, 2014; Ishikawa, 2020). Even though such internal spatial representations are not necessarily map-like (Downs & Stea, 1973; Ishikawa, 2020; Piaget, 1976), the term "cognitive maps", originated from Tolman (1948), is widely agreed upon by researchers.

Humans constantly acquire, store, and update spatial knowledge to build cognitive maps. Despite the dispute in the developmental framework of spatial knowledge (Downs & Stea, 1973; Ishikawa, 2020), namely Siegel and White (1975) classical stagelike framework and the continuous framework from D. R. Montello (2005), they agree on the content of cognitive maps: landmark, route, and survey knowledge. When exposed to a new environment, humans identify and memorise specific objects and scenes, which are visually, semantically (or cognitively), or structurally salient (Siegel & White, 1975). As such, they acquire landmark knowledge. As human-environment interaction continues, connections develop between landmarks and form route knowledge. Then, landmark and route knowledge progress from topological to metric and are coordinated into a general frame of reference. It results in a configurational representation, namely the survey knowledge (Siegel & White, 1975).

Wayfinding is the planning and continuous decision-making process in which people try to orient and navigate themselves in an environment (Golledge, 1999). During wayfinding, people make decisions by coordinating the knowledge in their heads (their cognitive maps) and the knowledge in the world (the environment and its external representations) (Ishikawa, 2020; Norman, 2013). The interaction between people and the environment is two folds. On the one hand, the environment affords human beings its configuration; on the other hand, human beings pick up spatial information subject to their previous experience and make navigation decisions accordingly (J. J. Gibson, 2014; Ishikawa, 2020).

In terms of environmental affordance, compared with the outdoors, the indoor environment is enclosed by physical constraints. The architectural features, e.g., gates, doors, corridors, and staircases, introduce regulated access and constrained traversal (Kray et al., 2013). In addition to the restricted physical access, the reduced visual access contributes to the difficulty of indoor wayfinding by only allowing reference to local landmarks (Giudice et al., 2010). Moreover, indoor spaces are mostly three-dimensional, which escalates their complexity and increases the cognitive demand for navigators.

Due to the physical and functional segregated structure (Richter, 2017), navigating complex indoor environments can be a dilemma. Therefore, external representations of the environment, such as existing navigational aids (signs and floor plans) and navigation services, are designed to offload cognition and ease indoor wayfinding. At the same time, existing navigational aids are semantic landmarks to support human spatial knowledge acquisition. Depending on the structure and intended functions of the space, the potential users, and the typical wayfinding scenarios, distinct types of signs and floor plans should be placed at critical locations in a building (D. Gibson, 2009). For example, orientation signs and floor plans are commonly located at significant circulation points (e.g., main entrances, lobbies, and stairwells), whereas directional signs are at every decision point.

On the human side, indoor wayfinding begins with developing a general decision plan (Passini, 1984b), where several strategies can be employed, such as central point, direction, and floor strategy (Hölscher et al., 2006). Unfamiliar users favour the central point strategy, relying on a known location in a building for orientation (Hölscher et al., 2006). The direction and floor strategy differs in whether people first plan their route towards the destination's horizontal or vertical locations (Hölscher et al., 2006).

As the journey continues, wayfinders arrive at decision points en voyage, where they must evaluate the information at hand and decide on the next move. At decision points, decision point complexity (M. O'Neill, 1991; M. J. O'Neill, 1991) and environmental features, as well as group and individual differences, can affect decision-making. Important environmental features include illumination (Bell et al., 2005; Hidayetoglu et al., 2012; Hughes et al., 2020; Taylor & Socov, 1974) and corridor width (Sun & de Vries, 2013; Vilar et al., 2012; Zhang & Park, 2021). In addition, several noticeable behaviour patterns are associated with the environment, such as a right-turn tendency (Bitgood, 2006; Taylor & Socov, 1974; Whyte, 1980; Zhang & Park, 2021) and the inertia to choose the straight path and the central corridor (Bitgood, 2006). On the social side, Influential group differences involve age (Davis et al., 2008; Lee & Kline, 2011), gender (Cherney et al., 2008; Choi et al., 2006; Merrill et al., 2016), cultural backgrounds (Hashim et al., 2014; Joy Lo et al., 2016), and familiarity

(Hölscher et al., 2006; Li & Klippel, 2014). Individual traits like spatial ability and preference also lead to different decision choices (Kuliga et al., 2019).

Previous research looked into indoor wayfinding strategies at the general planning level and the factors influencing decision-making. Yet, in order to comprehend the indoor wayfinding mechanism, a systematic overview of detailed decision-making and reasoning processes at decision points in different scenarios is to be established. To fill this gap in the current body of knowledge, a dedicated explorative wayfinding experiment was conducted, and a comprehensive categorisation of indoor wayfinding tactics will be presented in Chapter 3.

Spatial cognition is essential for wayfinding, spatial reasoning, and many other cognitive processes (Bellmund et al., 2018; Epstein et al., 2017; D. R. Montello & Raubal, 2013). People acquire spatial knowledge from direct experience and external representations of the environment (Ishikawa, 2020). As one type of external environmental representation, existing navigational aids, such as floor plans, supplement spatial learning by enhancing survey knowledge acquisition (Moeser, 1988; Thorndyke & Hayes-Roth, 1982). Conversely, another type of external environmental representation, navigation services, impairs spatial knowledge acquisition (Brügger et al., 2019; Burnett & Lee, 2005; Fenech et al., 2010; Gardony et al., 2013; Hejtmánek et al., 2018; Ishikawa et al., 2008; Münzer et al., 2006; Parush et al., 2007; Ruginski et al., 2019). Empirical studies offer two justifications for such detrimental effects: passive decision-making (Bakdash et al., 2008; Brügger et al., 2019; Parush et al., 2007) and a lack of environmental attention (Burnett & Lee, 2005; Fenech et al., 2010; Gardony et al., 2013; Gardony et al., 2015; Ruginski et al., 2019; Willis et al., 2009).

To compensate for the negative impact on spatial learning, researchers suggested activating users in wayfinding decision-making (Brügger et al., 2019; Thrash et al., 2019). Yet, such active engagement should be employed tentatively subject to the use context, e.g., free exploration or goal-directed navigation (Ishikawa, 2020). The other recommendation is to direct users' attention from the navigation services to relevant environmental features (Chrastil & Warren, 2012; Ishikawa, 2020). The best practice outdoors is to include landmarks in route instructions (Gramann et al., 2017; Wunderlich & Gramann, 2018, 2021), because they are prominent environmental features and frequently mentioned in human route descriptions (Denis, 1997). Despite the challenges indoors, research in mixed reality demonstrated the benefit of spatial learning by including semantic landmarks in navigation services (B. Liu et al., 2021). Owing to the limited accessibility and specificity of MR devices, a method for integrating semantic landmarks into indoor navigation services on conventional devices and its influence on spatial learning remains to be explored. As previously mentioned, existing navigational aids are semantic landmarks by their designed nature. Hence, integrating existing navigational aids into navigation services may meet the challenges of indoor wayfinding and spatial learning.

To integrate existing navigational aids into navigation services, we need to address two key considerations. First, we must identify suitable existing navigational aids that are meaningful and practical to integrate. Second, we need to determine the methodological approach for integrating them effectively. Addressing the former requires understanding how people utilise existing navigational aids and the features they rely on to describe indoor environments. The forthcoming explorative wayfinding experiment in Chapter 3 will bridge this knowledge gap.

Exploring the methodological approach involves modelling the suitable existing navigational aids and their semantics into the indoor spatial model. Indoor spatial models can be categorised into geometrical, topological, and hybrid models (Afyouni et al., 2012; Worboys, 2011), with hybrid models combining the advantages of both geometrical and topological representations. As the graph model is the foundational data structure to support navigation, Yang and Worboys (2015) proposed a navigation graph incorporating indoor spaces' geometry, topology, and basic semantics. The demonstrated effectiveness of this navigation graph model can serve as a basis for incorporating further semantics. With the emergence of Building Information Modeling (BIM) technology, data such as building signage systems can be readily accessible and utilised to enrich navigation models.

As another essential component of navigation systems, indoor routing often adapts well-established outdoor navigation algorithms, such as Dijkstra's algorithm (Xu et al., 2015), the A* algorithm (Xiong et al., 2015), and the least risk algorithm (Vanclooster et al., 2013). The routing algorithms developed for indoor space predominantly focus on physical constraints (Karimi & Ghafourian, 2010) and path complexity (Viaene et al., 2018; Y. Zhou et al., 2018). Compared with their outdoor counterpart, promoting spatial learning and engagement with the environment has largely been overlooked in indoor routing.

Route information can be communicated to users through visual, audio, and haptic means, each with its advantages and considerations regarding resource requirements, user preferences, and accessibility for individuals with sensory impairments (Fallah et al., 2013). Since these modalities utilise distinct senses, they can be combined to cater to different user groups. As the bridge between visual and audio guidance, route instructions form the primary foundation for conveying route directions.

In summary, the main research gaps identified are:

- A systematic overview of detailed decision-making and reasoning processes at decision points in different scenarios
- The factors influencing the selection and utilisation of existing navigational aids
- Potential approaches to promote spatial learning in indoor navigation systems operating on conventional devices
- A methodological framework for integrating semantic landmarks (geometry, topology, and semantics) into indoor spatial data model
- Indoor routing algorithm considering spatial learning

As mentioned previously, Chapter3 will comprehensively categorise indoor wayfinding tactics, derived from a wayfinding experiment with human participants, and dive into the selection and utilisation of existing navigational aids. Chapter 4 will focus on developing an indoor navigation system incorporating existing navigational aids and their semantics. Furthermore, Chapter 5 will evaluate this system with human participants, examining its impact on navigation performance, spatial learning, and overall user experience.

Chapter 3

Explorative indoor wayfinding study

3.1 Introduction

Wayfinding can be challenging in indoor environments, especially in large-scale public buildings such as museums, universities, hospitals, shopping malls and transportation hubs, due to the segregated nature of indoor spaces' physical, functional and social structure (Richter, 2017). Wayfinding difficulties may lead people to frustration, particularly when looking for a place within a limited time, which happens to be a situation in daily life.

Existing navigational aids and navigation services are designed and implemented to facilitate indoor wayfinding. Still, empirical studies revealed user confusion between existing navigational aids and mobile navigation services (Fian & Hauger, 2021; Wang et al., 2019) and an impairment in their spatial learning caused by navigation services (Dahmani & Bohbot, 2020; Ishikawa, 2018). In response, Willis et al. (2009) suggested that navigation services be user-centred and prompt spatial knowledge acquisition. In order to tailor such services to users' requirements, we need to understand the mechanisms of human indoor wayfinding.

Chapter 2 reviewed previous research on indoor wayfinding decision plans, general planning strategies, and their influencing factors. In spite of their importance, reminded early by Best (1970), the decision-making and reasoning processes at decision points failed to attract enough attention. Aiming to understand human indoor wayfinding comprehensively, we conducted an explorative indoor wayfinding study[1] aiming to address the first research question:

RQ 1 What factors influence navigators' decision-making at decision points, and how are the selection and utilisation of existing navigational aids affected?

Addressing this research question allows us to gain insights into indoor human wayfinding decision-making and its influencing factors, laying the theoretical foundation for this dissertation. In order to broaden the applicability of the theoretical findings, we conducted

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[1] This chapter contains parts from publication in connection with this dissertation (Wang et al., 2018).

experiments in two buildings with distinct structures and functions. Such experiment design further allows us to investigate the impact of building characteristics on indoor wayfinding behaviour, thereby enriching our understanding of this complex phenomenon.

We introduce the term indoor wayfinding tactic to represent the indoor wayfinding decision-making and reasoning process at a decision point. It is the process of carefully planning the following action during an indoor wayfinding task, performed at a decision point. Compared with an indoor wayfinding strategy, which is the overall planning of the whole wayfinding task (Hölscher et al., 2006), it is specific to the current decision point. Hence, we name it a "tactic" (Bates, 1979).

3.2 Methodology

This study is mainly designed to gain insights into how navigators make indoor wayfinding decisions at decision points and the relevance of existing indoor navigational aids. Due to its explorative nature, we conducted an exploratory study without experimental manipulation.

Three types of data were collected: behavioural observation to record participants' wayfinding behaviour, verbal protocols, and sketch maps. In previous indoor wayfinding studies, behavioural observation was the most direct way to collect behaviour data (Hölscher et al., 2006; Mandel, 2013; D. Montello & Sutton, 2012). Verbal protocols and sketch maps have since long been used to explore people's mental representation of space and obtain a deeper insight into the human cognitive process (Lynch, 1960; Passini, 1984b). In this study, we employed the think-aloud method (Ericsson & Simon, 1993) to encourage participants to verbalise their thoughts during the study, especially their decision-making process regarding what information they refer to at decision points. In addition to the reasoning at decision points, the verbal protocols include route descriptions for each target and the end interview.

3.2.1 Study setup

3.2.1.1 Selection of buildings and wayfinding targets

In this study, we selected two buildings as our venues: the Albertina and the main building of the Vienna University of Technology (TU). The buildings differ in floor plan configuration complexity, function and signage system used. Built in the 18th century, the Albertina was originally a palace in the neoclassical style. It has been renovated and transferred into a modern museum. The signage system is well designed (Figure 3.1A), with floor plans mounted on the walls (Figure 3.1B) and printed ones freely available at the ticket office.

In the Albertina, the three targets were "The entrance of the exhibition Contemporary Art ", "Room 8 of the exhibition Monet bis Picasso", and "The toilet close to the exhibition Wege des Pointillismus". Their locations are marked in Figure 3.2. We chose these targets because they were typical wayfinding destinations in Albertina. For the second target, we chose a specific room in an exhibition to determine whether a pre-defined order would affect people's wayfinding strategies. In this case, once arriving at Level 2, the participants following the order would have to take a longer route to Room 8.

Figure 3.1 - Signs and floor plans. (A) A sign in the Albertina. (B) A wall-mounted floor plan in the Albertina. (C) The ground floor configuration of the main building of Vienna University of Technology. (D) The signs with different styles at a staircase in the TU.

The main building of the Vienna University of Technology was built in the 19th century. Later, several separate buildings nearby were joined by staircases into a whole complex (Figure 3.1C). Due to its configuration, different sections in this building differ in floor heights and signage systems. The staircases are numbered and utilised as the major wayfinding guidance by local students. Students report getting lost easily inside the building owing to its complexity, a lack of floor plans, and multiple and inconsistent signage systems (Figure 3.1D).

In the TU, our choices of targets were limited, as there were many locked doors and dead ends. In addition, only lecture rooms, ceremony halls, and departments appeared on the signs. Potential choices were restricted to locations that could be publicly reachable and directed by signs. In the end, we chose a ceremony hall “Festsaal”, and two lecture rooms “Hörsaal 15” and “Hörsaal 17”. Their locations are marked in Figure 3.3.

3.2.1.2 Participants

28 participants (16 female, 12 male, age: M = 29, SD = 6.77) were recruited through our website, social media and flyers posted on other universities’ campuses. They hold different professions, such as mathematicians, English teachers, musicians, painters, etc. All participants confirmed to have no visiting experience to either building. They were all fluent in English and at least understood basic German. All participants read and agreed with the informed consent before participating in the experiment. Each participant received a free entry to the Albertina and a small gift.

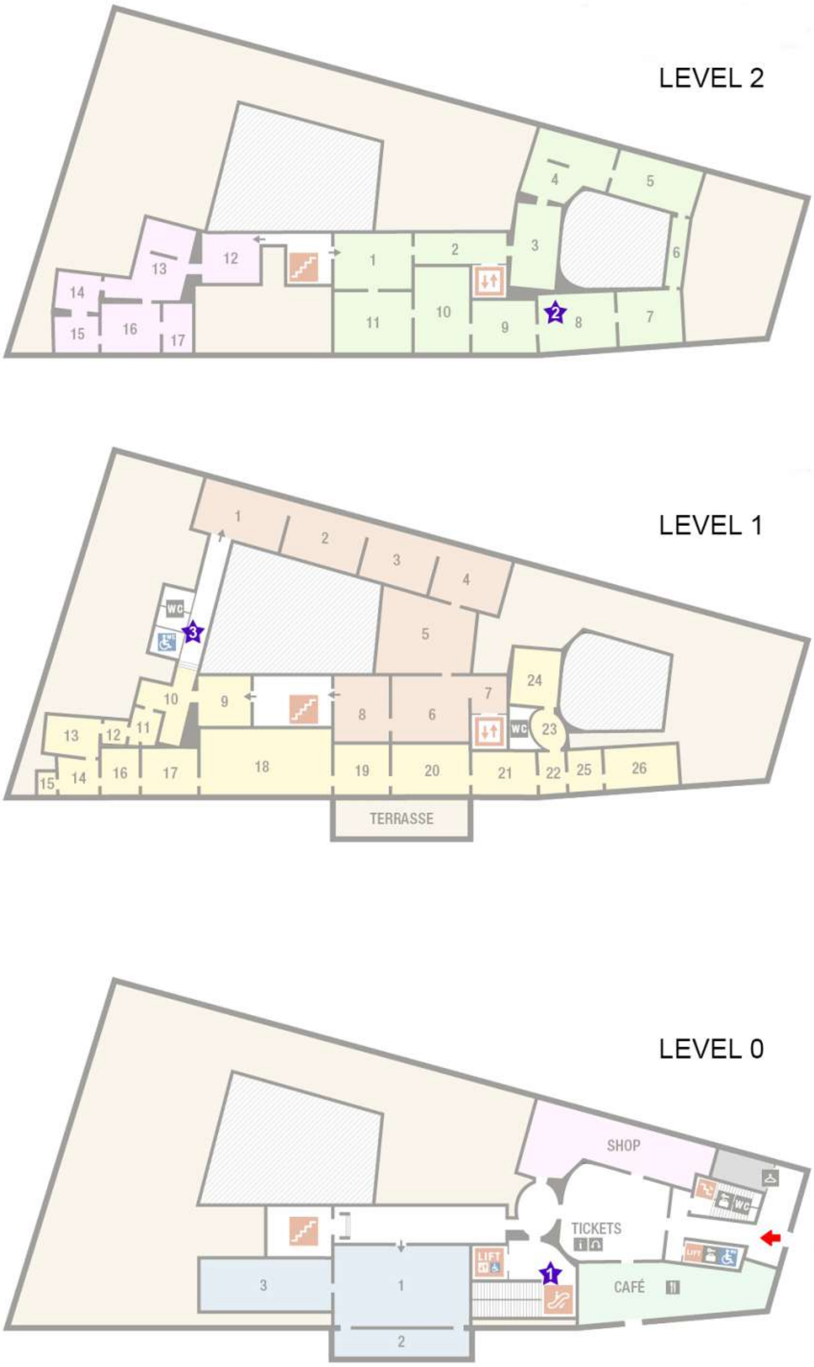

Figure 3.2 - The starting point and targets' locations in the Albertina. The starting point is marked with a red arrow. Targets are marked as purple stars with the corresponding target number. (This illustration is created from the official floor plan at www.albertina.at)

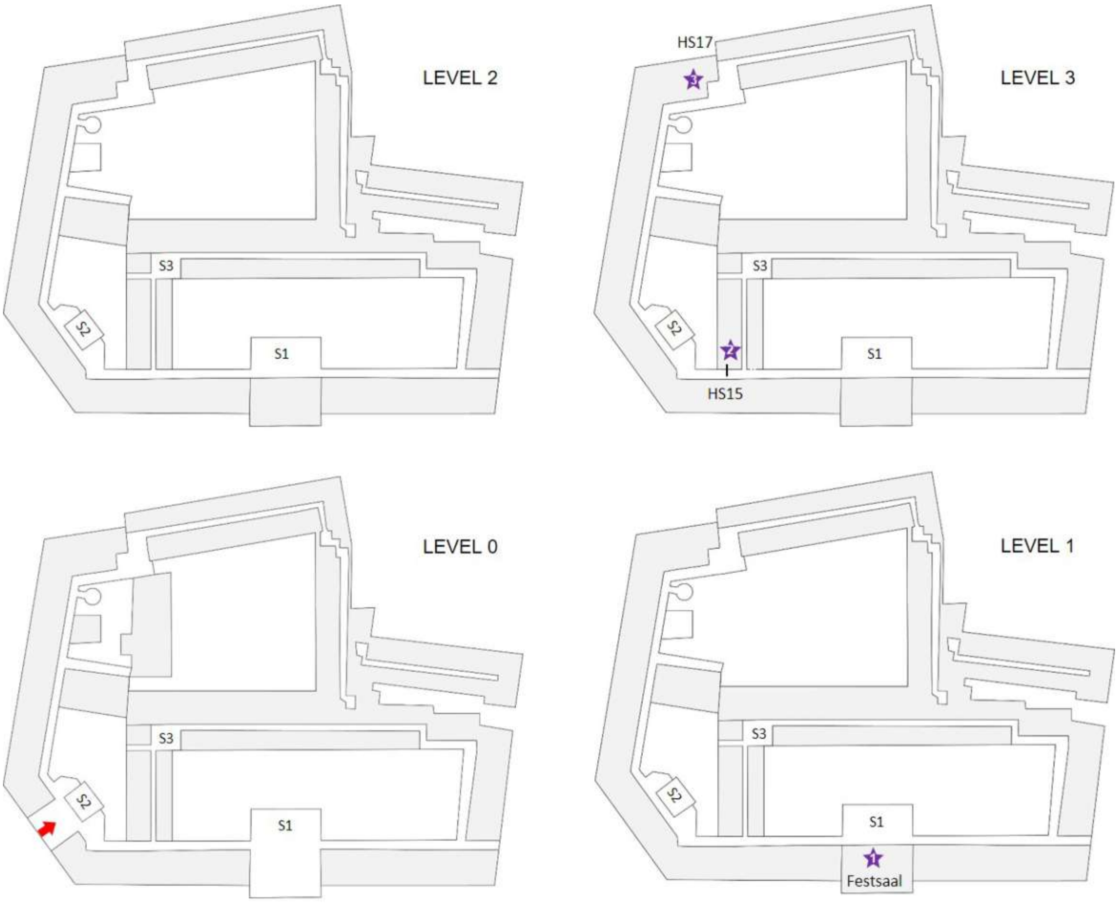

Figure 3.3 - The starting point and targets' locations in the TU. The floor plan of the TU is simplified, with only relevant room and staircase information. "S1", "S2", and "S3" stand for "Staircase 1", "Staircase 2", and "Staircase 3", respectively. "HS15" and "HS17" are short for "Hörsaal 15" and "Hörsaal 17", respectively. The starting point is marked with a red arrow. Targets are marked as purple stars with the corresponding target number.

3.2.1.3 Procedure

An experimenter met a participant in front of one of the buildings. After a short opening conversation, the participant signed the informed consent form. Then they were led to the starting point within the building. The experimenter provided an introduction, informing the participant to locate three targets in each building. The participant was then given the first target and asked to describe their strategy for reaching it. They were also instructed to stop at every decision point along the way to the target, and to describe their wayfinding options, hints revealing the destinations of these options, to make their decision, and to justify it (Figure 3.4B).

Once the participant reached the first target, they were asked to describe the route from the starting point to the first target as if they were giving directions to someone unfamiliar with

Figure 3.4 - Study setup. (A) Targets shown to the participants. (B) A participant was justifying her decision with a sign at a decision point in the TU.

the building. Additionally, they were requested to draw a sketch map. Subsequently, the next target was presented, and the process was repeated, with each target serving as the starting location for the subsequent task. The wayfinding process continued until all the targets had been located. Following the completion of the tasks, the participants were interviewed to gather their general impressions of the existing wayfinding aids in both buildings.

Throughout the wayfinding process, the participant was encouraged to think aloud and utilise any available information to aid wayfinding, except for directly asking the experimenter for correct directions. The experimenter followed the participant and recorded the entire process using a head-mounted GoPro Hero 4 Silver and a voice recorder.

Half of the participants started from the Albertina and the other half from the TU to avoid learning effects. All participants received the targets printed on cardboard in the same order (Figure 3.4A).

After the experiment, each participant was contacted individually by e-mail to fill out an online questionnaire on the Santa Barbara Sense-of-Direction Scale (SBSOD) (Hegarty et al., 2002). Such practice reduced the questionnaire's influence on the experiment (Hölscher et al., 2006).

3.2.2 Data processing and analysis

The videos and the audios were synchronised and merged using a video editor[2]. Afterwards, the merged videos were transcribed into verbal protocols. Both the behaviour observation recorded by the videos and the verbal protocols were analysed qualitatively.

We draw the walked routes onto floor plans based on the recorded behaviour observation. They were used to identify crucial decision points and to reference the verbal protocols when interpreting indoor wayfinding behaviour.

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[2] http://www.videosoftdev.com/

To analyse the verbal protocols effectively, it was necessary to segment them into various units before classification (Ericsson & Simon, 1993; D. Montello & Sutton, 2012). We first segmented the described strategies and the route descriptions at the beginning and the end of each task, respectively, as well as the end interviews. Subsequently, we closely examined the verbal protocols recorded during the wayfinding process of each task. Our focus was on analysing the decision justifications provided by the participants to better understand the indoor wayfinding tactics. Consequently, we specifically coded the verbal justifications expressed at decision points, while considering the thoughts expressed during the journey as supplementary information to enhance our comprehension.

We applied the structuring method of qualitative content analysis to code the verbal protocols expressed at decision points and classify them into wayfinding tactics. This content analysis method starts with a defined category or coding scheme from existing theory and keeps revising these categories while coding (Mayring, 2014). To establish our initial category system for wayfinding decision-making tactics, we adopted Passini (1984b) theory (see Section 2.1.2.1).

To ensure reliability, two independent researchers initially coded and categorised the verbal protocols of ten randomly selected participants iteratively. Beginning with the initial coding scheme, the researchers applied the codes and assigned categories to the verbal protocols. When they encountered statements that could not be categorised into the existing ones, they proposed new categories independently. Then they discussed and refined them until both researchers mutually recognised the categories. This iterative process continued until inter-rater reliability with a kappa value of 0.8 was reached (Landis & Koch, 1977). The primary researcher then coded and categorised the remaining participants' verbal protocols based on the refined coding scheme. The second researcher assisted in the categorisation process in cases where ambiguity arose.

For the wayfinding strategies, Hölscher et al. (2006) categorised them both objectively (matching the taken routes to pre-defined alternative routes, which corresponds to specific strategies) and subjectively (described by the participants) and found a significant correlation between the two analysis methods. In their study, both familiar and unfamiliar participants were recruited. However, we only recruited unfamiliar participants who had no prior knowledge of the building. On the one hand, most of them described their strategy as "look around and find something", which did not align with any specific strategy. On the other hand, once they found relevant information, their routes exhibited the pattern of certain strategies. For these reasons, we decided to combine the subjectively mentioned strategies and the objectively exhibited patterns for our coding and categorisation. The coding and categorising procedure was similar to that employed for the tactics, except that we did not refine the categories from Hölscher et al. (2006) (see Section 2.1.2.1).

3.3 Categorisation of indoor wayfinding tactics

Prior to categorising indoor wayfinding tactics, we distinguish two scenarios at a decision point encountered by a wayfinder: Scenario_Aided, when relevant wayfinding support information is explicitly accessible and perceived, and Scenario_Unaided when no relevant wayfinding support information is perceived.

We summarise the categorisation of indoor wayfinding tactics as follows.

1. Tactics used when relevant wayfinding support information is explicitly accessible and perceived (Scenario_Aided):
    - Sign: Wayfinders decide based on identification signs, directional signs, and floor directories without a graphical floor plan, e.g., "There is a sign straight ahead for HS 17, so I'll follow that."
    - Floor plan: Wayfinders decide based on floor plans, e.g., "That will be on level 2 according to this plan."
    - External help: Wayfinders decide based on external help from other people or electronic devices, e.g., "He said that I need to go this way to find the 4th."
2. Tactics used when no relevant wayfinding support information is perceived (Scenario_Unaided):
    - Memory: Wayfinders decide based on certain information they memorised about the setting or similar settings, e.g., "Now I'm going out of the bridge. And with my memory then I should go right."
    - Inference: Wayfinders decide based on their mental manipulation and reasoning without relevant information, e.g., "I'm going to decide to go up another floor because 14 and 15 are on this floor and a higher number should be on the floor above."
    - Searching: Wayfinders decide because they wish to find signs, floor plans, someone to ask or any relevant information on the option they choose, e.g., "I'm going to come down to see if there is some signage out here."
    - Preference
        - Architectural feature preference: Wayfinders decide based on corridor width, room size, brightness, colour, and their preferred direction, e.g., "I took this side because I think this room is bigger. That attracts me to go inside."
        - Non-spatial related preference: Wayfinders decide based on cultural and personal preferences, e.g., "Don't want to go through this crowd."
    - Random: Wayfinders decide randomly, without specifying any reasons, e.g., "This is just a sort of random decision to get my bearings."

Starting from Passini's distinction of the scenarios or "situations" (Passini, 1984b, p. 70), where he distinguished them depending on whether relevant information was available, we also distinguish these two scenarios. Departing from his theory, which categorised the use of wayfinder's memory and inference into the situation that the relevant information was available, we see them differently. Memory, defined by the American Psychological Association (n.d.) as "the ability to retain information or a representation of past experience, based on the mental processes of learning or encoding, retention across some interval of time, and retrieval or reactivation of the memory", is the knowledge in the head and therefore highly individualised. A scenario one considers as having relevant information in memory, such as when one is familiar with the building, can be seen as not having any information for another unfamiliar with the building. To avoid ambiguity, we differentiate these scenarios based on whether relevant wayfinding information is explicitly available in the environment. That is, in such a scenario, the environment offers "the knowledge in the world", as coined by Norman (2013, p. 75). Conversely, in the other scenario, one can only refer to the knowledge in the head. To recognise the possibility that relevant wayfinding information is available but navigators may overlook it, we define Scenario_Aided as the scenario, in which relevant wayfinding support information is explicitly accessible and perceived. Whereas in the scenario that they are not perceived, that is Scenario_Unaided, one can only rely on the knowledge in the head. We acknowledge that perception is also highly individualised and strongly associated with one's previous experience, creating ambiguity. Nonetheless, we argue that there are means to improve the affordance of the environment or wayfinding aids, or to signify them, so that they can be perceived easier. This will be discussed together with our study findings in Section 3.5.

In Scenario_Aided, we distinguish the tactics into the sign, floor plan, and external help tactic, based on the wayfinding information people rely on. The main distinction between the sign and the floor plan tactic is that the latter offers a configurational representation of the indoor space, as discussed in Section 2.1.1.1. Besides the existing navigational aids, navigators can seek help from other people (e.g., museum staff, porters, and passers-by in our study) or electronic devices (e.g., mobile navigation systems).

In Scenario_Unaided, relevant wayfinding information is not perceived by the wayfinders. They rely on the knowledge in the head. Compared with the tactics in the aided scenario, those unaided are less accurate. We distinguish them into memory, inference, searching, architectural feature preference, non-spatial related preference, and random tactics. Although we diverge from Passini (1984b) theory on categorising the memory and inference tactics into the aided scenario, we agree with and adopt his definitions. Wayfinders use a memory tactic when they cannot find confirmation in the environment yet remember the setting. When the memory information is insufficient for the decision, they consciously reason based on their knowledge of the building and their memory. In the example above, the participant reasoned, based on the current room number and their previous knowledge that a bigger numbered room should be on a higher level. When neither memory nor inference is satisfactory for decision, wayfinders use the searching tactic to find relevant information that could support decision-making. This searching tactic is systematic, meaning the wayfinder has a plan of what they want to search for and how to search for it.

The preference and random tactics are at the more intuitive end of all tactics. Both the architectural feature preference and non-spatial related preference are inclinations without justification. Worth mentioning is the difference between the preference tactic and the inference tactic. Taking architectural features as an example, if a participant chooses a bigger room and justifies that they think the target is a bigger room based on its name, this is inference. While in our example, the participant chose a bigger room because it attracted them. We considered this out of intuition rather than reasoning, so it was categorised as preference. The random tactic is used when wayfinders decide randomly.

3.4 Results

We qualitatively analysed the behaviour observation, verbal protocols and sketch maps. The tactics and strategies were then quantified and compared. Our primary focus was on understanding the participants' reasoning processes rather than establishing a direct relationship between the tactics employed and their navigation performance. Therefore, we did not measure their performance. This is also because we encouraged participants to stop at decision points to justify their decisions and think aloud along the way. The duration of their navigation process cannot be solely attributed to their efficiency in finding the target. Factors such as the time taken to thoroughly explain their thought processes during the think-aloud may have also contributed to longer durations.

3.4.1 Sense of direction

The SBSOD was a self-reported measure to assess participants' ability to acquire spatial knowledge (Hegarty et al., 2002). It consists of 15 questions, with half of them phrased positively. The score ranges from 1 (strongly agree) to 7 (strongly disagree). We reversed participants' responses so that a higher score represented a better sense of direction. Of the 28 participants we contacted, 23 completed the online questionnaire. Their average score is 4.388 (SD = 1.151), which indicates a balanced group. Compared with participants from other studies (Huang et al., 2021), our participants reported having a similar spatial ability.

3.4.2 Indoor wayfinding tactics in the Albertina and the TU

We coded and categorised the verbal protocols expressed at decision points into the proposed indoor wayfinding tactics. The frequency and proportion of tactics used in the Albertina and the TU are shown in Table 3.1. In both buildings, referring to signs was the most frequently used tactic, despite the inadequate signage system in the TU. A comparison of the two scenarios reveals that 61% of the decisions in the Albertina were made with wayfinding support information. In contrast, this proportion decreased to 54% in the TU due to the limited availability of existing navigational aids.

Considering the aided scenario, in the Albertina, although both wall-mounted and paper-printed floor plans were available, the sign tactic (64%) usage was more than twice as much as the floor plan tactic (29%). This is probably due to a higher cognitive load associated with using floor plans than signs. Since the TU did not offer floor plans to its visitors, no floor plan tactic was employed there. As the sole information source other than asking other

Table 3.1 - Indoor wayfinding tactics and their frequency and proportion in the Albertina and the TU

Scenarios	Indoor wayfinding tactics	Frequency (n)		Proportion (%)	
		Albertina	TU	Albertina	TU
Scenario Aided	Sign	122	186	39	47
	Floor plan	55	0	18	0
	External help	13	26	4	7
	Sum of Scenario_Aided	190	212	61	53
Scenario Unaided	Memory	19	57	6	14
	Inference	79	84	25	21
	Searching	12	37	4	9
	Architectural feature preference	3	3	1	1
	Non-spatial related preference	4	1	1	0
	Random	3	6	1	2
	Sum of Scenario_Unaided	120	188	39	47

people, the sign tactic dominated at the TU with a percentage of 88%. The tactic of seeking external help was not popular in either building.

In the unaided scenario, participants used the inference and the memory tactics more regularly in both buildings. It is not surprising, as these tactics are more reliable than those relying on intuition. However, the distribution of these two tactics exhibited different patterns between the buildings. In the Albertina, the ratio of inference to memory (4.158) was high because the building structure was simple and easy to infer. Whereas in the TU, the ratio of inference to memory (1.474) was considerably lower. This disparity can be attributed to the complexity of the TU, as explained by the behaviour observation. Using the inference tactic there sometimes led participants in the wrong direction. They then backtracked, where the memory tactics were used.

3.4.3 The choice of indoor wayfinding tactics among tasks

Not only do the building architecture and the existing navigational aids affect the choice of tactics, but also the tasks. Distinct targets evoke distinct senses of the corresponding tasks, thus affecting the selection of tactics.

In the Albertina (Table 3.2), the ratio of using signs to floor plans varies substantially among tasks. In Task 1, participants were required to find the entrance of an exhibition. There was no wall-mounted floor plan before finishing this task. Participants, therefore, applied the sign tactic extensively. While the targets became more specific and wall-mounted floor plans started to appear from Task 2 on, the ratio of using signs to floor plans decreased.

There were two decision points with signs and floor plans, which the participants could pass during both Task 2 and Task 3. By comparing the decision points in both situations, we

Table 3.2 - Indoor wayfinding tactics and their frequency and proportion among tasks in the Albertina

Indoor wayfinding tactics	Frequency (n)			Proportion (%)		
	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3
Sign	39	46	37	52	40	31
Floor plan	4	21	30	5	18	25
External help	8	1	4	11	1	3
Sum of Scenario_Aided	51	68	71	68	60	59
Memory	0	8	11	0	7	9
Inference	21	33	25	28	29	21
Searching	3	3	6	4	3	5
Architectural feature preference	0	1	2	0	1	2
Non-spatial related preference	0	1	3	0	1	2
Random	0	0	3	0	0	2
Sum of Scenario_Unaided	24	46	50	32	40	41

Figure 3.5 - The floor plan of the Albertina at Level 2. The green area is the exhibition Monet bis Picasso. Target 2 is marked with a purple star. A wall-mounted floor plan and a sign are located at the landing of Level 2 and marked with a red dot.

discovered that participants employed more floor plan tactics only at the landing of Level 2 during Task 3. In that situation (Figure 3.5), participants just left the exhibition Monet bis Picasso on Level 2 (Figure 3.5, green area) and were to find the toilet close to the exhibition Wege des Pointillismus on Level 1. Since the description of the Target 3 contained spatial relations, the participants preferred floor plans to signs to get an overview of the spatial structure. Once they acquired the spatial information, they would tend to refer to signs for immediate directions at later decision points.

Table 3.3 - Indoor wayfinding tactics and their frequency and proportion among tasks in the TU

Indoor wayfinding tactics	Frequency (n)			Proportion (%)		
	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3
Sign	56	95	35	77	50	26
Floor plan	0	0	0	0	0	0
External help	0	14	12	0	7	9
Sum of Scenario_Aided	56	109	47	77	57	35
Memory	0	27	30	0	14	22
Inference	17	28	39	23	15	29
Searching	0	24	13	3	13	10
Architectural feature preference	0	1	2	0	1	1
Non-spatial related preference	0	0	1	0	0	1
Random	0	2	4	0	1	3
Sum of Scenario_Unaided	17	82	89	23	43	65

In the TU, the tasks greatly influenced the tactics used in different scenarios (Table 3.3). The use of tactics in the aided scenario dropped considerably from Task 1 to Task 3 due to the insufficient existing navigational aids in the building. There was a higher proportion of relying on memory in the TU than in the Albertina because participants returned to a familiar location more often in the TU. This is due to a lack of overview from the floor plans and directory signs. Participants had to return to the starting point where a directory sign was available.

Target 3 (Hörsaal 17) was spatially close to Target 2 (Hörsaal 15), but there was no direct sign from Target 2 to Target 3. Because of the numbering, many participants inferred that Target 3 should be higher. However, in reality, they were at the same level. This led some participants to detours to many dead ends and locked doors. They got lost during Task 3, contributing to the high proportion of using memory, inference, searching, and random tactics.

3.4.4 The choice of indoor wayfinding tactics at crucial decision points

The crucial decision points identified in the Albertina are those installed with floor plans and signs. The task at hand influenced participants' preferences at those decision points, as discussed in Section 3.4.3. In the TU, we compared the routes participants took with the pre-defined shortest path and identified two crucial decision points, where many participants diverged from the shortest path.

The first crucial decision point was immediately after Target 1 at Staircase 1 (see Figure 3.3). Going upstairs to the third floor was the shortest, but only one participant took this way using the searching tactic. This resulted from a lack of signs directing to Target 2 at that position. 14 participants (50%) went down to the ground floor, because they expected a general directory sign, similar to the one at the starting point, to be at every staircase. However, no directory sign was on the ground floor at Staircase 1. The remaining 13 participants (46%) followed their memory back to the starting point, because they wanted to find information on the directory sign there.

The second crucial decision point was an intersection between the primary and side corridors on the third floor, marked as a red dot in Figure 3.6. Participants could encounter this intersection in two situations.

In the first situation, during Task 2, 20 participants arrived on the third floor either from Staircase 1 or Staircase 2. In front of both staircases, signs directed to Target 2, providing additional information about the corridor it was located in, labelled as "Hörsaal 14, 14A, 15 (Durchg. Stg. 3)" (see Figure 3.6). However, at this crucial intersection (red dot in Figure 3.6), there was a sign pointing towards Staircase 3, but it did not provide any information regarding the lecture rooms. To find Target 2, participants would have to turn to the side corridor. Out of the 20 participants, 12 participants (60%) continued straight on the main corridor when they first encountered this decision point. Remarkably, eight of them failed to recognise this as a decision point and overlooked the presence of the side corridor. Video footage at a similar intersection on Level 1 revealed the same pattern. It showed that participants tend to continue straight and ignore side corridors. As for the remaining four participants, they justified their choice by stating that they would only change their direction if directed by a sign. Otherwise, they would prefer to continue straight on the main corridor. Videos showed that the sign at the intersection was grey and placed high above in a dimly lit corridor, leading to participants overlooking it due to the design, placement, and lack of contrast with the surrounding environment.

The second situation was during Task 3. 18 participants left Target 2 and reached the main corridor again. Turning to Staircase 2 would lead them to the next helpful sign and then to Target 3. Ten participants (56%) turned to Staircase 2 using the memory tactic. Using the same tactic, one participant turned to Staircase 1. Three participants (17%) took a wrong turn to Staircase 1, because that side had brighter lighting and looked newer, which seemed to be positive environmental cues.

3.4.5 Observed indoor wayfinding strategies

3.4.5.1 Strategies for multiple levels

We coded and categorised indoor wayfinding strategies by combining participants' mentioned strategies from the verbal protocols and their exhibited route patterns. During the first task in both buildings, participants did not have a specific plan and primarily relied on searching for information. To engage participants in the wayfinding process, we designed the study so that the relevant information for Target 1 was accessible at the starting point. All participants found and followed navigational aids in both buildings. In the Albertina, Target 1 was at the same level as the starting point, so we could not identify a precise strategy either from verbal protocols or the route patterns. In the TU, all participants referred to a sign that showed Target 1 was on Level 1, resulting in their unanimous decision to proceed to Level 1. Although the route patterns suggested using a floor strategy, the verbal protocols did

Figure 3.6 - The floor plan of the TU at Level 3. The crucial decision point is marked with a red dot. Target 2 and Target 3 are indicated with numbered purple stars. The signs with information about Hörsaal 15 are linked to their locations.

not reveal anything alike. Consequently, we excluded the first tasks in both buildings and compared the remaining ones in Figure 3.7.

In our study, the choice of wayfinding strategies appeared to be building relevance rather than an individual trait. Only two participants continued the same strategy throughout the four tasks in Figure 3.7, one each for the central point and floor strategies.

Wayfinding strategies exhibited similar patterns among tasks in the same building. Between buildings, it is influenced by the building structure and the availability of wayfinding aids. The Albertina has a simple layout with only one central staircase and an elevator to change between levels. Floor plans and signs were available at each level beside the staircase and in the elevator. The structure suggested that the floor strategy was more practical than the direction strategy. The availability of navigational aids allowed the participants to plan for the tasks based on the offered overview. Consequently, the floor strategy was applied most frequently and followed by the central point strategy when participants decided to return to the staircase or the elevator for navigational aids. Participants rarely used the direction strategy.

Compared with the Albertina, the TU was considerably more complex in structure and offered significantly sparser wayfinding information. After warming up with Task 1, many participants initially walked around to look for information for the second target. Unsuccessful try-outs suggested they return to the directory sign at the starting point, which resulted in many using the central point strategy. This strategy is further fortified after successfully reaching Target 2. 13 out of 16 participants stuck to this strategy for Task 3. One of the three participants who changed to the direction strategy asked a passer-by and followed his guidance. The other two had already walked passed Target 3 while searching for Target 2, so they returned in that direction. Four more participants switched to the central point strategy for Task 3

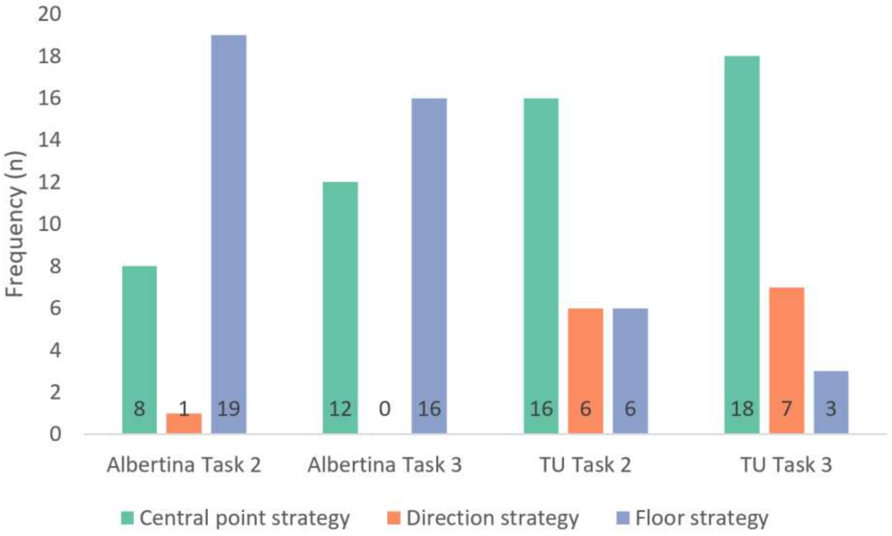


Figure 3.7 - The frequency of indoor wayfinding strategies used for Task 2 and Task 3 in the Albertina and the TU.

after spending much time searching for information for Task 2.

The lack of navigational aids in the TU favours the central point strategy, yet its organisation prefers the direction strategy to the floor strategy. As mentioned in Section 3.2.1.1, this building complex was connected by staircases. The staircases were numbered, and the staff, especially the porters, used the numbers to refer to each building section. The porters advised nine cases among the thirteen total use of the direction strategy. They provided both the staircase information (direction) and the level (floor), but they all suggested going to the staircases first. As first-time visitors, most people followed their advice.

The participants employed the floor strategy had different reasons. Numbering contributed the most. For instance, one participant explained her strategy to find Hörsaal 15 (Target 2): "The number 15 makes me think it will be on the first floor". All three participants chose the floor strategy for the Hörsaal 17 (Target 3) inferred similarly, e.g., "I guess it's maybe upstairs, because here is 15 and 14, so maybe 17 is upstairs". The remaining participants received external help either from the porters or from a passer-by, and they decided to go to the relevant floor before the staircase.

3.4.5.2 Strategies within one level

When relevant wayfinding information is available, and several options are all possible, people start to calculate and choose the "best" way according to their criteria. We decided "Room 8 of the exhibition Monet bis Picasso" as the second target in the Albertina to determine whether a pre-defined order would affect people's wayfinding strategies. In this case, once

Table 3.4 - Frequency of landmarks given by participants in verbal or visual forms in the Albertina and the TU

Landmark Category	Frequency (n) in the Albertina		Frequency (n) in the TU	
	Verbal description	Sketch map	Verbal description	Sketch map
Sign	38	18	65	54
Elevator	33	33	33	25
Stairs	33	29	59	69
Door	32	32	49	34
Building entrance/exit	22	31	8	12
Ticket check	17	7	NA	NA
Ticket office	9	11	NA	NA
Floor plan	6	2	NA	NA
Escalator	5	5	NA	NA
Entrance/exit of an exhibition	5	8	NA	NA
Statue	4	1	NA	NA
Cafe	3	8	2	0
Museum shop	3	7	NA	NA
Toilet	1	2	0	1
Courtyard	0	4	3	1
Lecture room	NA	NA	6	5
Building bridge	NA	NA	3	0
Pillars	NA	NA	0	4
Information point	NA	NA	0	1
Window	NA	NA	0	1

arriving at Level 2, the participants following the order would have to take a longer route to Room 8 (Figure 3.5).

Half the participants explained that they chose to follow the pre-defined order because it was “intuitive” or “don’t want to walk against the stream of people”. Eight participants (29%) took the shorter path. Two participants (7%) chose the path with fewer turns, and the remaining four (14%) did not specify their reasons.

To leave the exhibition, 14 participants (50%) retraced their way of entering, while the other half went further through the exhibition. The former ones reasoned such as “already know the way”. The latter ones justified like “to explore the exhibition”, “go further to look for signs”, and “don’t want to go against the current of people”.

3.4.6 Landmarks in verbal descriptions and on sketch maps

We summarised in Table 3.4 the number of each kind of landmark in the verbal route descriptions and on the sketch maps. Specific landmarks are unavailable in one of the buildings and were marked as "NA" (not applicable) in the table.

Both buildings shared common landmarks such as signs, stairs, elevators, doors, building entrance/exit, and a cafe. These landmarks appeared with similar frequency in both buildings. Additionally, in the Albertina, participants frequently mentioned landmarks related to tickets.

In general, semantic landmarks (e.g., sign and floor plan) and functional landmarks (e.g., stairs, elevator, door, and building entrance/exit) are presented most frequently in both forms. The sign was the most frequently mentioned landmark in the verbal description in both buildings, while the elevator stood out as the most depicted landmark in the Albertina, and the stairs took precedence in the TU.

3.4.7 Sketch map styles

As identified by Appleyard (1970), sketch maps can be "sequentially dominant" and thus route-like, or "spatially dominant" as survey-like. We analysed participants' sketch map styles in terms of their "route-likeness" and "survey-likeness", based on the criteria proposed by Krukar et al. (2018). Each sketch map received scores for route-likeness and survey-likeness, respectively (3.8). We then normalised the scores to reach an overall rate. As we were interested in whether using more sign tactics or floor plan tactics would be related to the style of the sketch maps, we normalised the rate of using the sign tactic to using the floor plan tactic in the same manner. However, no significant relationship between the choice of tactics and sketch map styles was disclosed, $r = .135$, $p = .387$.

3.4.8 End interview

The general remarks in the end concentrated on two topics: the building structure and the existing navigational aids. Regarding the building structure, most participants agreed that the Albertina has a simple structure, with only two participants saying it was confusing. In the TU, eight participants reported it being confusing, especially the seemingly different parts of the building.

With respect to the existing navigational aids, 17 participants praised them in the Albertina, while three gave negative comments. Some participants suggested potential improvements, e.g., "more signs for toilet", "more signs needed in empty rooms". Conversely, three participants thought the signs were sufficient in the TU, while 18 criticised its overall wayfinding system. They recommended having floor plans at every entrance and floor level (n = 11) and providing more information on the signage system (n = 5). The room numbering was also called to follow a general logic (n = 7).

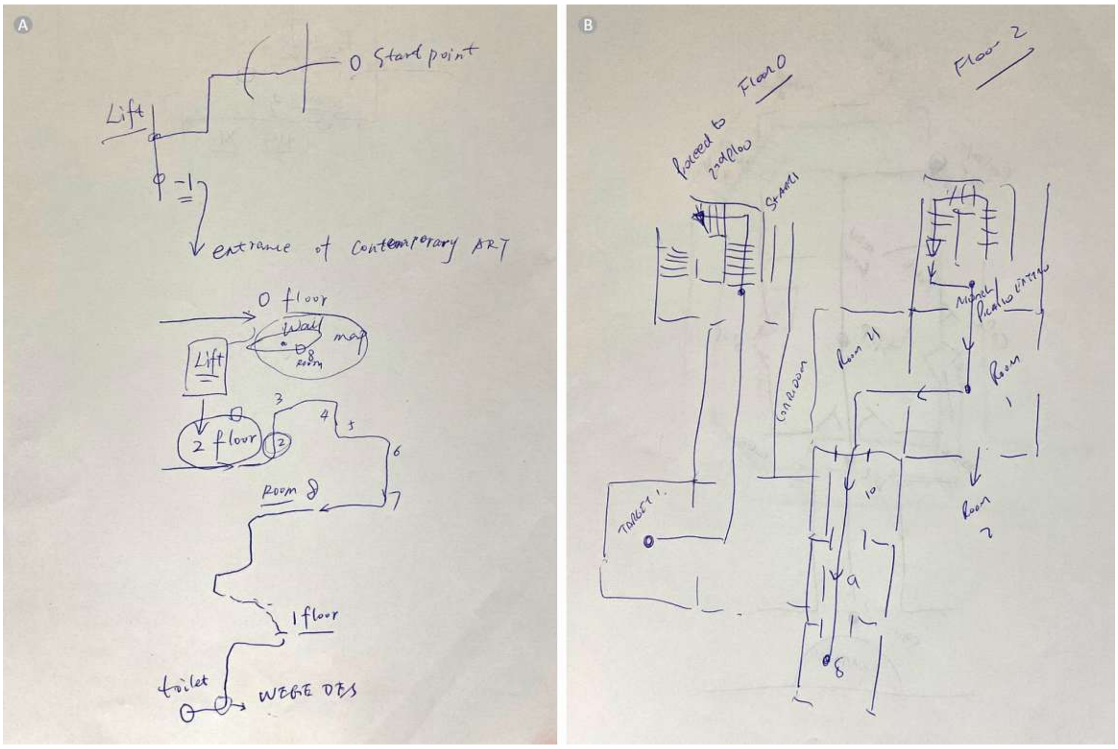


Figure 3.8 - Example sketch maps. (A) A sketch map covering three Albertina tasks together. It received a high route-likeness score and a low survey-likeness score. (B) A sketch map with high scores on both route-likeness and survey-likeness.

3.5 Discussion

In this section, we first elaborate on our findings on indoor wayfinding tactics. Then, we compare and justify the preference for floor plans and signs in different situations. Next, we discuss the three- and two-dimensional wayfinding strategies used and how they are affected by the building structure and semantics. Before ending with recommendations for the wayfinding system in the TU, we look into the presented indoor landmarks in visual and verbal forms.

3.5.1 What influences the choice of indoor wayfinding tactics at decision points?

In Section 3.3, we distinguished and elaborated the two possible scenarios at a decision point: Scenario_Aided and Scenario_Unaided, based on whether wayfinders perceive relevant wayfinding support information. Not surprisingly, this is the primary determinant of the choice of tactics. In our study, we asked the participants to describe their wayfinding options and hints revealing the destinations of these options, before making and justifying their decision, at every decision point. Investigating the hints they described allowed us to access what the participants perceived back then. All participants chose among the sign, floor plan, or external help tactic, when they perceived relevant wayfinding information. In addition, when applying the inference tactic, participants use the available information to exclude specific options.

In the aided scenario, wayfinders decide on the tactics based on their current task, the characteristics of the navigational aids and their individual wayfinding style. Albeit in most cases, participants had to proactively ask for external help (in our study, only from other people), which seemed to be an extra barrier, we observed consistent use of this tactic over all other tactics by several participants. One of them said, “This (a floor plan) is complicated. She (a museum staff) must know”. This leaves us with the explanation that the choice is affected by wayfinding system design, i.e., the legibility of the signs and floor plans. Another possible explanation from our observation is the wayfinder’s spatial ability. Participants who preferred the external help tactic to the sign or floor plan tactic struggled during the process. Yet, to disclose this, we would need to conduct an additional experiment with two groups, categorised by their sense of direction, like the experimental manipulation in Burte and Montello (2017). Regarding the choice of sign or floor plan, we discuss it in Section 3.5.2.

Informed by previous studies (Hölscher et al., 2009; Li & Klippel, 2014; Meilinger, 2008), familiarity plays a vital role in indoor wayfinding behaviour and strategies. It is also observed in the choice of wayfinding tactics. Although we only recruited participants unfamiliar with the environment, they gradually familiarised themselves with the buildings during the study. Participants sometimes followed their memory and completely ignored any other information at decision points. This suggests that familiarity was so dominant at such decision points that they did not need further information for assistance or confirmation.

At the decision points, where participants did not perceive any relevant wayfinding information, nor were they familiar with the setting, the next tactic they chose was inference. This confirms Passini (1984b) decision-making strategy theory. We detected several influencing factors and behaviour patterns by looking into participants’ justifications. We present the observed factors and patterns here, acknowledging that further studies are needed to uncover the mechanisms. First, participants expect room numbering to follow a certain logic, such as rooms with adjacent numbers being close by. In the task of finding Hörsaal 17, when participants saw a sign with Hörsaal 18, they followed it by justifying: “it tells me that Hörsaal 13 and 18 to my right. So I’m gonna have a quick look to my right.” Another pattern is that participants tend to continue straight. Justifications include “There is no sign telling me to change direction, so I will stay on this corridor”, “There is a corridor to my left, plus a door, but none of them seem to be what I’m looking for,... so I’m gonna carry on straight on”. This can be clarified by the inertia principle and the action continuation heuristic that people tend to continue straight unless there is a more potent force for changing direction (Bitgood, 2006; Van Tilburg & Igou, 2014).

When the amount of reliable information, either in the world or in the head, further decreases, participants make decisions based on their preferences. The architectural feature preference exhibited in our study includes illumination, corridor width, and right-turn tendency. Similar to the findings of Hughes et al. (2020), one participant preferred the brighter corridor among the possible options with different lighting conditions. Several participants preferred the wider corridor, which can be interpreted as feeling safer in wider corridors (Zhang & Park, 2021).

The right-turn tendency, which was discovered by previous behaviour research (Bitgood, 2006; Taylor & Socov, 1974; Whyte, 1980; Zhang & Park, 2021), was also detected in our study. When there were no hints, participants turned right, possibly because one walks fewer steps by turning right than turning left, thus costing less energy (Bitgood, 2006). Although the observed architectural feature preference appeared personal in our study, further controlled experiments with more participants will significantly benefit the wayfinding design of public buildings. For example, an immediate suggestion to the TU main building is to provide consistent lighting conditions in all parts of the building, which could prevent unnecessary wayfinding confusion.

Apart from architectural features, preference could also originate from culture or individual experience. In our study, one participant "just follow the people" in the museum, whilst another "don't want to go through this crowd".

So, what influences the choice of indoor wayfinding tactics at decision points? The answer includes the wayfinding task, the availability of relevant wayfinding information, people's familiarity with the environment, the established human movement patterns, environmental features, culture, and individual experience. As an explorative study with limited sample size, our study is the first step to discovering the possible influencing factors for the choice of indoor wayfinding tactics at decision points. Further controlled experiments can help unfold their interaction and mechanisms.

3.5.2 Floor plans and signs

Overall, participants preferred signs to floor plans when both were provided in the Albertina. It was not surprising, as floor plans require more endeavour from wayfinders. To use a floor plan, one must first match the reality with the floor plan and localise oneself. In the case of a YAH map, like the wall-mounted ones in the Albertina, one's location is already shown. Then one should find the destination on the floor plan before planning a route. Afterwards, one has to switch from the allocentric reference framework to the egocentric one, to translate the planned path on the floor plan into a route in reality (Shelton & McNamara, 2004). Next, one memorises and executes the route segments, which generates a high load in the working memory and often needs confirmation en route (Hölscher et al., 2007).

On the contrary, using signs involves no route planning nor memorising route segments. One receives immediate guidance, which induces a much lower cognitive load. As such, one saves internal cognitive resources by offloading them to signs. Cognitive scientists suggest that any cognitive agents behave in a way to optimise the cost-benefit mechanism (McFarland & Bösser, 1993). This mechanism explains why wayfinders refer more frequently to signs than floor plans.

Our findings on the choice of tactics at the task level indicate that the selection between floor plans and signs may be even more complex. The description of a wayfinding task may influence wayfinders' preference for a particular wayfinding aid. In the Albertina, Target 3, "the toilet close to the exhibition Wege des Pointillismus" contains a spatial relation "close to", as opposed to other targets worded without spatial relations (e.g., The entrance of the exhibition Contemporary Art). It was during Task 3 appeared the only decision point where the floor plan was more frequently used. Verbalised by participants, the task description intended that there must be several toilets; one was close to that exhibition. It motivated them to seek an overview of the spatial structure. In this case, the floor plan is a more reliable choice if they want to ensure the correct target before taking any action. After informing themselves about the spatial relations and finding the target location on the floor plan, they can plan and follow the route with certainty. They may forget some route segments or actions at decision points en route, but they can always find confirmation as long as they are on the correct path. It was the exact behaviour we observed. The participants who chose the floor plan later referred to signs for affirmation along the route.

Returning to that decision point, when they refer to signs, they can find information about the exhibition and follow it. Still, they are uncertain about where the toilet is. An exhibition can be extensive in size, with multiple doors for entrance and exit. If they follow the sign to the other side of the exhibition, they must go all the way through to reach the target. This choice poses a higher uncertainty to the decision. Compared with the time and cognitive resources spent to understand the floor plan, choosing the sign is uncomplicated but may cost more time and mental capacity later. This uncertainty en route also seemed to affect the participants' impression of the environment, as in the end interview, a participant suggested "more signs for toilet".

According to the cost-benefit mechanism, we can consider preferring a floor plan to a sign in this situation as a balance between cognitive load and certainty. Floor plans increase the possibility of finding the right target, although comprehending requires more effort. Following a sign requires less effort but may lead to potentially higher cognitive costs. Wayfinders balance the cost and the benefit and then decide.

With the overall configurational information presented in floor plans, they are often considered as supporting survey knowledge. In contrast, signs are deemed to provide sequential point-to-point information, supporting route knowledge (Butler et al., 1993; Hölscher et al., 2007). To reflect on this and check whether using a survey or route knowledge supporting tactic would result in a difference in participants' spatial learning, we analysed the sketch maps regarding their survey-likeness and route-likeness. A positive relationship was revealed, yet not significant. This is probably due to our wording on the sketch map task. We asked participants to describe the route and draw a sketch to help other first-time visitors find their way. The language biased the route representation. It partially explains their sketch maps' low score on survey-likeness. Another reason is the rating method we used from Krukar et al. (2018), which was developed to assess outdoor sketch maps. Three out of six criteria in the survey-likeness scale focused on global landmarks, which was a known deficit indoors (Bahm & Hirtle, 2017). Notably, sketch maps are highly dependent on an individual's drawing skills. Other methods to measure spatial knowledge acquisition may unfold a different picture. An approach tailored to measure indoor sketch maps or to implement other spatial knowledge measures in the study may uncover different patterns.

To summarise, due to the cognitive load involved in processing information on floor plans and signs, wayfinders generally favour signs. Yet, this preference is not only individualised but also influenced by the description of a wayfinding task. With regard to their influence on spatial learning, we found a tendency that the preference for floor plans fosters survey knowledge acquisition, whereas signs encourage route-like sketches. Nevertheless, the sample size and the method we used limit our findings to a generalisable result. A future controlled experiment with suitable spatial knowledge measures may inform how the different aids support spatial learning.

3.5.3 Indoor wayfinding strategies

Our analysis of indoor wayfinding strategies confirms that participants adapt their strategies to building characteristics and tasks, and unfamiliar participants primarily rely on the central point strategy (Hölscher et al., 2009; Hölscher et al., 2006). They tend to return to where they are familiar with, because they fear getting lost. The building structure and existing navigational aids compensate for this uncertainty for first-time visitors. If a building has a simple design with a consistent wayfinding system, like in the Albertina, the central point strategy is less dominant than in a complex building, like in the TU.

Besides the overall popular central point strategy, whether using the floor strategy or the direction strategy is guided by the building structure. In the Albertina, the direction strategy is hardly practical, with only two vertical connections (a staircase and an elevator). If one uses the direction strategy to go to the corresponding section first, one still needs to return to the staircase or the elevator to change the level. Whereas in the TU, the building sections are joined by staircases, and each section is reachable by the corresponding staircase, while it may not be so cross sections on the same floor. The "same" floor is by itself an ambiguous concept in the TU because of the half-level difference between some sections. For example, the porter told one participant that Hörsaal 17 should be accessible by Staircase 7 and on the fourth floor. When she entered the elevator at Staircase 7, she saw Hörsaal 17 beside the button for the third floor. She was immediately confused. The level confusion, together with locked doors and dead ends within one floor, do not promote the floor strategy. On the other hand, the direction strategy benefits from such an organisation. It is also reflected in the wayfinding suggestions the porter and staff members gave.

In addition to the indoor wayfinding strategies involving three dimensions, we also looked at the two-dimensional strategies within one exhibition area in the Albertina. Outrunning the well-established criteria (e.g., shortest path and fewest turns), following the pre-defined order turned out to be the most popular. One explanation is following the ascending numbers is straightforward and thus generates a low cognitive load. A low-cost choice is preferred by humans (McFarland & Bösser, 1993). The semantics of the building, a museum, can also account for this strategy preference. Museums typically organise their exhibitions based on a variety of factors, including the exhibition's theme or subject, the artwork's chronological order, and the exhibition's narrative (Kirchberg & Tröndle, 2012; Mao & Fu, 2021). To achieve the desired experience, visitors typically follow the pre-defined order. Brought up by one participant, going reverse order will be against the flow of visitors and may disturb others. These general social behaviours stay valid in a wayfinding scenario. On that account, one potential implication could be implementing order in public buildings, especially during large events. Such a design can guide the population and prevent possible accidents. Regarding navigation systems, whether analogue or digital, pre-defined orders in the environment must be considered and respected during route planning to avoid user confusion and potential accidents.

Overall, the central point strategy is popular among unfamiliar wayfinders. The strategies concerning vertical first or horizontal first are subject to the building structure and their existing wayfinding aids. In the area bearing an explicit order, wayfinders prefer to follow the pre-defined order. It is probably because of a low cognitive load and the consideration of culture and social impact.

3.5.4 Indoor landmarks in visual depictions and verbal descriptions

Overall, the landmarks mentioned in sketch maps and route instructions display building-specific characteristics. Some landmarks frequently referred to in the Albertina, such as the ticket office, do not exist in the TU. The mentioned frequency of common landmarks shows similar patterns in both buildings, while it differs between the forms of presentation (visual or verbal).

In visual depictions, the most frequently presented landmarks are the functional ones (e.g., stairs, elevator, door, and building entrance/exit), followed by the semantic landmarks like signs and floor plans. Our finding supports the high saliency of indoor functional landmarks proposed by previous research using sketch maps (Bahm & Hirtle, 2017; B. Liu et al., 2021) and eye tracking (Ohm et al., 2014). We agree with Bahm and Hirtle (2017) that functional landmarks, especially the ones supporting floor-to-floor transitions such as staircases, afford a functional feature (to support floor transition) and a referential trait (to act as an anchor point). Thus, they are often referred to indoors.

In verbal descriptions, the semantic landmarks are most frequently referred to, followed by the functional ones. This can be expected from the high reliance on the sign and floor plan tactics. After finding their destinations with the help of signs and floor plans, it is natural that participants instruct others accordingly. As landmarks, they bear both visual and semantic saliency. Compared with other environmental objects, they carry concise information, making them unambiguous and easy to describe verbally. Whereas in visual depiction, unless indicated as “sign”, “floor plan”, or with the content on the sign, it is hard to distinguish them from the sketch maps. This result differs from Viaene et al. (2014), where other objects largely outnumbered semantic landmarks. In their study, participants were encouraged to think aloud about all possible salient objects along the way, to collect all potential landmark candidates. In this way, the frequency of landmarks mentioned is tied to the number of such objects in the environment. In contrast, we look at mentioned objects in route instructions, which are participants’ selection of the candidate landmarks.

Apart from the categories of landmarks, the purposes of landmarks included in the visual and verbal forms also differ slightly. Overall, global landmarks appear rarely in both forms, which is the nature of indoor environments (Giudice et al., 2010). However, participants drew landmarks with a distance (i.e., the ones neither at decision points nor along the way) to help with orientation, while verbally mentioning almost none of such landmarks. We share the opinion of Anacta et al. (2017) that the configurational nature of sketch maps invites participants to include contextual information about the environment in which a route resides.

3.5.5 Recommendations for the wayfinding system in the TU

"Fortunately, you are doing this experiment because the signs are horrible here!" said one participant during wayfinding in the TU. It expresses many participants' feelings towards the building. Compared with the Albertina, the complex structure poses inherent wayfinding challenges to the TU main building. Additionally, the existing wayfinding system contributes to waydinders' frustration, especially under time pressure. We summarise the wayfinding difficulties the current study reveals and link them to potential improvements.

The most severe wayfinding difficulties come from incomplete and inconsistent signage systems. Many decision points in the TU are deprived of signs, while some are equipped with different signage systems. Figure 3.1D shows an example of two signage systems at Staircase 1, the central staircase, once people enter from the front gate. It is where the participants expected a directory sign, yet not offered. Instead, it provides two different signage systems, which is confusing. With no wayfinding information, people get lost. While too much information overloads people (Arthur & Passini, 1992; Mandel, 2013). Therefore, it is essential to synchronise all signage systems and provide unified signs at all decision points. Arthur and Passini (1992) suggest designing the information system according to the building circulation. As the TU is circulated around the staircases, we share our participants' recommendation on placing a directory sign at every staircase on every floor. Each directory sign has its own coverage, within whose the wayfinding information is communicated in detail, and links to other directory signs. The long corridors in the TU also generate a feeling of insecurity. Participants doubted whether they were on the right path when there was no information along a long corridor between two signs. Providing confirmation signs along a long route segment will increase the confidence for wayfinding.

The second major issue is room numbering. Participants stated certain associations with room numbering, such as Hörsaal 17 might be on a higher level than Hörsaal 15 and should be close to Hörsaal 18. However, the reality did not meet their expectation in the TU. In fact, the TU has a standard and logical room coding system, but the codes are different from room names and are not well known. It codes each room by the section and the floor it locates, followed by a room counting within that area. The targets in our study Hörsaal 15 and Hörsaal 17, are coded as AB0314 and AE0341, respectively. From their codes, we know they are on the same floor but in different sections. Should the participants, who found Hörsaal 18 and thought Hörsaal 17 should be nearby, know the code of Hörsaal 18 as AE0238, they would have a different expectation. We view the room numbering issue as caused by synchronisation, similar to the multiple signage systems. The room names should be synchronised with room codes and follow a user-friendly naming convention.

The next difficulty is related to the sign design and placement. In the decision point level analysis, we discovered that most participants first ignored the information on the sign at

Staircase 2 and then overlooked the sign pointing to Staircase 3. In the former case, the information was written small and in brackets. In the latter case, the grey sign was placed high above in a dimly lit corridor. The contrast of the information with the background was insufficient in both cases, so participants overlooked them. Sign information must be suitable for environmental perception, i.e., scanning while walking. Therefore, we suggest placing signs at an appropriate height, with distinguishable colours from the environment. Guidelines on sign design and placement are out of the scope of the current study. See Arthur and Passini (1992) and D. Gibson (2009) for an overview.

Finally, we call for consistent lighting conditions in the TU. Studies indicate that illumination affects wayfinding decisions (Hidayetoglu et al., 2012; Hughes et al., 2020; Taylor & Socov, 1974) and influences people's emotions (Bell et al., 2005). The TU should illuminate different areas coherently to avoid unnecessary wayfinding confusion and provide a balanced environment.

3.6 Summary and conclusions

To clarify the nature of human indoor wayfinding and the relevance of existing indoor navigational aids, we conducted an empirical study in the Albertina and the TU with 28 first-time visitors who had to think aloud while performing wayfinding tasks. During the study, participants had to find three targets in each building and describe their wayfinding strategies. They were asked to stop at every decision point along the way: to describe their wayfinding options and hints revealing the destinations of these options, to make their decision, and to justify it. After finding each target, they were required to draw a sketch map and give route instructions. In the end, we arranged an interview for general comments and debriefing.

Qualitative analysis was applied to the recorded behaviour observation and the verbal protocols due to the explorative nature of the study. Focusing on decision points, we distinguished two decision-making scenarios, Scenario_Aided and Scenario_Unaided, depending on whether relevant wayfinding support information is explicitly accessible and perceived. Based on previous theories and our analysis, we proposed categorisations of indoor wayfinding tactics to define decision-making at decision points. Further, we looked into the choice of tactics influenced by the characteristics of the buildings, the tasks and the decision points. We then zoomed out to the overall planning and analysed indoor wayfinding strategies at the building and floor levels. Besides the indoor wayfinding planning and decision-making, we also investigated the communication of wayfinding information, i.e., the visual depiction and the verbal description of the route, along with the exhibited wayfinding style.

Our analysis presents a systematic overview of indoor wayfinding tactics at decision points. The choice of tactics is affected by the wayfinding task, the availability of navigational aids, environmental features, and familiarity with the environment. The established human movement patterns, cultural background, and individual experience also guide the choice of tactics. The most popular is the sign tactic, independent of the building structure and function. The design of the signage system affects the selection in a way that wayfinders may overlook it when not appropriately designed and placed. In such situations, the decision-making scenario changed from aided to unaided. However, once perceived, the reliance on signs is irrelevant to the design quality.

Since processing information on signs is less cognitively demanding than floor plans, wayfinders generally favour signs. Yet, this preference for signs is individualised and influenced by the description of a wayfinding task. Our analysis suggests the target descriptions that include spatial relations (e.g., "A close to B") motivate wayfinders to find configurational representations, i.e., floor plans.

Signs, especially directional signs, provide an immediate direction to the navigator, which is associated with facilitating the development of route knowledge. Conversely, with the configurational representation of the environment, using floor plans may help to develop survey knowledge. Our findings confirm this tendency, but the sample size and the experimental method limit it to a generalisable result. A future controlled experiment with suitable spatial knowledge measures may inform how they support spatial learning.

Regarding three-dimensional indoor wayfinding strategies, the central point strategy is favoured among unfamiliar wayfinders. While concerning vertical first or horizontal first is subject to the building structure and its existing wayfinding aids. In a two-dimensional space with a pre-defined order, such as a museum exhibition, wayfinders prefer to follow the order, possibly because of a low cognitive load and social consideration.

Although the landmarks in sketch maps and route instructions show building-specific characteristics, the shared landmarks reveal a similar pattern. Participants verbally instructed more semantic landmarks (signs and floor plans) than others, while functional landmarks (staircases, elevators, etc.) were the most drawn. We interpret the former as a result of semantic landmarks' high visual and semantic saliency and the wayfinding tactics employed, whereas the latter as functional landmarks' high visual saliency and their structural contribution to the space.

Wayfinders' dependence on signs and their high occurrence in human verbal instructions encourage us to integrate them and their semantics into indoor navigation services, which we address in Chapter 4.

Chapter 4

Indoor Sign Integrated Navigation System

4.1 Introduction and research questions

In Chapter 3, we discovered that wayfinders rely heavily on signs, especially directional signs, for indoor navigation. When asked to provide instructions to other wayfinders, signs were most frequently mentioned. As a result, we propose integrating signs and their semantics into mobile navigation services, aiming to enhance the user experience. Informed by the theoretical findings, unless explicitly stated as directional or directory signs, we use the term "sign" to refer to an object specifically created to convey spatial information and guide travel directions with arrows. The spatial information presented on the sign is referred to as sign semantics. Correspondingly, we modify the second research question to:

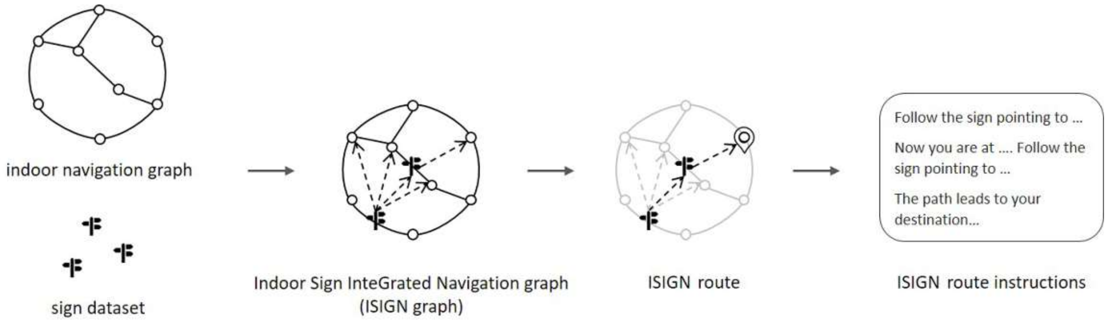
RQ 2 How do we integrate signs into indoor mobile navigation services?

In the case of signs, their significance lies not only in their location, but also in the meaning they convey. To tackle this research question, especially focusing on the semantics of signs, the signs and their semantics need to be modelled into an indoor navigation model. Then, routes considering sign semantics should be generated and communicated to navigators. We propose the Indoor Sign InteGrated Navigation System (ISIGNS), addressing the above processes.

4.2 Methodology

4.2.1 Overall workflow

Figure 4.1 illustrates the workflow of building the ISIGNS. It starts from the automatic generation of the Indoor Sign InteGrated Navigation graph (ISIGN graph) by modelling signs' geometry, topology, and semantics from a sign dataset into a given navigation graph. From the ISIGN graph, a routing algorithm that considers and prioritises sign semantics is developed



Follow the sign pointing to ...

Now you are at .... Follow the sign pointing to ...

The path leads to your destination...

Figure 4.1 - The overall workflow of constructing the ISIGNS.

to generate semantic routes, named ISIGN routes. Finally, to communicate these routes to navigators, we have also proposed an approach to generate ISIGN route instructions.

4.2.2 Indoor sign integrated navigation graph

In this section, we first set out a few definitions and then present the approach for creating an indoor sign integrated navigation graph. The generation of this graph requires a navigation graph and a sign dataset as input. A navigation graph can be created from building floor plans or BIM data, using methods like the one introduced by Yang and Worboys (2015). Similarly, a sign dataset can be derived from BIM data or a table with pertinent geometry and attributes. In this study, we take the navigation graph described by Yang and Worboys (2015) as the input graph and a table with geometry and attributes as the input sign dataset. We consider all the rooms as simple rooms, i.e., represented by their centroids. To help illustrate the approach, we have created a fictional example presented in Figure 4.2.

Definition 4.1 A *navigation graph*, formulated as $G = (N, E)$, is a graph that consists of a set of nodes N and a set of edges E. Each node $n \in N$ represents a node with geometry and attributes. Depending on the attribute n.class, they are further divided into room node, portal node, stairwell node, elevator node, and junction node. The name of a room, stairwell or elevator is stored in the attribute n.name, as long as a name is available. Each edge $e \in E$ represents a path between two nodes. The geometry is passed through the connecting nodes, and the e.length attribute is the actual length between the nodes.

Definition 4.2 A *sign node* represents a node n with the attribute n.class as "Sign", and all the information on the sign is stored in the attribute n.semantics. In the n.name attribute, a sign is noted as "sign at $\{location_{sign}\}$", where $location_{sign}$ refers to the nearest named room, stairwell or elevator node.

Definition 4.3 A *semantic edge* represents an edge $edge_{sem}$ connecting a sign and the destination on the sign (dashed directed lines in Figure 4.2). Its attribute $edge_{sem}$.length stores the length of the shortest path between its start and end. It distinguishes itself from other navigation graph edges by the attribute $edge_{sem}$, which is set as true. To support the route instruction generation, in case a transition from a semantic edge to other types of edge

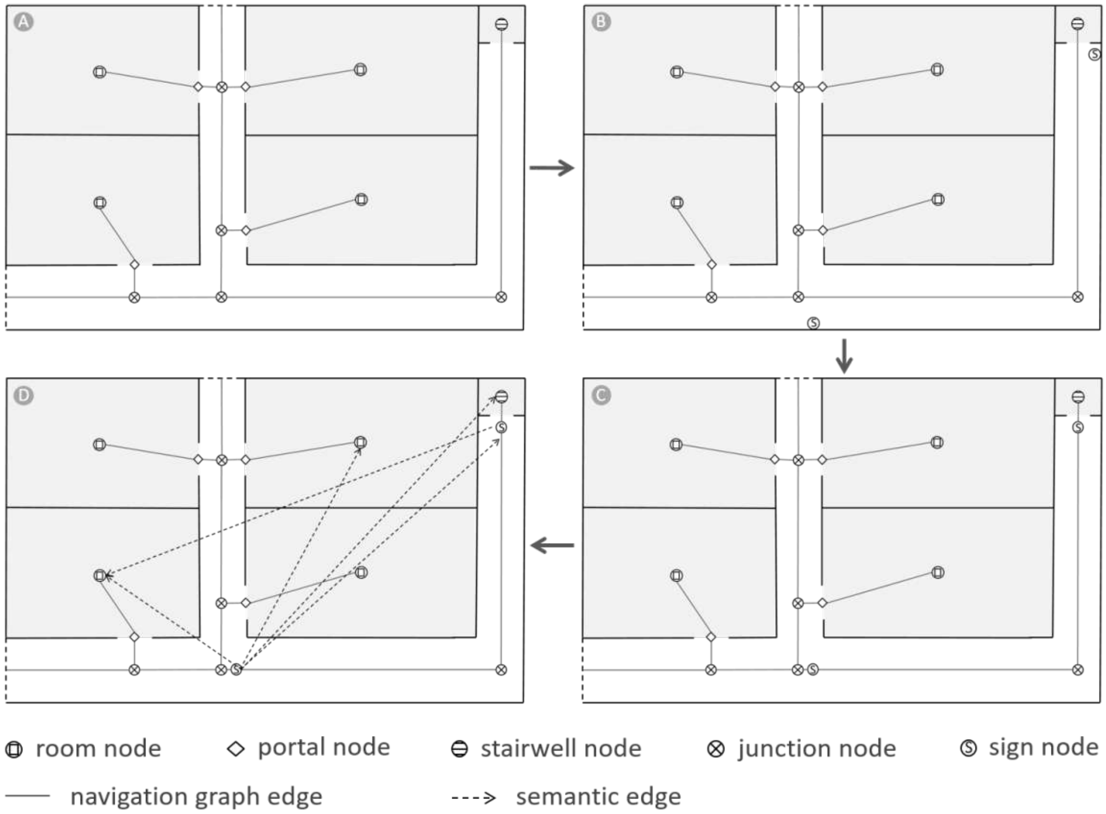


Figure 4.2 - An example of the stages of generating the indoor sign integrated navigation graph: (A) the original navigation graph visualised on a floor plan, where corridors are depicted with dashed lines to indicate their continuation beyond what is shown; (B) sign dataset visualised on the floor plan, with signs situated at their actual location; (C) sign nodes added to the navigation graph; (D) semantic edges added to the navigation graph, i.e., the indoor sign integrated navigation graph.

occurs, its attribute $edge_{sem}$.last_edge stores the last edge of the actual traversable path from the sign to the destination.

Generating an indoor sign integrated navigation graph involves two main steps: adding sign nodes to the graph (Figure 4.2C) and adding semantic edges (Figure 4.2D). Algorithm 4.1 summarises the approach.

To begin, we start by adding sign nodes to graph G, which entails iterating through the entries in the sign dataset. For each sign, we find its nearest edge in graph G, based on its geometrical information (Line 3). We then find the point on that edge closest to the sign and create a new node, incorporating the sign's attributes and the coordinates of the nearest point. This new sign node is then added to G (Lines 4-6). To keep the correct connection of G, the connecting edges in G must be updated accordingly. We split the original edge into two separate edges: one from the start node to the new sign node, and another from the new sign node to the end node. Afterwards, the two new edges are added to the graph, and the previous edge is removed. This process ensures that all signs in the dataset are integrated into G (Lines 7-10).

Before moving on to the second step, we convert G to a directed graph G_{sem}, ensuring that the semantic edges to be added are directed (Line 14). Then, we first find the sign nodes in G_{sem}. For each sign node, we create a destinations list referring to its attribute sign.semantics (Line 17). Subsequently, for each node n in G_{sem}, we check whether the node's name n.name matches any entry in the destination list. If a match is found, a semantic edge $edge_{sem}$ is added to G_{sem} (Lines 19-24). The length attribute $edge_{sem}.length$ is set to be the distance of the shortest path between the sign node and this node, while the $edge_{sem}.last\_edge$ attribute stores the last edge of the shortest path (Lines 20-21). The assignments of these two attributes are derived from the assumption that a sign leads the shortest traversable path to its destination. In case the sign system is designed differently, these attributes should be modified accordingly. The attribute $edge_{sem}.semantic\_edge$ is set to true (Line 22). This process establishes the connections between the sign node and its destinations in G_{sem}.

However, in some instances, reaching a specific room may require following signs that lead to an area first and then to the room itself. To facilitate a smooth transition between signs, we also add a semantic edge, if there is another sign located at a position that is included in the destination list of the current sign. For example, if the current sign leads to Staircase 1, where another sign is located, then semantic edges from the current sign to Staircase 1, as well as to the sign at Staircase 1, are generated. To accomplish this, we check if a node is a sign node and extract its location (Lines 24-25). In our study, the sign location is stored in the name attribute. If a name is omitted, the location can be easily calculated by selecting a location of a given class attribute within a distance radius. If the location appears in the destination list, a semantic edge is added to G_{sem} (Lines 26-30). By traversing the entire graph, all the necessary semantic edges are added, resulting in the construction of the indoor sign integrated navigation graph G_{sem}.

4.2.3 Generation of ISIGN routes

After incorporating the sign semantics into the navigation graph, we have developed a routing algorithm that prioritises the semantic information of signs. Our goal is to guide navigators in a way that maximises their reliance on signs while keeping the route length reasonable. Following the approach of Huang et al. (2014), we utilise Yen's top-K shortest path algorithm (Yen, 1971) to manage the length of the path. This algorithm identifies all paths that are not longer than a threshold $(1 + \delta)$ compared to the shortest path. The value of δ determines the extent to which a navigator is willing to walk extra distance to follow sign guidance, and can be set by the user individually.

Algorithm 4.2 provides an overview of the sign semantic aware routing method. The algorithm requires an ISIGN graph G_{sem}, a threshold value δ, and the starting and ending points of the route (s and e). First, we calculate the shortest distance between s and e (Line 2). Then, we consider all paths within a distance of $(1 + \delta) * distance_{shortest}$ as candidate paths (Line 2).

Algorithm 4.1 - ISIGN graph generation

```
Input: a navigation graph $G$, and a sign dataset as $Signs$
Output: a semantics enriched navigation graph $G_{sem}$
# add the sign node to the nearest point on its nearest edge, and update the connecting edges
for each node sign in Signs do
    $edge_{nearest} = nearest\_edge\ (G,\ sign.geometry)$
    $pointnearest.geometry = nearest\_point_{o}n_{e}dge\ (G,\ sign.geometry,\ edge_{nearest})$
    $pointnearest.attributes = sign.attributes$
    add_node $(G,\ point_{nearest})$
    $segment1,\ segment2 =$ split_edge $(G,\ edge_{nearest},\ point_{nearest})$
    add_edge $(G,\ segment1)$
    add_edge $(G,\ segment1)$
    delete_edge $(G,\ edge_{nearest})$
end
# add semantic edges to the graph from the sign node to the destinations (including the signs at these locations) on the sign.
$G_{sem} =$ to_directed $(G)$
for each node sign in $G_{sem}$ do
    if $sign.class ==$ “Sign” then
        destinations = sign.semantics
        for each node $n$ in $G_{sem}$ do
            if $n.name$ in destinations then
                $edge_{sem}.length =$ shortest_distance $(G,\ sign,\ n)$
                $edge_{sem}.last\_edge =$ last edge of the shortest path $(G,\ sign,\ n)$
                $edge_{sem}.semantic\_edge =$ true
                add_edge $(G_{sem},\ edge_{sem})$
            else if $n.class ==$ “Sign” then
                $location_{sign} =$ extract_sign_location $(n.$name$)$
                if $location_{sign}$ in destinations then
                    $edge_{sem}.length =$ shortest_distance $(G,\ sign,\ n)$
                    $edge_{sem}.last\_edge =$ last edge of the shortest path $(G,\ sign,\ n)$
                    $edge_{sem}.semantic\_edge =$ true
                    add_edge $(G_{sem},\ edge_{sem})$
                end
            end
        end
    end
end
return $G_{sem}$
```

For each candidate path, we calculate the route segments covered by semantic edges (Line 6). This allows us to determine the coverage of semantic edges by dividing the $length_{sem}$ by the total length of the route $length_{total}$ (Lines 7-9). Finally, we update $route_{sem}$ by selecting the path with the highest coverage of semantic edges as the chosen route (Lines 10-12).

Algorithm 4.2 - ISIGN routing

```
   Input: a navigation graph $G_{sem}$, threshold $\delta$, a start $s$ and an end $e$
   Output: a list $route_{sem}$ from $s$ to $e$
1  $route_{sem}$ = None
2  $distance_{shortest}$ = shortest_distance ($G_{sem}$, $s$, $e$)
3  $paths_{candidate}$ = Yen_topk ($G_{sem}$, $s$, $e$, $(1 + \delta) * distance_{shortest}$)
4  $coverage_{max}$ = 0
5  for each path in $paths_{candidate}$ do
6      $edges_{sem}$ = edges in path that edge.semantic_edge is true
7      $length_{sem}$= sum ($edge$.length) for all $edge$ in $edges_{sem}$
8      $length_{total}$ = sum ($edge$.length) for all $edge$ in $path$
9      $coverage$ = $length_{sem}$ / $length_{total}$
10     if $coverage >= coverage_{max}$ then
11         $coverage_{max}$ = $coverage$
12         $route_{sem}$ = $path$
13     end
14 end
15 return $route_{sem}$
```

4.2.4 Generation of ISIGN route instructions

Finally, we must generate route instructions for navigators to communicate the route information. Route instructions address two fundamental aspects: how to navigate to a decision point and what action to take once the decision point is reached (Richter & Klippel, 2005). This corresponds to providing instructions for route legs and decision points. To achieve this, we have developed a route instruction generation approach that considers both edges and nodes in the navigation graph.

For edges, we have adapted the schemas used for route legs and floor level changes from the indoor landmark-based route instructions (Fellner et al., 2017). In case an edge is not a semantic edge, we utilise metric-based turn-by-turn instructions, with the direction concept from (Klippel, 2003).

Regarding nodes, our approach begins by instructing navigators on their current location. This helps them orient themselves within the indoor space. Subsequently, we provide instructions on their next move to proceed along the route. By considering both edges and nodes in the route instruction generation process, we aim to provide comprehensive and easily understandable guidance to navigators.

Algorithm 4.3 - ISIGN route instructions generation

```
Input: a navigation graph $G_{sem}$, and a route $route_{sem}$ from $s$ to $e$
Output: a list $instructions$
initialise $instructions$, $edge_{prev}$, $edge_{last}$, $direction$, $direction_{prev}$, $distance$,
  $distance_{prev}$
for $i$ in the range of the length of $route_{sem}$ do
    $node_{curr} = route_{sem}\ [i]$
    $node_{next} = route_{sem}\ [i+1]$
    $edge_{curr} = G_{sem}[node_{curr}][node_{next}]$
    #instructions for the nodes (excluding the start): where it is, and next move
    if $edge_{prev}$ != $None$ then
        if $node_{curr}.name$ != $None$ then
            $name_{location}$ = get_location_name ($node_{curr}$, $G_{sem}$)
            append to $instructions$ "Now you are at {$name_{location}$}."
        end
        if $edge_{curr}.semantic\_edge$ == $true$ then
            $name_{location}$ = get_location_name ($node_{next}$, $G_{sem}$)
            append to $instructions$ "Follow the sign pointing to {$name_{location}$}."
        else
            # use metric_based tbt, with only turn information at nodes
            $direction$ = get_turn_direction ($edge_{prev}$, $edge_{curr}$)
            if $direction$ == "straight" and $direction_{prev}$ == $None$ then
                append to $instructions$ "Go straight."
            else if $direction$ == "straight" and $direction_{prev}$ != $None$ then
                delete the previous item in the $instructions$ list
            else
                append to $instructions$ "Turn {$direction$}."
            end
        end
    end
    # generate instruction for the edges
    if $edge_{curr}.semantic\_edge$ == $true$: then
        $name_{location}$ = get_location_name ($node_{next}$, $G_{sem}$)
        append to $instructions$ "Follow the sign pointing to {$name_{location}$}."
        $edge_{last}$ = $edge_{curr}$.last_edge
    else if $edge_{curr}.from\_level$ != $edge_{curr}.to\_level$: then
        append to $instructions$ "Use the $edge_{curr}$.path_type to go to the Level
          {$edge_{curr}$.to_level}."
```

```

    else
        $direction$ = get_turn_direction ($edge_{prev}$, $edge_{curr}$)
        $distance = edge_{curr}$.length
        if $direction$ == "straight" and $direction_{prev}$ == None: then
            append to instructions “Go along the {$edge_{curr}$.path_type} for {$distance$}m.”
        else if $direction$ == "straight" and $direction_{prev}$ != None: then
            $distance = distance + distance_{prev}$
            append to instructions “Go along the {$edge_{curr}$.path_type} for {$distance$}m.”
        else
            append to instructions “Go along the {$edge_{curr}$.path_type} for {$distance$}m.”
        end
        $edge_{last} = edge_{curr}$
    end
    # handle the last route leg
    if $node_{next}$ == $e$: then
        if $edge_{curr}$.semantic_edge == true then
            append to instructions “The {$edge_{curr}$.path_type} leads to your destination {$e$.name}."
        else
            $side$ = get_spatial_relation ($e$, $edge_{prev}$)
            if $side$ == “right” or $side$ == “left” then
                append to instructions “Your destination {$e$.name} is located on the {$side$} side of the {$edge_{prev}$.path_type}."
            else
                append to instructions “The {$edge_{prev}$.path_type} leads to your destination {$e$.name}.”
            end
        end
    end
    $edge_{prev} = edge_{last}$
    $directionprev = direction$
    $distance_{prev} = distance$
end
return instructions
```

Algorithm 4.3 provides an overview of the ISIGN route instructions generation process. This algorithm operates on an ISIGN graph G_{sem}, and a route $route_{sem}$ from the start node s to the end node e. To begin, we initialise several variables, including the instructions list and the variables to prepare for the metric-based turn-by-turn instructions: the previous edge ($edge_{prev}$), the last edge ($edge_{last}$) holding the last edge of a semantic edge's traversable path, the current and previous turning directions (direction and $direction_{prev}$), the distance of consecutive route segments without any turns ($distance$), and the previous distance ($distance_{prev}$) (Lines 1-7).

For each node $node_{curr}$ in the route that is not the starting node, we check whether it has a name. If $node_{curr}$ has a name, we use the get_location_name ($node$, G) function to retrieve $name_{location}$ as the name of the current location. We add an instruction to the instructions "Now you are at $\{name_{location}\}$." to inform navigators of their current location (Lines 14-17). Next, we need to provide instructions for the next move at this node. We examine the current edge $edge_{curr}$, which connects $node_{curr}$ to the next node $node_{next}$, and differentiate between semantic and non-semantic edges. If $edge_{curr}$ is a semantic edge, we request the name of the next node and add an instruction to the list "Follow the sign pointing to $\{name_{location}\}$." (Lines 18-20). If $edge_{curr}$ is not a semantic edge, we provide metric-based turn-by-turn instructions consisting of turning directions and distances. Based on the current and previous turning directions ($direction$ and $direction_{prev}$), we add to the instructions "Go straight." or "Turn $direction$." (Lines 21-31).

It is important to note that several route legs may continue straight. To generate a single instruction for edges without direction changes, we examine the current direction ($direction$) and the previous direction ($direction_{prev}$). If $direction$ is "straight" and $direction_{prev}$ is none, we add an instruction "Go straight." (Lines 23-24). If $direction$ is "straight" and $direction_{prev}$ exist, we remove the last item from the list, which corresponds to the instruction "Go along the $edge_{curr}$.path_type for $\{distance\}$m." generated from the operation on the previous edge (Lines 25-26).

For each edge, we must instruct navigators on reaching the next decision point. We handle different situations based on the current edge ($edge_{curr}$). If $edge_{curr}$ is a semantic edge, we request the name of the next node and add an instruction to the list "Follow the sign pointing to $\{name_{location}\}$." (Lines 33-35). Afterwards, we assign the last edge of the traversable path that a semantic edge represents to $edge_{last}$. This is to prepare for the next edge, in case direction needs to be calculated (Line 36). If $edge_{curr}$ represents a level change, we add an instruction to the list "Use the $edge_{curr}$.path_type to go to the Level $edge_{curr}$.to_level." (Lines 37-38). For other situations, provide metric-based turn-by-turn instructions like "Go along the $edge_{curr}$.path_type for $\{distance\}$m." (Lines 39-49). Similar to the previously mentioned situation that consecutive edges continue straight, we consider and perform operations to present the total distance. Like handling the semantic edge, we need to assign a value to $edge_{last}$, to prepare for the update in the end (Line 66). In this case, we assign the current edge to $edge_{last}$ (Line 50).

To handle the last route leg, we check whether it is a semantic edge. If it is, we add an instruction "The $edge_{curr}$.path_type leads to your destination e.name." (Lines 54-55). If it is not a semantic edge, it means that the last edge should be an edge connecting a path to a room node. Therefore, we calculate the spatial relation between the destination e and the edge before the last ($edge_{prev}$ in this case) and assign it to a variable side (Line 57). If side is "right" or "left," we add an instruction "Your destination e.name is located on the $side$ side of the $edge_{prev}$.path_type." (Lines 58-60). Otherwise, we add an instruction "The $edge_{prev}$.path_type leads to your destination e.name." (Lines 61-62).

After iterating all the nodes in $route_{sem}$, ISIGN route instructions are generated and stored in instructions. If the route has no semantic edge, metric-based turn-by-turn instructions are generated.

4.3 Proof-of-concept prototype and evaluation

To demonstrate the feasibility of the proposed approach, we developed a prototypical ISIGNS. We first report on the preparation for the input data in Section 4.3.1 and then detail the implementation in Section 4.3.2. Section 4.3.3 presents the resulting ISIGN graph. Four test scenarios are considered to showcase ISIGN routes and route instructions. They are presented in Section 4.3.4, with the evaluation of the readability of each route. Finally, Section 4.3.5 compares ISIGN route instructions with metric-based turn-by-turn instructions.

4.3.1 Preparation for the input navigation graph and sign dataset

To assess the viability of ISIGNS and evaluate the route instructions, we utilised real-world data from the TU Wien main building. Initially, the available data from the university was in the form of PDF floor plans. These floor plans were digitised using ArcGIS Pro as part of a student project. Additionally, a skeleton navigation graph was created in the same software. Following the approach outlined by Yang and Worboys (2015), we refined the skeleton navigation graph to generate the input navigation graph for ISIGNS using Python.

The sign dataset was compiled by collecting sign information within the publicly accessible areas of the TU main building, employing ArcGIS Pro 3.0. It was then exported in GeoJSON format and imported as a GeoDataFrame with attributes as data and the coordinates as geometry. As described in Section 4.2.2, the process of generating the ISIGN graph can also be accomplished when the sign dataset is stored in a table, as long as both attributes and geometry are available.

4.3.2 Implementation of ISIGNS

The ISIGNS was implemented in Python, utilising the network manipulation library NetworkX (Hagberg et al., 2008) and the geographic data analysis library GeoPandas. For ISIGN routing, a threshold δ was required to determine how much a navigator is willing to walk an extra distance to follow sign guidance. Since no previous recommendation was available indoors, we set it as 10%, following the practice from Huang et al. (2014) for outdoor routes considering affective rating. The code for Algorithm 4.1, 4.2, and 4.3 are provided in Appendix A.

We implemented ISIGNS as a proof-of-concept on the third floor of the TU Wien main building. However, the creation of a multi-level graph is feasible by connecting stairwell and elevator nodes and assigning “from_level”, “to_level”, and “length” attributes to the edges. The automatic generation of the ISIGN graph is not affected by floor levels, so as the routing. The changing of floor level has been considered in generating route instructions. Although the input data was predominantly generated manually in our case, we believe that utilising accessible BIM data could simplify the process, and full automation could be realised.

4.3.3 The resulting ISIGN graph

As the first step, ISIGN graph is generated from the input navigation graph and sign dataset. We visualised them with the visualisation library Matplotlib in Python. Figure 4.3A depicts the input graph, while Figure 4.3B illustrates the resulting ISIGN graph. The sign nodes are highlighted in red, and the semantic edges are in dashed purple lines in the ISIGN graph.

4.3.4 Sample routes and readability evaluation of the route instructions

We differentiate the test scenarios into four categories based on the availability of relevant signs at the start and the indication of the end on a sign. Scenario 1 corresponds to a situation where a relevant sign is available at the start, and the end is indicated on a sign. Scenario 2 represents a scenario where a relevant sign is available at the start, but the end is not indicated on a sign. In Scenario 3, a relevant sign is not available at the start, but the end is indicated on a sign. Lastly, Scenario 4 refers to a situation where neither a relevant sign is available at the start nor is the end indicated on a sign.

Empirical experiments involving people following route instructions are the most effective method for evaluating their effectiveness (Daniel & Denis, 1998; Denis, 1997; Klippel, 2003), as will be discussed in Chapter 5. However, there is an additional approach for assessing the route instructions, i.e., the readability test of route instructions, as suggested by Zhou (2022). The Flesch Reading Ease Score (FRES) (Flesch, 1979) evaluates the text based on sentence length and the number of syllables in words. It ranges from 0 to 100, with higher scores indicating a more readable text. Generally, a FRES score above 70 indicates that the text is fairly easy to read.

4.3.4.1 Sample Route 1: sign available at the start and the end indicated

The first sample route starts at Staircase 1 (Stiege 1), the staircase at the main entrance, and ends at Projektraum 8 (Project Room 8), a space where architecture students work on their projects. This scenario is common in university settings, where a student enters through the main entrance and seeks a specific room.

Figure 4.4A illustrates the route calculated by ISIGNS. As the semantic edges are not physically traversable, Figure 4.4B shows the actual walkable path. The resulting path consists of two route legs and one decision point. With a relevant sign available at the start, ISIGNS

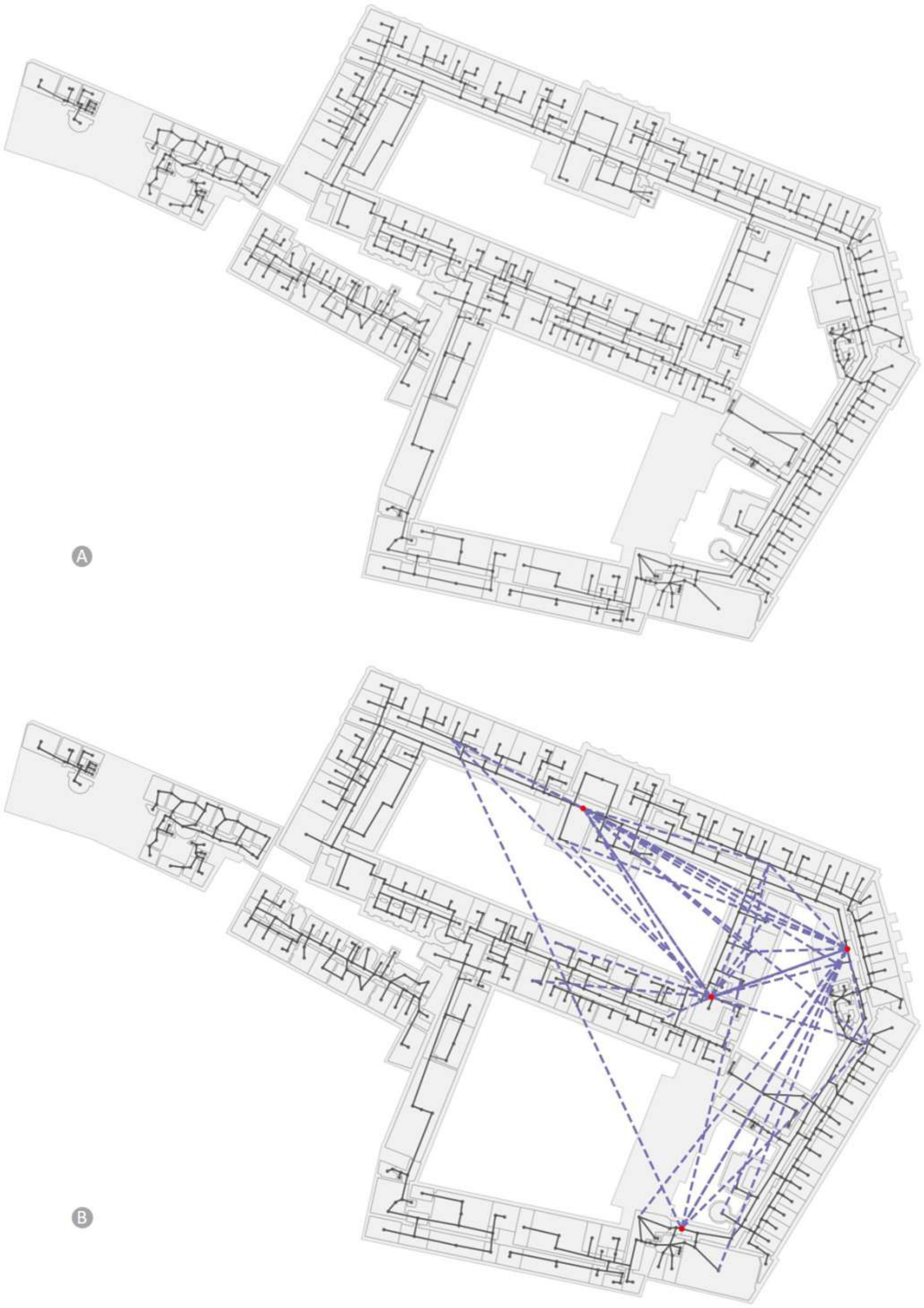


Figure 4.3 - The input navigation graph (A) and the ISIGN graph (B). The red dots depict the sign nodes, and the purple dashed lines represent the semantic edges.

Figure 4.4 - Sample Route 1 with pictures illustrating signs en route. (A) The resulting ISIGN route is highlighted in dashed purple lines on the ISIGN graph. The decision point is marked in an orange circle. (B) The actual traversable route is represented in green lines on the floor plan. In both figures, the start is represented as a red arrow, with the end as a red star. The pictures are linked to their locations.

directs navigators to follow the sign until they reach the decision point, which is another staircase (Stiege 3). From there, another sign guides them to the destination. The signs and destination are shown in Figure 4.4. However, in the actual traversable route, before reaching Stiege 3, one needs to turn at a corridor, with a sign guiding to Stiege 3, as shown in Figure 4.4B.

Table 4.1 presents the generated route instructions and their readability scores. Instructions 1, 3 and 4 are generated from route legs, with instruction 4 addressing the last leg. Instruction 2 corresponds to the decision point, providing navigators with their current location before guiding them to the next action. As the FRES score is meant to calculate readability in English, we translated the German place names to English (Staircase 1 and Project Room 8, respectively) before the calculation. All the readability scores indicate that the text is easy to read.

Table 4.1 - Route instructions by ISIGNS for Sample Route 1 and the corresponding readability score.

ISIGNS (Sample Route 1)	Readability	Decision Point
1. Follow the sign pointing to Stiege 3.	89.8	
2. Now you are at Stiege 3. Follow the sign pointing to Projektraum 8.	89.8	1
3. Follow the sign pointing to Projektraum 8.	80.3	
4. The path leads to your destination Projektraum 8.	79.3	

4.3.4.2 Sample Route 2: sign available at the start, end not indicated

The second sample route begins from Staircase 2 (Stiege 2) and ends at an office (AE0309A) within Department E212. Many departments in the TU main building have an entrance door leading to the foyer. People must enter this door before reaching the offices within the department (Figure 4.5). This route represents a common scenario when someone needs to visit an office starting from the nearest staircase.

Illustrated in Figure 4.5A, the ISIGN route consists of two parts, with one semantic edge (dashed line) and several standard edges. Since Department E212 is indicated on the sign at Staircase 2, a semantic edge leads to E212. Within the department, no publicly accessible signs are available, so the remaining path consists of standard edges.

Table 4.2 presents the generated route instructions and their readability scores. Instruction 1 guides navigators to the department; upon reaching it, they are informed and directed to the next move (Instruction 2). Instruction 4 receives a score between 60 and 70, indicating plain English. This score suggests that the text is understandable by 13- to 15-year-old students (Flesch, 1979). The relatively lower score compared with other instructions of the same schema, is likely due to the room code "AE0309A".

This instruction functions well in such a building structure, as it reflects the organisation of the building and departments therein. However, an issue revealed in this route is that semantic edges connect to the centroids of rooms. In this case, the centroid of the foyer of Department E212. Consequently, it does not address the previous decision point, namely the entrance door to the department (depicted in the door picture in Figure 4.5). One potential improvement could be connecting the portal nodes instead of the room nodes, when generating the ISIGN graph.

4.3.4.3 Sample Route 3: sign not available at the start, end indicated

Sample Route 3 involves travelling from an office (AA0320) to a lecture room (Hörsaal 17). This is another common occurrence, where a lecturer leaves their office to give a lecture or a student attends a class after visiting a staff member's office.

The ISIGN route for sample 3 includes both semantic and standard edges. Since there is no sign at the start, the route first guides navigators to Stiege 2, where a sign leading to Hörsaal

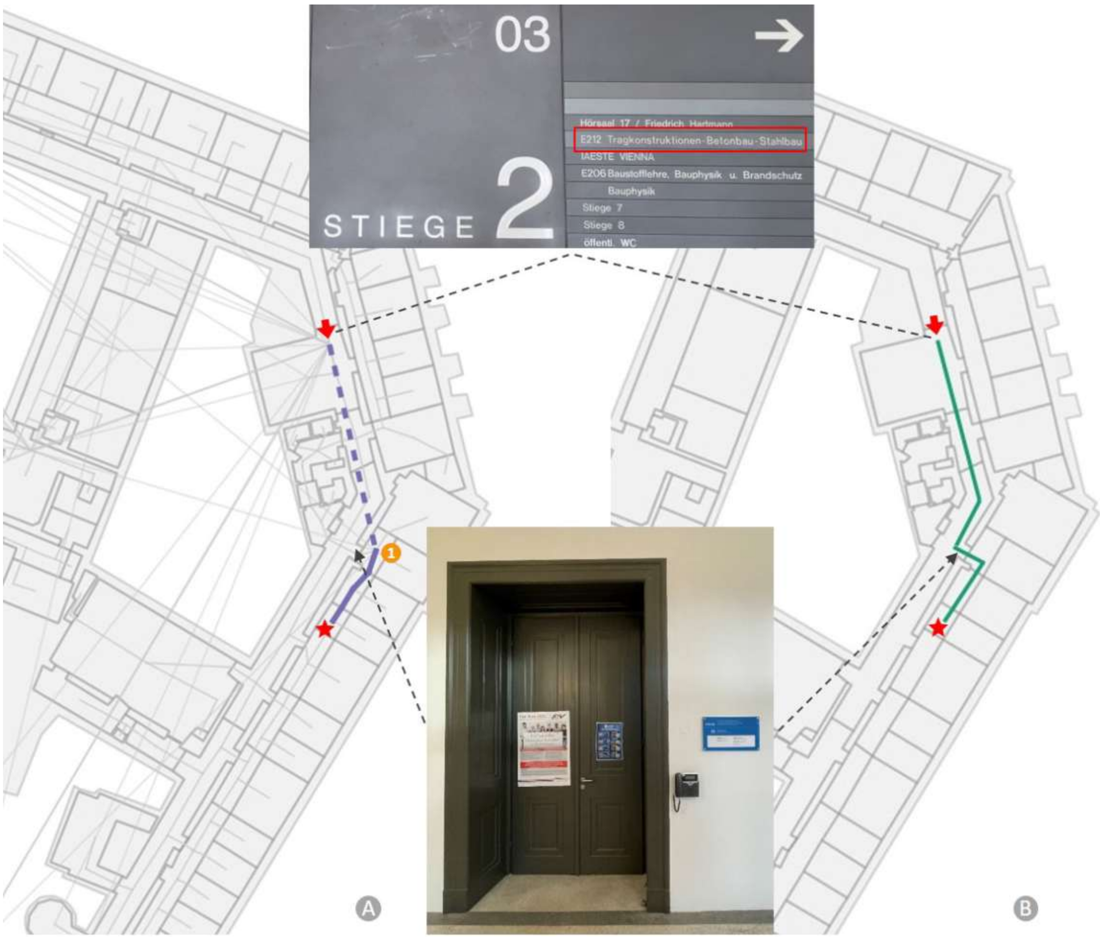


Figure 4.5 - Sample Route 2 with pictures illustrating the sign at the start and the entrance door to Department E212. (A) The resulting ISIGN route is highlighted in purple on the ISIGN graph. The semantic edge is depicted in dashed lines, while standard edges are solid. The decision point is marked in an orange circle. (B) The actual traversable route is represented in green lines on the floor plan. In both figures, the start is represented as a red arrow, with the end as a red star. The pictures are linked to their location.

Table 4.2 - Route instructions by ISIGNS for Sample Route 2 and the corresponding readability score.

ISIGNS (Sample Route 2)	Readability	Decision Point
1. Follow the sign pointing to E212.	90.8	
2. Now you are at E212. Turn right.	100	1
3. Go along the path for 9m.	99.2	
4. The path leads to your destination AE0309A.	64.4	

Figure 4.6 - Sample Route 3 with pictures illustrating signs en route and the entrance door to Hörsaal 17. (A) The resulting ISIGN route is highlighted in purple on the ISIGN graph. The semantic edge is depicted in dashed lines, while standard edges are solid. The decision points are numbered and marked in orange circles. (B) The actual traversable route is represented in green lines on the floor plan. In both figures, the start is represented as a red arrow, with the end as a red star. The pictures are linked to their location.

17 is available. Along the corridor, a prominent sign points to Hörsaal 17, as shown by the arrow pointing to its location in Figure 4.6B.

The route instructions first employ metric-based turn-by-turn instructions. No semantic information is available at decision points 1 and 2 (Figure 4.6A, Table 4.3), so only instructions regarding the next move are generated. The German place names are translated into English (Staircase 2 and Lecture Room 17, respectively), and then the instructions' FRES scores are calculated. All the readability scores indicate that the text is easy to read.

Table 4.3 - Route instructions by ISIGNS for Sample Route 3 and the corresponding readability score.

ISIGNS (Sample Route 3)	Readability	Decision Point
1. Go along the path for 5m.	99.2	
2. Turn left.	100	1
3. Go along the path for 5m.	99.2	
4. Turn slightly right.	93.8	2
5. Go along the path for 10m.	99.2	
6. Now you are at Stiege 2. Follow the sign pointing to Hörsaal 17.	89.8	3
7. Follow the sign pointing to Hörsaal 17.	80.3	
8. The path leads to your destination Hörsaal 17.	79.3	

4.3.4.4 Sample Route 4: sign not available at the start, end not indicated

Sample Route 4 showcases a scenario where neither a relevant sign is available at the start nor is the end indicated. In some cases, this results in a shortest path with metric-based turn-by-turn instructions, while in other cases, such as Sample route 4 illustrated in Figure 4.7, semantic edges are involved en route.

This route starts from an office (AA0362A) and leads to the nearest toilet (AA0303). Along the route, one must leave the office, pass from Staircase 1 to Staircase 2, and continue a short distance, as illustrated in Figure 4.7. Instead of instructing users to go along the path for a long distance, the instructions guide navigators to refer to the available signs. Although these signs may not initially seem directly relevant to the current location, they invite navigators to attend to their surroundings, which can enhance situational awareness and spatial learning.

Similar to the previous routes, the readability scores are calculated after translating the place names (Staircase 1 and Staircase 2, respectively). All the readability scores indicate that the text is easy to read (Table 4.4).

4.3.5 Comparison with metric-based turn-by-turn instructions

Although landmark-based route instructions have been proposed in the literature (Fellner et al., 2017; Viaene et al., 2018; Zhou, 2022), most conventional navigation systems use metric-based turn-by-turn (MTBT) instructions. As a benchmark, we qualitatively compare ISIGNS with MTBT instructions in this section.

The comparison in Table 4.5 reveals that ISIGNS generates fewer instructions, particularly when signs are involved at the beginning or end of the route. This reduction in instructions lessens reading and reaction time, potentially enhancing navigation performance.

Humans prefer interpreting qualitative rather than metric information (Daniel & Denis, 1998; Winter et al., 2021). In addition, according to (Zhou, 2022), long distances, such as 61 meters in Sample Route 3 or 73 meters in Sample Route 4, impose even more significant

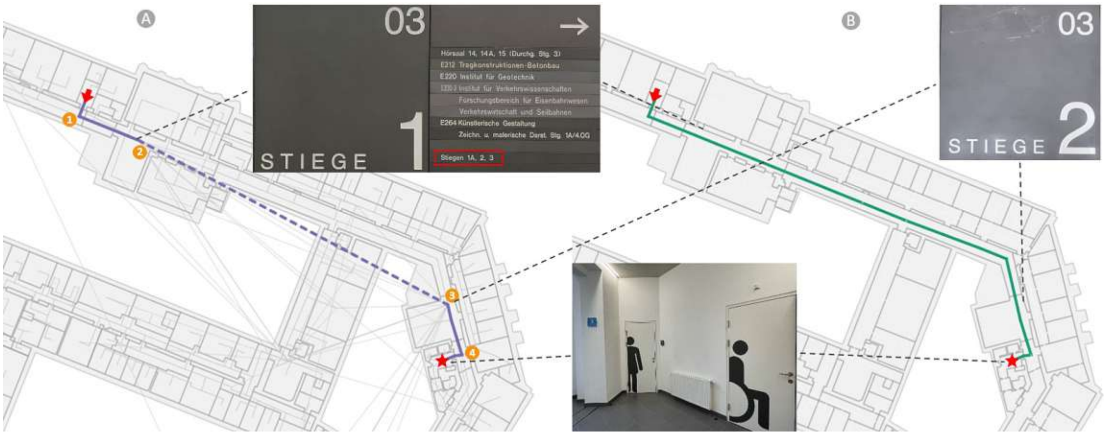


Figure 4.7 - Sample Route 4 with pictures illustrating signs en route and the destination. (A) The resulting ISIGN route is highlighted in purple on the ISIGN graph. The semantic edge is depicted in dashed lines, while standard edges are solid. The decision points are numbered and marked in orange circles. (B) The actual traversable route is represented in green lines on the floor plan. In both figures, the start is represented as a red arrow, with the end as a red star. The pictures are linked to their location.

Table 4.4 - Route instructions by ISIGNS for Sample Route 4 and the corresponding readability score.

ISIGNS (Sample Route 4)	Readability	Decision Point
1. Go along the path for 5m.	99.2	
2. Turn left.	100	1
3. Go along the path for 13m.	99.2	
4. Now you are at Stiege 1. Follow the sign pointing to Stiege 2.	90.3	2
5. Follow the sign pointing to Stiege 2.	81.3	
6. Now you are at Stiege 2. Go straight.	100	3
7. Go along the path for 10m.	99.2	
8. Turn right.	100	4
9. Go along the path for 4m.	99.2	
10. The path leads to your destination AA0303.	81.3	

cognitive burdens on navigators. In contrast to arbitrary numbers, ISIGNS leverages the meaningful and unambiguous guidance provided by signs, making it easier to comprehend and execute. The semantic value conveyed by signs may also aid spatial understanding (Sweller et al., 2011).

As suggested by Fellner et al. (2017), MTBT instructions can lead to confusion and incorrect navigation decisions during long route legs with multiple potential turning points. In addition, some indoor turns are dictated by the building layout, e.g., the structural turn of a corridor, rather than possible outgoing options. At such locations, if other potential outgoing options exist nearby, e.g., turning to a department or another corridor (Figure 4.8), navigators can be easily confused. Such cases exist in locations like Figure 4.8A and Figure 4.8B, where two possible turns exist, potentially causing uncertainty for navigators. While turning angles may differentiate these scenarios in Figure 4.8A, experiment participants (see Chapter 5) still struggled to follow such instructions without error or hesitation. Figure 4.8B presents a situation where two right turns occur in close proximity at the end of a long route leg, making it particularly challenging for navigators to make the correct decision. ISIGNS addresses these issues by incorporating semantic edges and sign-based guidance, mitigating ambiguity in instructions.

Table 4.5 - Comparison of route instructions by ISIGNS and metric-based turn-by-turn instructions for all sample routes

	ISIGNS	**MTBT**
Sample Route 1	1. Follow the sign pointing to Stiege 3. 2. Now you are at Stiege 3. Follow the sign pointing to Projektraum 8. 3. Follow the sign pointing to Projektraum 8. 4. The path leads to your destination Projektraum 8.	1. Go along the path for 37m. 2. Turn right. 3. Go along the path for 30m. 4. Turn right. 5. Go along the path for 4m. 6. Turn left. 7. Go along the path for 5m. 8. Turn right. 9. Go along the path for 33m. 10. Turn left. 11. Go along the path for 6m. 12. The path leads to your destination Projektraum 8.

Continued on next page

Table 4.5 - continued from previous page

	ISIGNS	**MTBT**
Sample Route 2	1. Follow the sign pointing to E212. 2. Now you are at E212. Turn right. 3. Go along the path for 9m. 4. The path leads to your destination AE0309A.	1. Go along the path for 19m. 2. Turn slightly right. 3. Go along the path for 6m. 4. Turn left. 5. Go along the path for 2m. 6. Turn slightly left. 7. Go along the path for 2m. 8. Turn sharp right. 9. Go along the path for 8m. 10. The path leads to your destination AE0309A.
Sample Route 3	1. Go along the path for 5m. 2. Turn left. 3. Go along the path for 5m. 4. Turn slightly right. 5. Go along the path for 10m. 6. Now you are at Stiege 2. Follow the sign pointing to Hörsaal 17. 7. Follow the sign pointing to Hörsaal 17. 8. The path leads to your destination Hörsaal 17.	1. Go along the path for 9m. 2. Turn left. 3. Go along the path for 6m. 4. Turn slightly right. 5. Go along the path for 26m. 6. Turn slightly right. 7. Go along the path for 61m. 8. Turn right. 9. Go along the path for 8m. 10. Turn left. 11. Go along the path for 3m. 12. The path leads to your destination Hörsaal 17.
Sample Route 4	1. Go along the path for 5m. 2. Turn left. 3. Go along the path for 13m. 4. Now you are at Stiege 1. Follow the sign pointing to Stiege 2. 5. Follow the sign pointing to Stiege 2. 6. Now you are at Stiege 2. Go straight. 7. Go along the path for 10m. 8. Turn right. 9. Go along the path for 4m. 10. The path leads to your destination AA0303.	1. Go along the path for 5m. 2. Turn left. 3. Go along the path for 73m. 4. Turn slightly right. 5. Go along the path for 20m. 6. Turn right. 7. Go along the path for 4m. 8. The path leads to your destination AA0303.

Figure 4.8 - Potentially confusing turning situations. (A) The steps used to connect two building sections with different level heights are omitted in the database (see elaboration in Section 3.2.1.1). The two potential turns are instructed as “turn right” and “turn slightly right”. (B) The two potential turns are both instructed as “turn right” within a short distance.

4.4 Discussion

The proof-of-concept and the sample routes have successfully demonstrated the feasibility of ISIGNS in automatically incorporating sign semantics into navigation graphs, planning routes, and generating easy-to-understand instructions.

The proposed ISIGNS assumes the availability of a navigation graph and a sign dataset, which can typically be derived from existing indoor spatial databases. This means that the approach can be applied to construct sign integrated navigation systems for various indoor environments where graph-based modelling suits. However, it should be noted that this method may not be appropriate for indoor spaces with large open areas, such as exhibition halls, as Yang and Worboys (2015) discussed.

One identified limitation is that the semantic edges in ISIGNS currently connect to the centroids of rooms, disregarding the decision point before entering the room (see Section 4.3.4.2). This can be improved by assigning room semantics to portal nodes and connecting edges only to these portal nodes, enabling door-to-door indoor navigation.

It is important to consider that a semantic edge’s stored length and last traversable edge attributes are determined based on the assumption that a sign leads to the shortest path to its destination. Yet, in cases where the building circulation serves other purposes, such as chronological order in museum exhibition rooms, the signage system may be designed accordingly. When adapting the algorithm to other indoor environments, these attributes should be modified to align with the specific context.

ISIGNS relies on the consistency and completeness of the signage information in the database and the regular maintenance of the database. As it relies on accurate signage information to guide navigators, the absence of signs along a route where wayfinders need to change direction can lead to confusion. For instance, in Sample Route 1, if the sign at the corridor indicating Staircase 3 (Figure 4.4) is missing, users can easily become disoriented. It is also essential to update the database when there are changes in the physical environment.

On the other hand, ISIGNS can serve as a tool to assess the quality of the existing signage system in an indoor environment. If the signage system is effective and comprehensive, ISIGNS will predominantly use semantic edges and generate instructions based on signs. However, if the signage system is inadequate or inconsistent, ISIGNS will provide more metric-based turn-by-turn instructions. In the most extreme case, ISIGNS will generate instructions that rely entirely on metric information. This can serve as an indicator for building managers to detect where additional signs are needed, particularly in connecting points of building sections or along long-distance paths.

To evaluate the quality of the route instructions generated by ISIGNS, we employed the FRES readability score and conducted a qualitative comparison with MTBT instructions. The FRES score is a quantitative measure to assess the reading difficulty of English sentences. In general, the route instructions received scores indicating that they are fairly easy to read. However, the FRES score primarily considers the number of words in relation to sentences and syllables to words. Consequently, they favour short sentences with few syllables while failing to consider the actual content and their meaning. This explains the lower score received by Instruction 4 for Sample Route 2 compared to instructions with the same schema in other routes. Thus, while the FRES score serves as a quick check, empirical tests with human subjects offer a more comprehensive evaluation, which will be presented in Chapter 5.

As an initial evaluation, the qualitative comparison demonstrated the advantages of ISIGNS route instructions over MTBT. ISIGNS generated fewer instructions, utilised qualitative information, and addressed confusion at turning points, potentially improving wayfinding performance and overall navigation experience.

Furthermore, ISIGNS guides navigators to attend to signs in the environment, offering several advantages. Firstly, navigators can spend less time matching the navigation system to the surroundings, resulting in more efficient and effective instructions. Secondly, the convergence of route instructions and the environment provides mutual confirmation, making navigators affirmed and secure, and enhancing their confidence and overall experience. In addition, paying attention to the environment improves situational awareness and facilitates spatial knowledge acquisition (Brügger et al., 2019; Ishikawa, 2020). The design of the signage system not only guides navigators but also reflects the organisational structure of the building. Such encoded semantic nature aids humans in encoding spatial relations (Chrastil & Warren, 2012) and promotes meaningful spatial learning (Sweller et al., 2011).

However, to empirically validate the above qualitative analysis regarding the wayfinding performance, user experience, and spatial learning, an empirical experiment is necessary, which will be reported in Chapter 5.

4.5 Summary

In this chapter, we propose a method to integrate signs and their semantics into mobile navigation services, by first modelling signs and their semantics into an indoor navigation model. Then, routes considering sign semantics are generated and communicated to navigators as route instructions. A proof-of-concept for the Indoor Sign InteGrated Navigation System (ISIGNS) is developed to showcase the processes.

The implementation and evaluation of the proposed method have demonstrated its ability to automatically generate a navigation graph that incorporates semantic information from signs, plan routes and provide route instructions accordingly.

These route instructions are easy to understand in terms of readability. Moreover, a qualitative comparison has revealed multiple advantages of ISIGNS over metric-based turn-by-turn instructions, such as fewer instructions, utilising qualitative information, and addressing confusion at turning points. It can potentially improve wayfinding performance, overall navigation experience, and spatial knowledge acquisition.

Given our objective of enhancing user experience and promoting spatial learning by integrating signs into indoor navigation systems, evaluating ISIGNS in real-world scenarios was crucial. A navigation experiment was conducted in this regard, comparing ISIGNS with the conventional navigation system using metric-based turn-by-turn instructions. The settings and findings of this experiment will be detailed and discussed in the following chapter.

Chapter 5

User study in the TU Wien

In Chapter 4, we proposed the Indoor Sign InteGrated Navigation System (ISIGNS) and implemented a proof-of-concept prototype. We quantitatively evaluated the readability of the generated route instructions and qualitatively compared them with the metric-based turn-by-turn instructions from the conventional navigation system.

To evaluate the performance of the proposed ISIGNS in the real world, and test whether using ISIGNS prompts spatial learning, we conducted a navigation experiment comparing ISIGNS with the conventional navigation system using metric-based turn-by-turn instructions. In this chapter, we report on our in-situ experiment in the main building of the Vienna University of Technology.

5.1 Introduction and research questions

In Chapter 2, we reviewed previous studies and noticed that allocating human attention to relevant environmental features could assist spatial learning. In the outdoor environment, this is usually implemented by including landmarks in route instructions. The benefits are twofold. On the one hand, relevant environmental features help humans encode place–action associations and spatial relations of places, thus reinforcing the spatial knowledge of the travelled area (Chrastil & Warren, 2012). On the other hand, humans naturally refer to landmarks to direct others (Denis, 1997). Hence, adding landmarks to navigation instructions can reduce the system-user gap, which is the gap between the information presented by information systems and that processed by the human cognitive system (Norman, 2013; Raubal, 2009). Users need to bridge this gap before they can solve the same problem. The narrower the gap, the more accessible for humans to comprehend, which leads to less confusion and increased learning (Norman, 2013). The positive effect of including landmarks to support spatial learning has been verified for the outdoor environment in both virtual settings (Gramann et al., 2017; Wunderlich & Gramann, 2018; Wunderlich et al., 2022) and the real world (Wunderlich & Gramann, 2021).

Whereas indoors, B. Liu et al. (2021) confirmed that landmarks benefit spatial learning by augmenting semantic landmarks into navigation services on mixed reality devices. As informed by literature, existing navigational aids are semantic landmarks due to the messages they convey (see Chapter 2). In seeking a method to include semantic landmarks in navigation services on conventional devices (i.e., smartphones), we conducted an explorative study (reported in Chapter 3) to find out what semantic landmarks are most referred to in wayfinding and mentioned in human route directions. We concluded that humans use signs to instruct others, in addition to their high reliance on signs for wayfinding. Accordingly, we proposed the method ISIGNS to include them in navigation systems in Chapter 4. In addition to merely enriching the instructions with signs, we further consider the semantics of signs in indoor space modelling and route planning. Yet, whether ISIGNS can achieve similar advantages on spatial learning and its influence on user experience is still to be explored.

Consequently, we conducted an in-situ experiment, aiming to address the following research question:

RQ 3 Compared with conventional mobile navigation services, how do navigators' wayfinding performance, spatial learning, and user experience differ when navigating with the integrated indoor navigation service (ISIGNS)?

We hypothesised the following:

H1. Participants navigating with ISIGNS will perform better than the conventional metric-based navigation system, in terms of efficiency and effectiveness.

H2. Participants navigating with ISIGNS will acquire more spatial knowledge than the conventional metric-based navigation system.

H3. Participants will be more satisfied with ISIGNS than the conventional metric-based navigation system, in terms of preference and overall user experience.

ISIGNS generates fewer instructions than the conventional navigation system using metric-based turn-by-turn instructions. Additionally, the instructions are more unambiguous and easier to comprehend and execute. Furthermore, the route instructions and the environment mutually confirm each other, so participants are more affirmed rather than confused. They can spend less time matching the navigation system with the environment and focus more on the environment. Hence, we hypothesised in H1 that participants would be more efficient and effective using ISIGNS. ISIGNS explicitly instructs participants to follow the signs in the environment. To do so, they need to attend more to the environment. In addition, the semantic nature of signs facilitates navigators to encode spatial relations. We, therefore, hypothesised in H2 that participants would acquire more spatial knowledge. The route instructions from ISIGNS are more similar to human route instructions than the metric-based ones. By guiding their attention to the environment, participants are confirmed by the environment during navigation. Consequently, they feel assured and secure, and the overall experience was expected to be more satisfactory (H3).

5.2 Methods

The experiment consisted of two route-following tasks, each followed by a set of tasks for assessing spatial knowledge acquisition. We concluded the experiment with a semi-structured interview guided by a questionnaire. To minimise the effect of individual differences, as well as access participants' preferences on the different instructions, we applied a within-subject design. All participants experienced both instruction types on either of the two routes. To counterbalance the learning effect and fatigue, we randomised the order of which instruction type and route to start with.

5.2.1 Participants

A total of 52 participants (33 females and 19 males) were recruited through courses and volunteering groups. Their ages range from 20 to 45 years (M= 27.2, SD = 5.6). The participants recruited through courses were from geodesy and cartography backgrounds and were compensated with course credit.

5.2.2 Materials

5.2.2.1 Study area and routes

The study was conducted in the main building of the Vienna University of Technology, the same as one of the buildings in the explorative study reported in Chapter 3. The routes are displayed in Figure 5.1 and Figure 5.2, with corresponding route instructions in Table 5.1. We randomly named the routes as C and K, so that we could assign each participant a coded ID based on the order of the routes and instruction types they would encounter. The C route (Figure 5.1) was 142m long, started from the door to the left wing of the building on the ground floor, and ended at lab E242. The K route (Figure 5.2) started from the landing of staircase seven on the third floor (the highest level of that wing), while the destination was the hall Kuppelsaal. Due to the difference in the routing algorithm, the K route calculated by the shortest path algorithm was 155m long, while by the ISIGNS was 185m long.

We decided on this pair of routes for several reasons. First, the ISIGNS calculated route could be longer than the shortest path. We were interested in participants' perceptions and reflections on it. Due to the constraints on public accessibility, the detoured route to Kuppelsaal was the only possible publicly accessible route that resulted in different lengths by the two routing methods. The threshold δ was set to 20% for the calculation. Second, for a within-subject design, the pair of routes should be as similar as possible to avoid confounding effects by the routes. The C route was created by switching the start and destination pair of the K route and adding level differences. As the K route went half level [1] down and one level up, we initially planned the same for the C route. However, the second level and part of the

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[1] Several buildings with different floor heights existed in the current location of TU Wien main building. They were later linked by staircases into a building complex, which is today's main building. Thus, some areas have half level differences. However, this half level difference was not reflected in the official floor plan, so as in the ISIGNS.

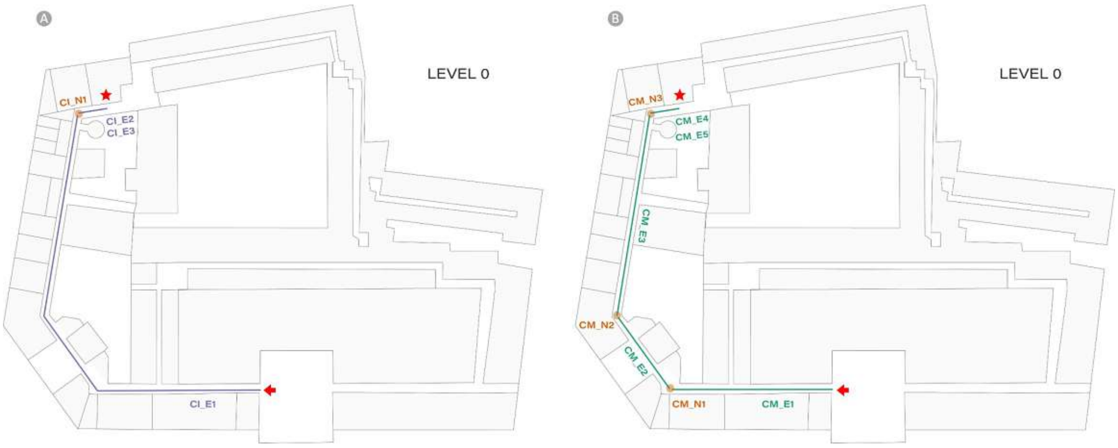

Figure 5.1 - The C route. The ISIGNS route (A) and the MTBT route (B) are visualised in purple and green, respectively, with instruction numbers labelled beside the coressponding segments. The start is represented as a red arrow, with the end as a red star. The decision points are visualised as orange circles, with instruction numbers labelled beside them.

first floor were under construction, and the Festsaal and the admission office were on the first floor, with which almost every student was familiar. Thus, we decided to place the C route on the ground floor, only with half a level up. Third, to evaluate the concept of ISIGNS, both possibilities for a destination (i.e., on a sign or not on a sign) should be considered. E242 was not on any sign, while signs could direct participants to Kuppelsaal.

5.2.2.2 Route following with mobile navigation service

Concerning potential localisation inaccuracy indoors, the “Wizard of Oz” method was used in the experiment. We used two different Android phones to distinguish the participant’s and the experimenter’s phones. A Samsung Galaxy S8 was used for the participants and a Sony Xperia Z5 Premium for the experimenters. The two phones were connected through TeamViewer [2] , allowing the experimenter to remotely control the participant’s phone. Similar to Bakogiannis et al. (2019), we created identical-sized static images to visualise the experiment routes and an application to switch the images to create the illusion of a functioning mobile navigation service (Figure 5.3). [3]

The images were created in Adobe Photoshop, with a base floor plan imitating the style of Google Indoor Maps. The features on the base floor plan were minimised, with only the basic geometry visualised. The routes were illustrated in grey dots, with a blue dot indicating the user’s current location. Each dot was 2.3 m apart, as was the difference between each image.

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[2] https://www.teamviewer.com/en-us/download/android/

[3] You can find the animated visualisations of the whole route in the links below.
Route C using ISIGNS: https://owncloud.tuwien.ac.at/index.php/s/o87j17hptb5mPlO
Route C using MTBT: https://owncloud.tuwien.ac.at/index.php/s/CXXwafwPt5PE70e
Route K using ISIGNS: https://owncloud.tuwien.ac.at/index.php/s/TNv9AojXa7wsXNq
Route K using MTBT: https://owncloud.tuwien.ac.at/index.php/s/EzL7IoP17v9vauD

Table 5.1 - The route instructions for both routes and systems.

	ISIGNS	**MTBT**
C route	CI_E1. Follow the sign pointing to **Hörsaal 8**. CI_N1. Now you are at Hörsaal 8. Turn **right**. CI_E2. Go along the path for **7m**. CI_E3. Your destination **E242** is located on the **left** side of the path.	CM_E1. Go along the path for **48m**. CM_N1. Turn **right**. CM_E2. Go along the path for **27m**. CM_N2. Turn **slightly right**. CM_E3. Go along the path for **60m**. CM_N3. Turn **right**. CM_E4. Go along the path for **7m**. CM_E5. Your destination **E242** is located on the **left** side of the path.
K route	KI_E1. Follow the sign pointing to **Stiege 2**. KI_N1. Now you are at Stiege 2. Follow the sign pointing to **Stiege 1**. KI_E2. Follow the sign pointing to **Stiege 1**. KI_N2. Now you are at Stiege 1. Follow the sign pointing to **Kuppelsaal**. KI_E3. Follow the sign pointing to **Kuppelsaal**. KI_E4. The path leads to your destination **Kuppelsaal**.	KM_E1. Go along the path for **15m**. KM_N1. Turn **left**. KM_E2. Go along the path for **60m**. KM_N2. Turn **slightly left**. KM_E3. Go along the path for **27m**. KM_N3. Turn **left**. KM_E4. Go along the path for **42m**. KM_N4. Turn **right**. KM_E5. Use the staircase to go to **level 4**. KM_N5. Turn **right**. KM_E6. Go along the path for **7m**. KM_E7. The path leads to your destination **Kuppelsaal**.

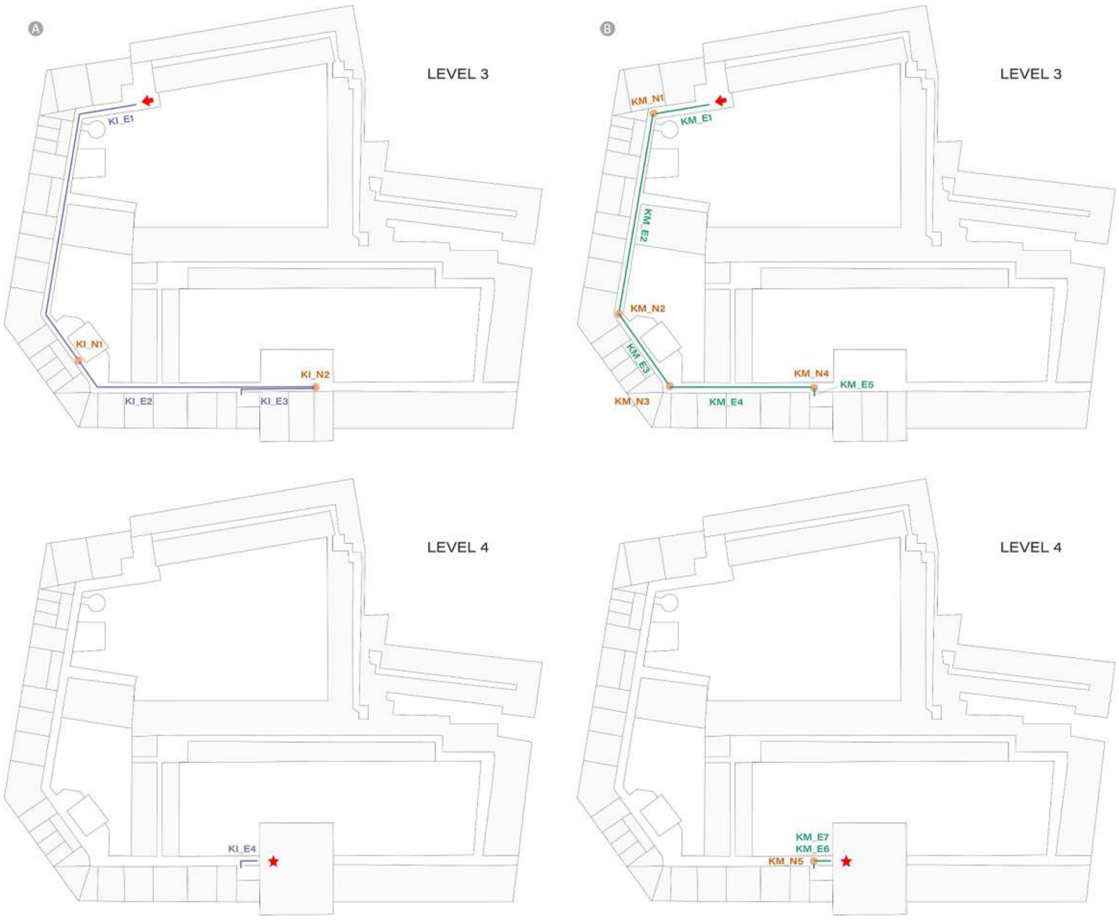
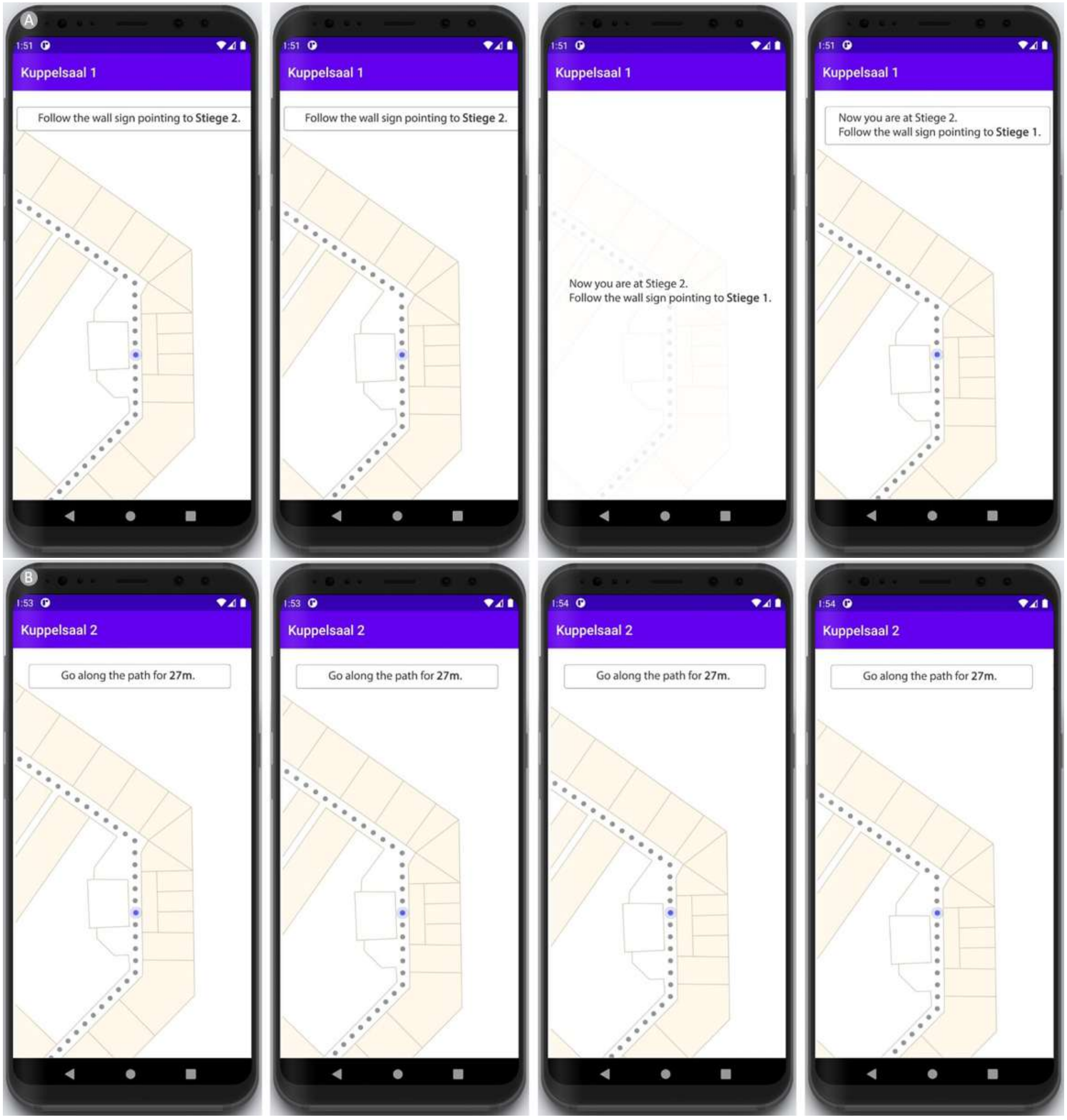


Figure 5.2 - The K route starts from Level 3 to Level 4. The ISIGNS route (A) and the MTBT route (B) are visualised in purple and green, respectively, with instruction numbers labelled beside the coressponding segments. The start is represented as a red arrow, with the end as a red star. The decision points are visualised as orange circles, with instruction numbers labelled beside them.

The images also included the corresponding route instructions. Two sets of instructions were created. Metric-based turn-by-turn instructions (abbreviated as MTBT) were used for the conventional navigation system. Based on the feedback from the pilot study, we modified “sign” to “wall sign” for the ISIGNS-generated instructions and included an instruction pop-up to highlight the instructions (Figure 5.3). In the pilot study, the participants were unsure where to find the signs due to the small signage on the wall and the different signage systems in the building (see Section 3.2.1.1). We will discuss the influence of the existing signage system on ISIGNS and user experience in Section 5.4.3.

The application was created in Android Studio. It was an image switcher with two invisible buttons to switch the images forward and backwards. The participants were informed not to interact with the application during the experiment. At the same time, the experimenter



Follow the wall sign pointing to **Stiege 2.**

Follow the wall sign pointing to **Stiege 2.**

Now you are at Stiege 2.
Follow the wall sign pointing to **Stiege 1.**

Now you are at Stiege 2.
Follow the wall sign pointing to **Stiege 1.**

Go along the path for **27m.**

Go along the path for **27m.**

Go along the path for **27m.**

Go along the path for **27m.**

Figure 5.3 - Illustration of the navigation service with ISIGNS and MTBT.

clicked on the buttons according to the participants' movements.

5.2.2.3 Spatial knowledge acquisition assessment tasks

To assess the spatial knowledge participants acquired during the route-following phase, they were asked to perform a set of eight tasks. We categorised the tasks by the spatial knowledge they assess in Table 5.2. They are described in detail below in the order of their appearance in the experiment.

Table 5.2 - Different types of spatial knowledge assessed by task performance.

Type of spatial knowledge	Tasks
Landmark knowledge	Sketching, Route description, Landmark recognition
Route knowledge	Sketching, Route description, Landmark ordering, Route direction recall
Survey knowledge	Direction estimation, Spatial awareness, Landmark placement

In accordance with the Vienna University of Technology's COVID-19 measurements, all the tasks that required interaction with physical media were held on paper. To minimise the influence of the experimenters, we printed out the task set and their descriptions for reading and showing to the participants (Appendix B).

Direction estimation task

At the end of each route, participants estimated the direction to the starting point of that route. They were given a sheet of paper, pre-drawn a circle with a line in the centre indicating their facing direction. They were asked to draw a line from the centre to estimate the direction to the starting point. All participants were shown the same facing direction. We used the direction estimation task to assess participants' acquired survey knowledge (Huang et al., 2021; Ishikawa & Montello, 2006).

We also asked the participants to rate their confidence level with the direction estimates, from 1 (not sure at all) to 7 (very sure).

Spatial awareness task

Participants drew their current location (with a circle) and orientation (with an arrow) on the provided floor plan. The floor plan presented only the basic geometry of the building, with the starting point marked as a black circle. All the participants were shown the same facing direction as the orientation estimation task.

The location and orientation awareness tasks together indicate the participant's overall spatial awareness, which is how well they build the spatial relations between themselves and the environment and link that to the spatial representation of the environment (Li & Klippel, 2014; Liben et al., 2010). Unlike Liben et al. (2010), who were interested in participants' abilities in self-localisation and thus distracted them along the way. We were interested in how well participants develop such spatial relations while navigating and could associate that with an allocentric reference system, i.e., the floor plan in our experiment. Accordingly, we use the spatial awareness tasks to assess acquired survey knowledge.

Sketching task

Participants drew the route they took on the previous floor plan and depicted the characteristics of the route as detailed as they could by adding landmarks.

As mentioned in Section 3.5, the sketching task is influenced by participants' drawing skills, especially in an indoor environment involving level changes. The methods (e.g., Krukar et al., 2018) developed for assessing the route and survey knowledge for outdoor sketch maps are not well suited for analysing indoor sketch maps. Therefore, we provided them with the base floor plan only depicting the base structure (Van Asselen et al., 2006) and looked into the sketches in terms of the number of landmarks drawn (landmark knowledge) and the accuracy of the drawn route (route knowledge).

Route description task

Participants verbally described the route as if another new student had asked them the way from the starting point to the destination. The verbal descriptions were recorded.

Similar to the sketching, the route descriptions were used to assess the acquisition of landmark knowledge by calculating the number of landmarks mentioned and route knowledge by the accuracy of the described route.

Landmark recognition task

Participants were presented with ten photos for each Route (Figure 5.4). Half of them (four at intersections and one within route segments) were along the route, taken from the same perspective as the participants' viewing perspective during route following. Another half were taken from other areas in the same building to pair with the on-route photos. They were randomly labelled with letters (e.g., "E", "O", "D"), and for the ones at intersections, all possible outgoing options were numbered (e.g., "D-1", "D-2", and "D-3"). The experimenter presented them to the participants in random order. Participants wrote down the IDs of all photos they thought were along the current route. We used this task to assess the landmark knowledge participants acquired (Huang et al., 2012; Wenczel et al., 2017).

Landmark ordering task

Participants ordered the photos they chose in the previous task according to the order they encountered them along the route. This task helped to assess route knowledge acquisition (Burte & Montello, 2017).

Landmark placement task

Participants placed the photos they chose, by writing their IDs on the corresponding locations on the floor plan. They were provided with a new floor plan to prevent interference with the previous sketching task.

Placing landmarks on a floor plan requires participants' understanding of relationships among landmarks and their relations to the overall environmental layout, which reflects participants' survey knowledge (Huang et al., 2012; Münzer et al., 2006; Wenczel et al., 2017).

Route direction recall task

The experimenter took the intersections from the participants' chosen photos and asked them to recall the direction taken by writing down the direction IDs. We used this task to estimate route knowledge acquisition (Huang et al., 2012; Münzer et al., 2006).

Figure 5.4 - Landmark recognition task photos for C route (A) and K route (B).

5.2.2.4 Post experiment questionnaire

Participants filled out a questionnaire at the end of the experiment. It consisted of questions concerning their familiarity with the building and routes, with outdoor and indoor mobile navigation services, perceived task difficulties, preference over the two instruction types, and user experience. For user experience, a modified Short Version of the User Experience Questionnaire (UEQ-S) (Schrepp et al., 2017) was included in the questionnaire. The UEQ-S is a short version of the user experience questionnaire to measure users' subjective impressions towards a product. It consists of semantic differential items, i.e., pair of terms with opposite meanings. We modified the questionnaire items in accordance with the suggestions from participants in the pilot study, while keeping the form of semantic differentials (Appendix B).

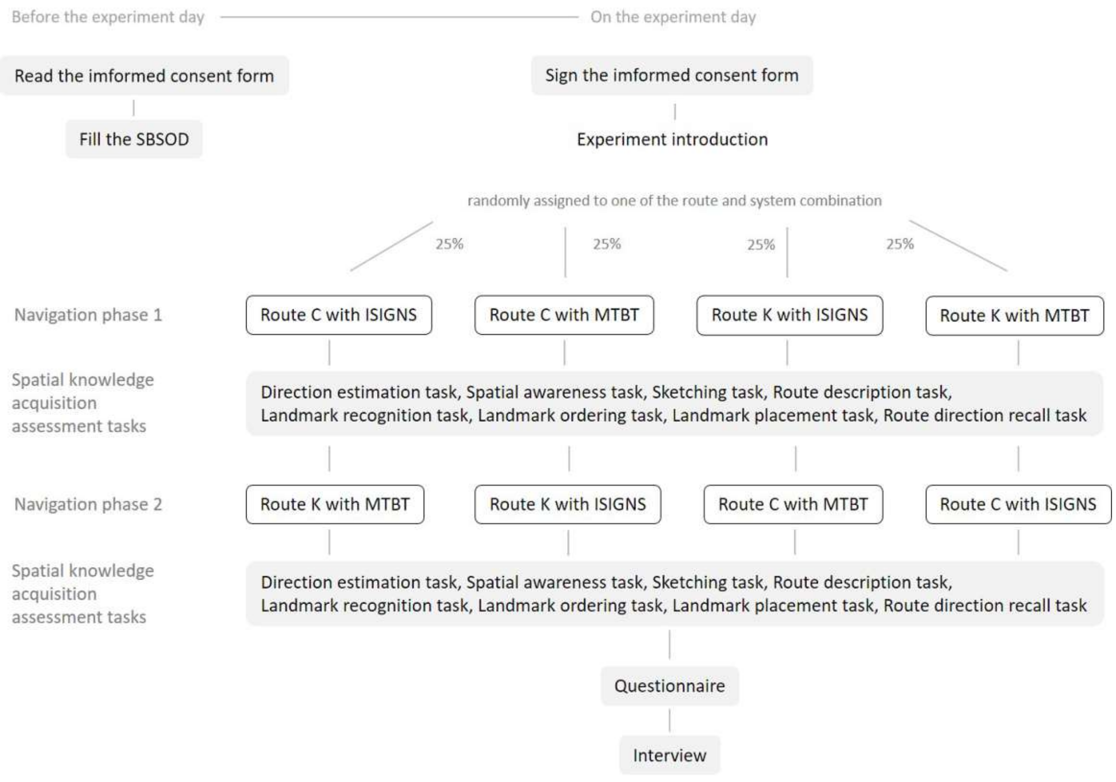


Figure 5.5 - Experiment procedure.

5.2.3 Experimental procedure

Figure 5.5 illustrates the overall procedure of the experiment. One day before the experiment, participants were randomly assigned IDs. We sent the ID, a digital version of the informed consent and an online questionnaire of the Santa Barbara Sense-of-Direction Scale (SBSOD) to each participant individually. The SBSOD was a self-reported measure to assess participants' ability to acquire spatial knowledge (Hegarty et al., 2002).

On the experiment day, the experimenters greeted the participants individually in front of the building. They were first asked to sign the informed consent form. If there were no online entry of the participant's SBSOD, a printed version was filled out on-site.

One experimenter then read an introduction, which explained to the participants that the experiment was about testing the newly developed indoor navigation system. The participants were set in a scenario of their study program's welcoming week. They would use the application to navigate to two rooms they would often encounter during their study: the lab E242 and the Kuppelsaal. As the navigation system was still under testing, we would set the application up for the desired destinations and asked them only to follow the instructions on the screen but not to interact with the phone, to avoid any potential technical failure. They were informed there would be tasks after each route and a final interview after both routes, but they were unaware of the detailed tasks. They were also notified that one experimenter would walk after them for assistance and look at the phone to check the route. The other experimenter would record the navigation process.

Afterwards, the participants were guided to one of the starting points according to their IDs. They were then given the phone to familiarise themselves with the interface, notified of the destination of the current route, and showed the starting direction. Then the participants followed the application to the destination. One experimenter shadowed the participants at a several-meter distance and manipulated the application to match the participants' movements (Figure 5.6). If participants went in the wrong direction at decision points, the experimenter indicated it was wrong but did not reveal the correct direction. The participants were only advised to follow the instructions on the phone. No other assistance was given during the experiment. The other experimenter kept another two-meter distance for the recording. When participants reached the first destination, they were asked to perform the spatial knowledge acquisition tasks for the current route. Next, the two experimenters led the participants to the second route's starting point and repeated the procedure.

After finishing both routes, the participants completed a questionnaire and a semi-structured interview to clarify their answers and gather general feedback. This interview was not recorded, but the experimenters made notes. In the end, the participants were thanked and debriefed. The whole procedure lasted 40 to 55 minutes.

5.3 Results

In this section, we begin by describing the participants' background and their self-reported spatial ability. Next, we look into navigation performance and analyse spatial knowledge acquisition. In the end, we report on our questionnaire findings, including task difficulty rating, preference and user experience.

For the following analyses, we used the paired *t*-test (two-tailed) when the dependent variable was measured at least at the interval level, and the data were normally distributed (Field et al., 2012), the Wilcoxon signed-rank test (two-tailed) for the data not fulfilling a normal distribution, and the McNemar test when the dependent variable was either correct or incorrect (Agresti, 2018; McNemar, 1947). We regard a statistical analysis result as significant at a *p*-value of .05. All statistical analyses were performed in RStudio and reported according to Field et al. (2012).

The results of all analyses using the paired *t*-test are reported in the text or listed in the tables below, including the mean (*M*) and standard deviation (*SD*) for each system, the *t*-statistic, the *p*-value, and the effect size measured by Pearson's correlation coefficient *r*. The results are visualised in bar charts with vertical error bars denoting 95% confidence intervals. The Wilcoxon signed-rank test results are reported in the text or listed in the tables below, including the median (*Mdn*) for each system, the *p*-value, and the effect size measured by Pearson's correlation coefficient *r*. The results are visualised in box plots. The results of the McNemar tests are reported in the text. If *p* is less than .001, we report it as "$< .001$"

Figure 5.6 - Experimental setup. A participant holds the smartphone, and an experimenter follows the participant during the experiment (Photo by Andrea Binn).

and mark it with “***”. Otherwise, we report the exact *p*-value, marking it with “*” and “**” for a p-value less than .05 and less than .01, respectively.

The results of all analyses using the paired t-test are reported in the text or listed in the tables below, including the mean (M) and standard deviation (SD) for each system, the t-statistic, the p-value, and the effect size measured by Pearson’s correlation coefficient r. If p is less than .001, we report it as “$< .001$” and mark it with “***”. Otherwise, we report the exact p-value, marking it with “*” and “**” for a p-value less than .05 and less than .01, respectively. The results are visualised in bar charts with vertical error bars denoting 95% confidence intervals. The results of the McNemar tests are reported in the text.

5.3.1 Participants

Participants rated their familiarity with the building and routes on a scale from 1 (not familiar) to 7 (very familiar). At the end of our experiment, we interviewed the participants on their familiarity choices. Some participants rated high for familiarity with the building, but were unfamiliar with any routes. They were working in a section of the building that differed from the two routes. We considered familiarity with the routes as the actual relevant factor. Previous studies (Huang et al., 2012; Li & Klippel, 2014) pointed out that familiarity with the environment significantly affects people’s navigation performance and spatial knowledge acquisition. Thus, we only selected the participants that rated their familiarity with both routes below 3 (inclusive) for the following analysis, similar to Burte and Montello (2017). The screening of familiarity resulted in 42 participants (29 females and 13 males), with an age range from 20 to 45 years ($M = 27.5$, $SD = 5.9$).

All participants had used an outdoor mobile navigation system before. Most of them used it at least weekly (ranging from 1 to 7, $M = 5.429$, $SD = 1.484$), while only eight participants ever used an indoor navigation system, and all of them were only a few times in a museum or an airport (ranging from 1 to 7, $M = 0.310$, $SD = 0.715$).

The SBSOD consists of 15 questions, with half of them phrased positively. The score ranges from 1 (strongly agree) to 7 (strongly disagree). We reversed participants' responses, so that a higher score represented a better sense of direction. The average score of our participants is 4.553 ($SD = 1.173$), which indicates a balanced group. Compared with participants from previous studies (Huang et al., 2021), our participants reported having a similar spatial ability.

5.3.2 Navigation performance

The navigation performance are represented in terms of efficiency (travel speed) and effectiveness (the errors and stops). We use the speed instead of time to assess the efficiency, because the two routes in the experiments differ in length. The travel time, navigation errors, and stops were obtained from the navigation videos.

5.3.2.1 Efficiency

Our first hypothesis is that navigating with ISIGNS is more efficient than using MTBT because of fewer instructions and the confirmation in the environment. We assessed the navigation efficiency by travel speed (m/s), which was calculated using the recorded travel time against the length of each route in one of the instruction conditions (C route: 142m, K route with MTBT: 155m, K route with ISIGNS: 185m). Figure 5.7 shows the average speed of participants using each system. A paired t-test did not reveal a significant difference between ISIGNS ($M = 0.914$, $SD = 0.159$) and MTBT ($M = 0.878$, $SD = 0.135$), $t(41) = 1.072$, $p = .290$, $r = .165$. This means navigating with ISIGNS did not significantly improve navigation efficiency.

5.3.2.2 Effectiveness

Navigation errors

The navigation errors and the number of stops indicate how effectively the system can support navigators. We counted as an error when participants turned wrong at a decision point or walked passed the destination.

We hypothesised that ISIGNS was more effective than MTBT, because the instructions are easier to comprehend and execute and provide more user confirmation. That is, participants

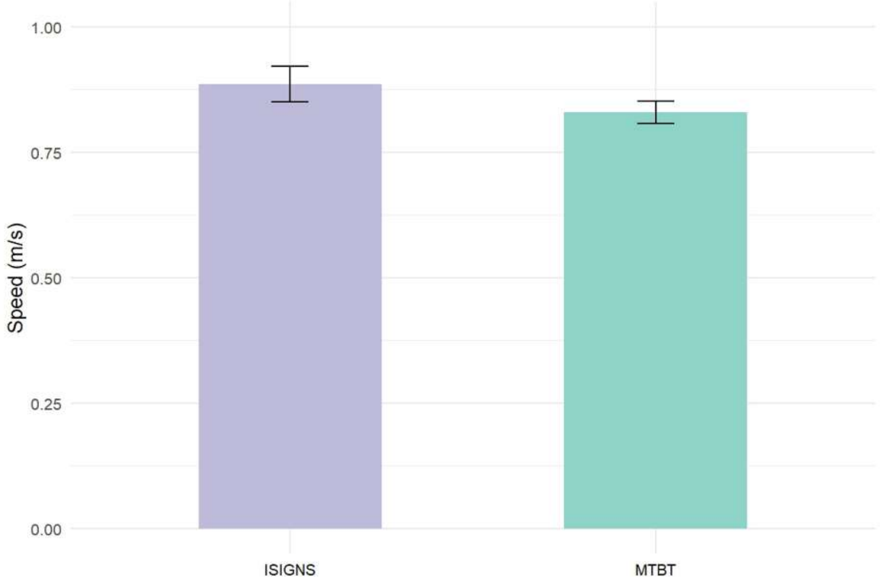


Figure 5.7 - The average speed of participants per system. Vertical error bars denote 95% confidence intervals. Navigating with ISIGNS did not significantly improve navigation efficiency.

using ISIGNS would make fewer errors than MTBT. However, a two-tailed Wilcoxon signed-rank test showed no difference between ISIGNS ($Mdn = 0.000$) and MTBT ($Mdn = 0.000$), $p = 1.000$, $r = .000$.

Figure 5.8A shows the average number of errors. On average, participants made very few errors. However, it differed between participants. Looking into the navigation errors of each participant, we found out that 50% of the participants made no error. Among the other half, 18 out of 42 (42.857%) participants at least once reached the destination without realising it and continued walking forward, which accounted for most errors. This error is more route related rather than the difference between the systems. It happened mainly on the C route, with the last two instructions being the same in both systems ("Go along the path for 7m." and "Your destination E242 is located on the left side of the path."). In the interview, participants explained that they started to look for room E242, when the final instruction popped up, but the door sign for the room was too small to recognise while walking. They expected seven meters to be longer, so they continued walking to look for the room further. This was not a common error for the K route, as the route ended at the door of Kuppelsaal, which was usually locked. Only two participants continued walking without realising they were at the destination when Kuppelsaal had an open door.

Other errors occurred only a few times, including turning to a wrong corridor or a staircase as instructed by MTBT. Participants also mistook the destination as the location on the previous sign when instructed by ISIGNS, i.e., three participants indicated to the experimenters that they were at the destination, when they reached Hörsaal 8.

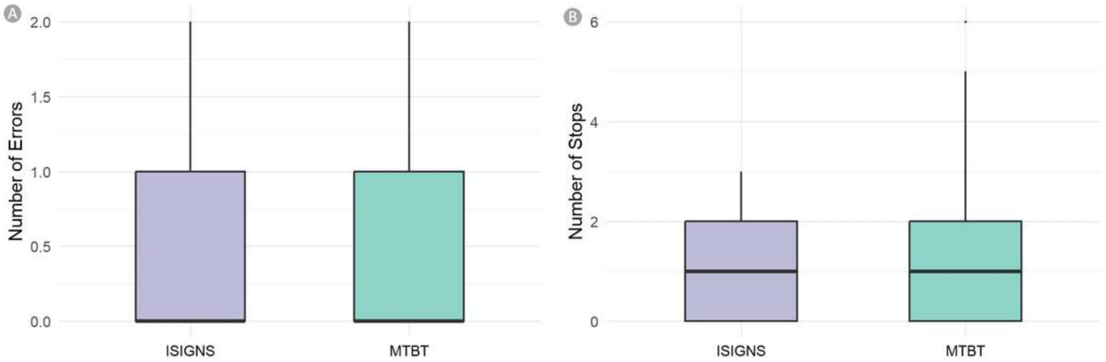


Figure 5.8 - Indicators of navigation effectiveness. (A) The average number of errors made by participants per system. (B) The average number of stops made by participants per system. Navigating with ISIGNS did not significantly reduce errors and stops.

Number of stops

Like Brügger et al. (2019), we defined a stop as when the participant stands still on the ground without moving in any direction. Stops indicate that participants experienced some level of uncertainty during navigation and needed to recalibrate themselves before continuing. We hypothesised that participants using ISIGNS stopped less than MTBT. However, the two-tailed Wilcoxon signed-rank test revealed an insignificant difference between ISIGNS (Mdn = 1.000) and MTBT (Mdn = 1.000), p = .568, r = -.062 (Figure 5.8B).

Most stops (86.364%) occurred at signs while using ISIGNS, especially for the K route, where most participants stopped at Staircase 1 and spent time reading the signs on the wall. As captured in Figure 5.9, there were two signs at this location, and they had different designs. Participants had to read through all the information on the signs to find the one leading to Kuppelsaal. In addition, to follow the sign to Kuppelsaal, participants had to retrace back for several meters, which is counterintuitive. Therefore, many stayed longer before deciding.

When using TBT, the stops occurred mainly on two occasions: at turns (51.852%) and at stairs (31.481%). Participants stopped to match the navigation system with reality before turning or taking the stairs. Compared with the stops at signs, these stops are shorter and more frequent.

5.3.3 Spatial knowledge acquisition

The direction estimation and landmark placement tasks were measured at least at the interval level, and the data were normally distributed, so we performed the paired t-test and aggregated the results in Table 5.3. The landmark analysis for the sketching and route description tasks, as well as the landmark recognition, landmark ordering and route direction tasks, were measured at least at the interval level, while the data did not fulfil a normal distribution. Therefore, we used the Wilcoxon signed-rank test (two-tailed) and presented the results in Table 5.4. The McNemar test was applied to analyse the spatial awareness task and the

Figure 5.9 - The sign at Staircase 1 on the K route, where many participants stopped.

Table 5.3 - Comparison of the spatial knowledge acquisition measures tested by the *t*-test between ISIGNS and MTBT.

Measures	**ISIGNS**		**MTBT**				
	M	*SD*	*M*	*SD*	$t(41)$	*p*	*r*
1. Direction estimation deviation (deg)	44.571	44.487	69.667	64.366	-2.481	.017*	.361
2. Direction estimation confidence	3.929	1.905	3.643	1.936	0.960	.343	.148
3. Landmark placement distance deviation (m)	192.918	191.220	371.165	310.799	-3.430	.001**	.472
4. Landmark placement canonical accuracy	0.793	0.160	0.626	0.335	2.771	.008**	.397

* $p < .05$
** $p < .01$

route correctness for the sketching and route description tasks, whose results were treated as categorical (Agresti, 2018; McNemar, 1947). Their results are reported in the text. We present the analyses and results of all tasks below.

5.3.3.1 Direction estimation

We measured the absolute deviation in degrees between the actual and pointed directions as participants' direction estimates. Figure 5.10A shows the average direction estimation deviation in degrees by ISIGNS and MTBT. A paired *t*-test revealed that participants' direction estimates deviated significantly less using ISIGNS than MTBT (Table 5.3, the first row).

Table 5.4 - Comparison of the spatial knowledge acquisition measures tested by the Wilcoxon signed-rank test between ISIGNS and MTBT.

Measures	**ISIGNS**	**MTBT**		
	Mdn	*Mdn*	*p*	*r*
1. Number of landmarks drawn	4	2	$< .001^{***}$	-.408
2. Number of landmarks mentioned	4	1	$< .001^{***}$	-.556
3. Landmark recognition errors	1	1	$< .001^{***}$	-.370
4. Landmark ordering error rate	0	0	.303	-.112
5. Route direction recall errors	0	0	.048*	-.216

* $p < .05$

*** $p < .001$

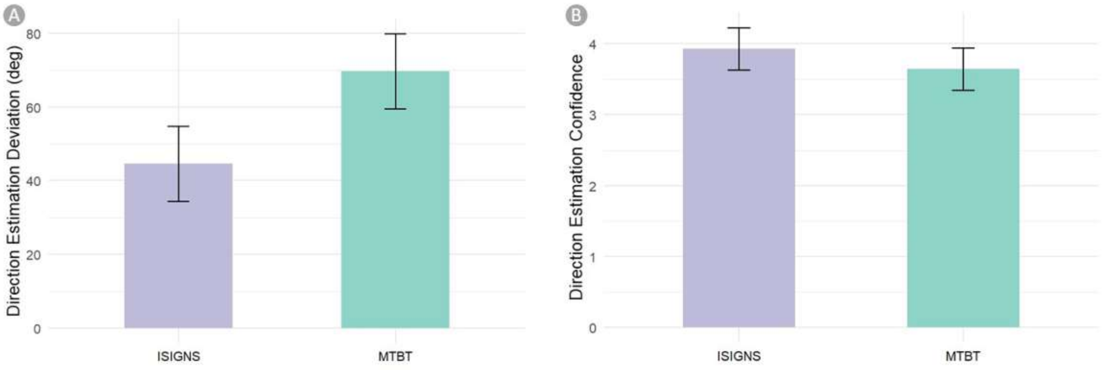


Figure 5.10 - The direction estimation task. (A) The average direction estimation deviation in degrees per system. (B) The average direction estimation confidence per system. Vertical error bars denote 95% confidence intervals.

Using ISIGNS, participants more accurately estimated the direction, indicating more survey knowledge was acquired.

Participants also rated how confident they were in the direction estimation, as shown in Figure 5.10B. They tended to be more confident using ISIGNS than MTBT, but the difference was insignificant (Table 5.3, the second row).

5.3.3.2 Spatial awareness

As participants either marked the correct location, or were unaware of where they were, we categorised their estimated location and orientation as either correct or incorrect. Like Li and Klippel (2014), we considered location estimates correct if the estimated location was within two meters of the actual location, and the orientation estimates correct if the facing direction was within a 10° deviation of the actual direction.

A McNemar test was performed to examine the relationship between the systems and the location estimates. The relation between these variables was significant, $X^2_{McNemar}$ $(1, N = 42) = 5.882$, $p = .015$. A significant relationship was also found between the systems and the orientation estimates, $X^2_{McNemar}$ $(1, N = 42) = 4.923$, $p = .027$. Navigating with ISIGNS is more likely than MTBT to be able to estimate the location and orientation correctly.

The significant influence of the systems on the location and orientation estimates indicates that ISIGNS assisted participants in better attaining an overall spatial awareness. This implies participants acquired more survey knowledge navigating with ISIGNS.

5.3.3.3 Sketch map accuracy

We provided a base floor plan for the sketching task to avoid the influence of participants' drawing ability. Since we were interested in the externalisation of participants' spatial knowledge in the visual and verbal forms in a comparable manner, we analysed these two tasks in an equivalent schema: the number of correct landmarks mentioned and whether the route drawn or described was correct. Some participants illustrated the route correctly and included many landmarks to help depict the route (Figure 5.11A). In contrast, others drew a path entirely into a different part of the building and as simple as possible (Figure 5.11B).

Number of landmarks

We hypothesised that by navigating with ISIGNS, participants could attend more to the environment, thus acquiring more spatial knowledge. One way to externalise the acquired landmark knowledge is to draw landmarks on sketch maps. On average, participants drew more landmarks when ISIGNS guided them, as shown in Figure 5.12. The total number of drawn landmarks revealed a significant difference per system (Table 5.4, the first row), confirming our hypothesis.

Route drawn correctness

The relation between the systems and the route drawn correctness was significant, $X^2_{McNemar}$ $(1, N = 42) = 5.263$, $p = .022$. Guided by ISIGNS, participants acquired more route knowledge.

5.3.3.4 Route description accuracy

Number of landmarks

Another way to actively externalise the acquired landmark knowledge is to mention the landmarks in route descriptions verbally. As displayed in Figure 5.13, the total number of mentioned landmarks revealed a significant difference per system (Table 5.4, the second row), confirming our hypothesis.

Route described correctness

Since there are no established standards for evaluating the quality of route descriptions other than whether the instruction taker has arrived at the target (Richter & Winter, 2014), we analysed it accordingly. The route description was considered incorrect when the participant

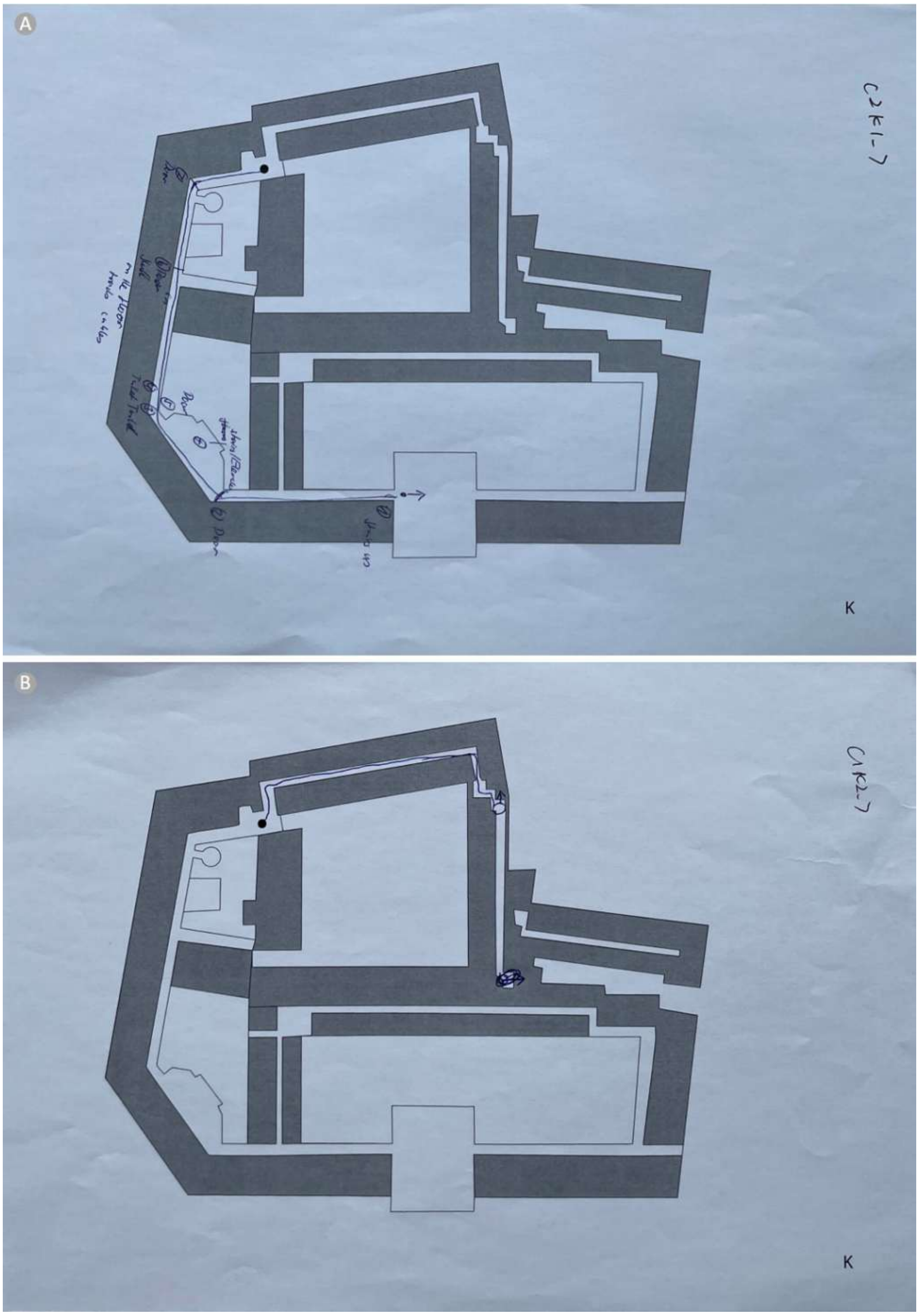


Figure 5.11 - Example sketch maps for the K route. (A) The participant drew the route correctly with many landmarks. (B) The participant drew the route incorrectly with no landmark.

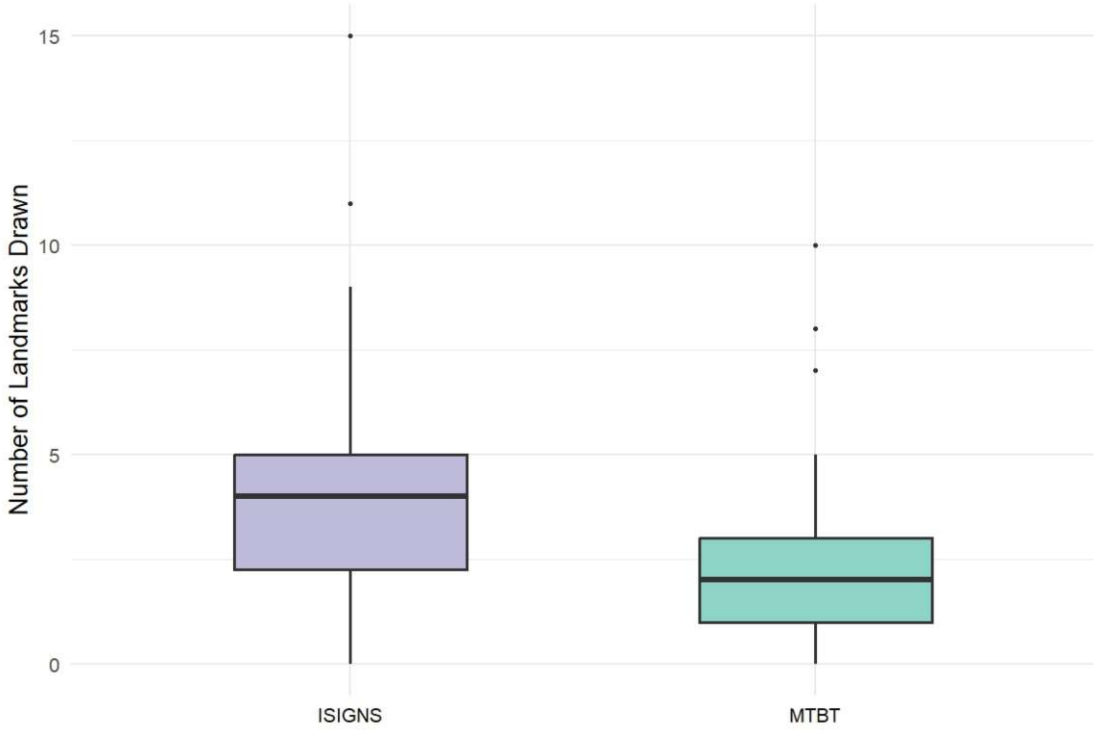


Figure 5.12 - The number of landmarks drawn in sketches per system.

could not verbally describe the route, or the route described was utterly wrong, i.e., to a different direction.

The relation between the systems and the route described correctness was significant, $X^2_{McNemar}$ (1, N = 42) = 6.261, p = .012. Nine participants (21%) repeated the exact instructions they received when navigating. They explained that the instructed route was the only way they knew about getting from the starting point to the destination. It was easier to remember the signs than all the turns, hence the significance.

5.3.3.5 Landmark recognition errors

Similar to Huang et al. (2012), we counted the number of correctly chosen photos from participants, and deducted by the total number of correct photos (5) to calculate the errors. We present the errors here to make this task measure consistent with the others, e.g., direction estimation.

On average, participants made fewer landmark recognition errors when navigating with ISIGNS, as shown in Figure 5.14. The landmark recognition errors revealed a significant difference per system (Table 5.4, the third row), indicating significantly more landmark knowledge acquired when guided by ISIGNS.

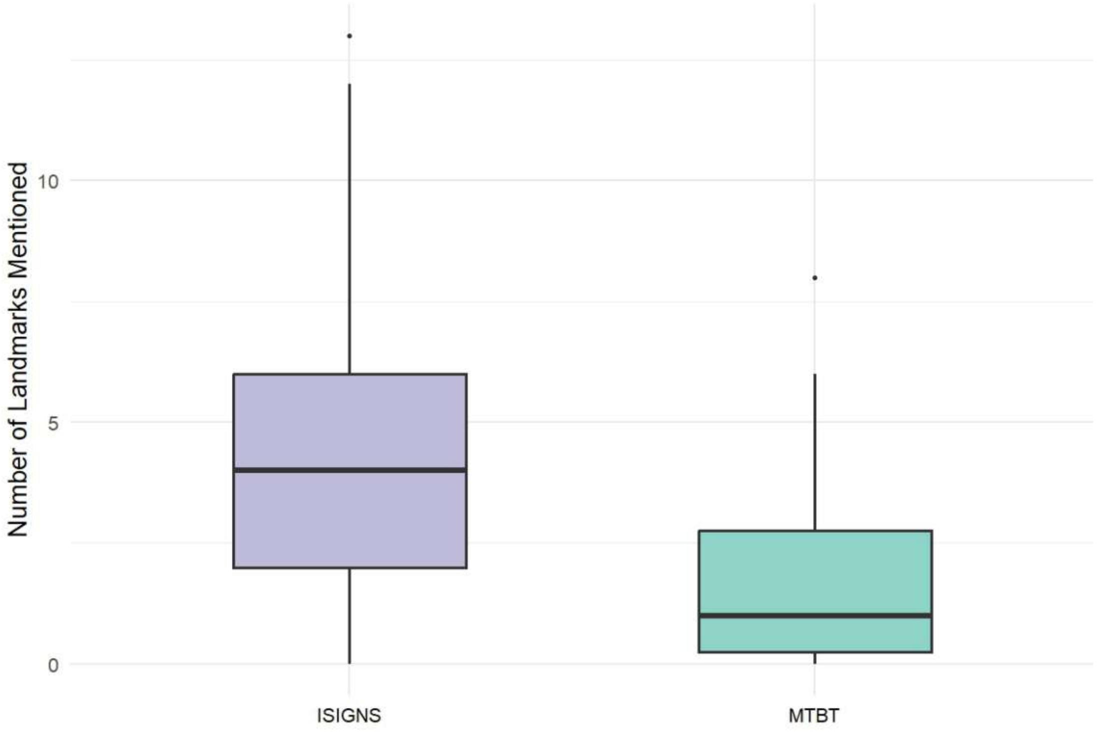


Figure 5.13 - The number of landmarks mentioned in route descriptions per system.

5.3.3.6 Landmark ordering error rate

Burte and Montello (2017) analysed the landmark ordering task with a pairwise sequence ordinal order. They counted the incorrectly ordered pairs with a fixed number of landmarks (not chosen by the participants). By scoring the incorrect ones (incorrect 1, correct 0), the higher score, the worse performance. In the current study, we let participants choose the landmark photos and then order them. Consequently, we adapted the method by dividing the score by the maximum possible score of their correctly chosen number of pictures (maximum score: n(n-1)/2). This resulted in a pairwise sequence ordinal order rate between 0 and 1: the higher rate, the worse performance.

Although navigating with ISIGNS, the average landmark ordering error rate is lower, illustrated by Figure 5.15. A paired t-test did not reveal a significant difference between systems (Table 5.4, the fourth row).

5.3.3.7 Landmark placement task performance

We assessed participants' landmark placement task performance by distance deviation (Huang et al., 2012; Wenczel et al., 2017) and canonical accuracy (Gardony et al., 2016). Both measures reflect a participant's configurational environmental understanding, i.e., survey knowledge acquisition, but differ in whether a missing landmark affects the overall assessment.

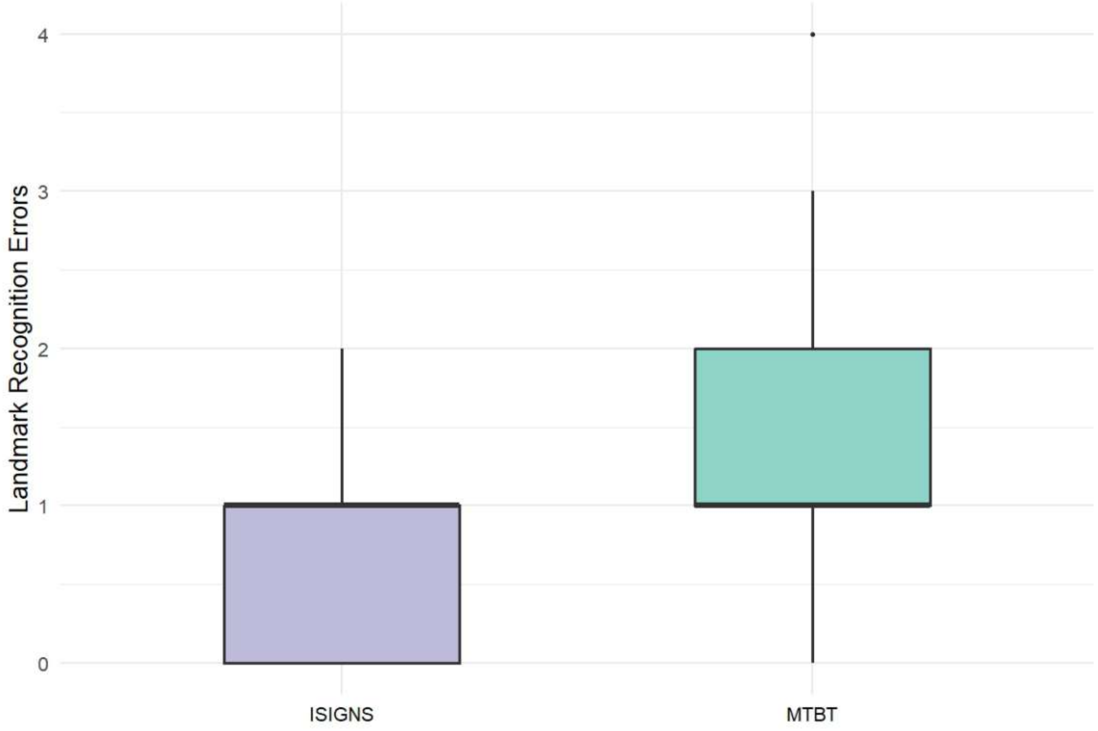


Figure 5.14 - The landmark recognition errors per system.

In our case of giving participants a blank floor plan, the distance deviation increased dramatically once a participant mismatched the floor plan with the environment and placed the landmarks in the opposite direction from the starting point. Conversely, this misorientation does not affect canonical accuracy.

Distance deviation

Similar to Huang et al. (2012), we measured the distance deviation as the route distance between the placed position and the correct position. We transformed the measured distance (mm) to meters into the real-world scale. If a picture was missing, we used the distance from the last landmark to the missing one (for the first landmark, it was the distance from the starting point) as the deviation. The average deviation was calculated as each participant's score on that route.

As suggested by Figure 5.16A, navigating with ISIGNS, the distance deviation of the landmark placement was significantly less than MTBT (Table 5.3, the third row). The distance deviation varies dramatically between different participants, as reflected in the high standard deviation. Some participants placed the landmarks in a different part of the building, causing a considerable increase in the distance deviation. However, the landmark positions relative to each other were rather accurate. Therefore, we combine it with canonical accuracy to assess the survey knowledge reflected by the landmark placement task.

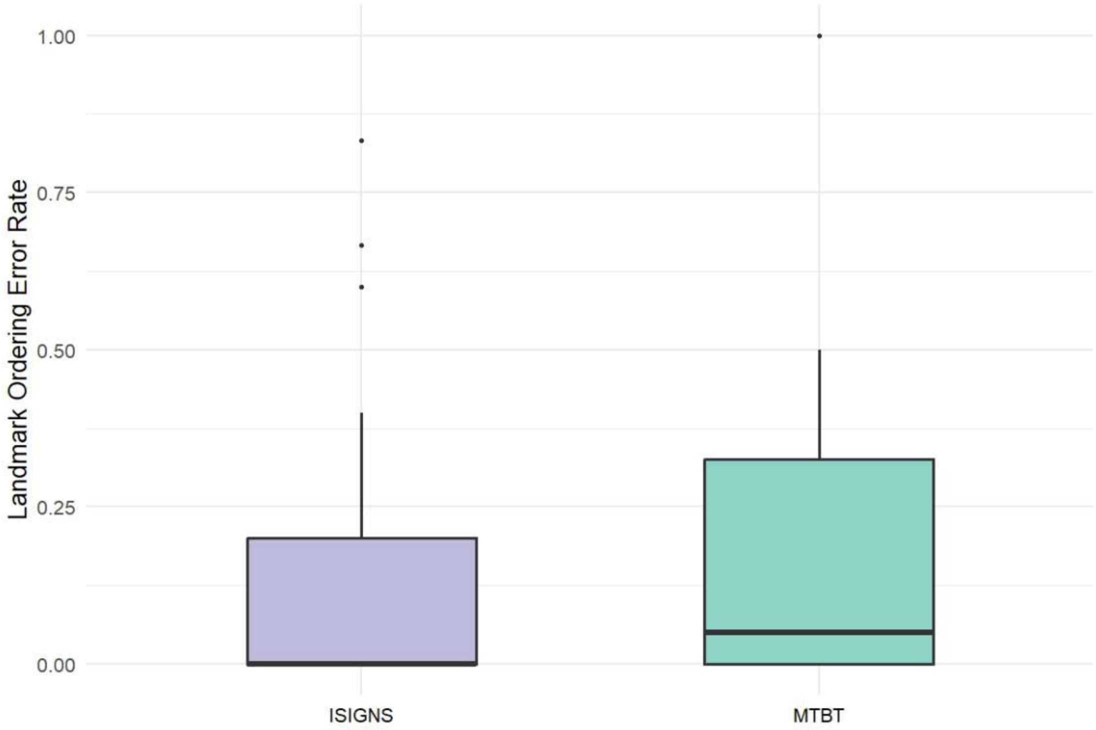


Figure 5.15 - The landmark ordering error rate per system.

Canonical accuracy

Canonical accuracy is a proportional measure that calculates each landmark's position in relation to other landmarks in Cartesian space (Gardony et al., 2016). Given known correct landmarks and their position, it measures the degree of the sketch map fitting the environment. Unlike the distance deviation, which punishes the missing landmarks, this score only considers the drawn landmarks and their relations compared with the pre-defined "perfect" sketch map. The score ranges from 0 to 1. The higher, the better the configurational fitting to the depicted environment. If the participant had chosen only one landmark, it was not possible to calculate the canonical accuracy. We assigned a score of 0 to such a case, as it was considered the worst possible.

As shown in Figure 5.16B, navigating with ISIGNS, the canonical accuracy of the landmark placement floor plans was significantly better than MTBT (Table 5.3, the fourth row).

This result, combined with the distance deviation, indicates that navigating with ISIGNS significantly improves participants' survey knowledge acquisition.

5.3.3.8 Route direction recall

Like Huang et al. (2012), we counted the number of incorrectly recalled route directions. Participants seldom made errors in general. As suggested by Figure 5.17, navigating with

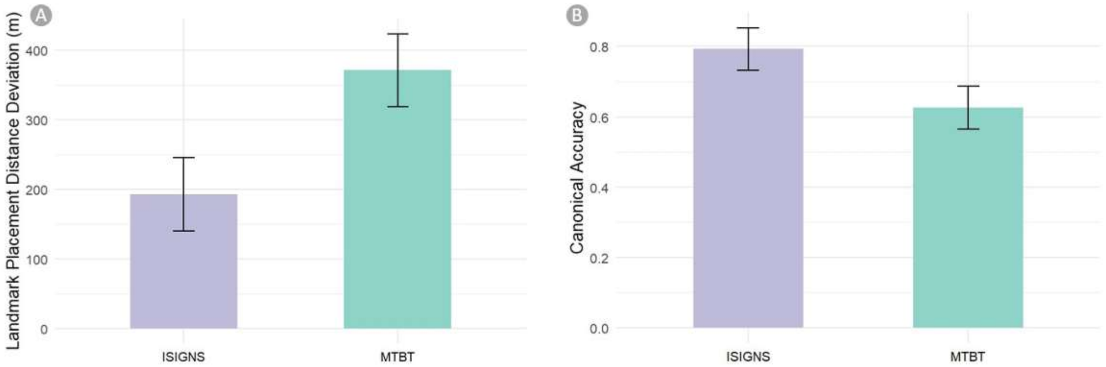


Figure 5.16 - Indicators of landmark placement task performance. (A) The average landmark placement distance deviation per system. The lower deviation, the better performance. (B) The average canonical accuracy of the landmark placement floor plans per system. It ranges from 0 to 1, with a higher score representing better performance. Vertical error bars denote 95% confidence intervals.

ISIGNS, participants made significantly fewer route direction recall errors than MTBT (Table 5.4, the fifth row), indicating better route knowledge acquisition.

5.3.3.9 Tasks difficulty rating

In the questionnaire, participants rated their overall impression of the spatial knowledge acquisition tasks from 1 (very difficult) to 7 (very easy). On average, performing the tasks while guided by ISIGNS ($M = 4.714$, $SD = 1.798$) was rated slightly easier than MTBT ($M = 4.524$, $SD = 1.714$), but no significant difference was detected, $t(41) = 0.595$, $p = .555$, $r = .093$ (Figure 5.18).

5.3.4 User experience

5.3.4.1 Confidence during navigation

Participants were given two statements, “I felt confident navigating using the first route instruction during the experiment” and “I felt confident navigating using the second route instruction during the experiment”. They rated their confidence during navigation on a Likert-type scale from 1 (strongly disagree) to 7 (strongly agree). We hypothesised that they would feel more confident navigating with ISIGNS, as they could find confirmation in the environment. In general, participants were confident using both systems. The median rating for ISIGNS ($Mdn = 6$) was the same as for MTBT ($Mdn = 6$), and no significant difference was detected by the Wilcoxon signed-rank test (two-tailed), $p = .278$, $r = -.118$ (Figure 5.19).

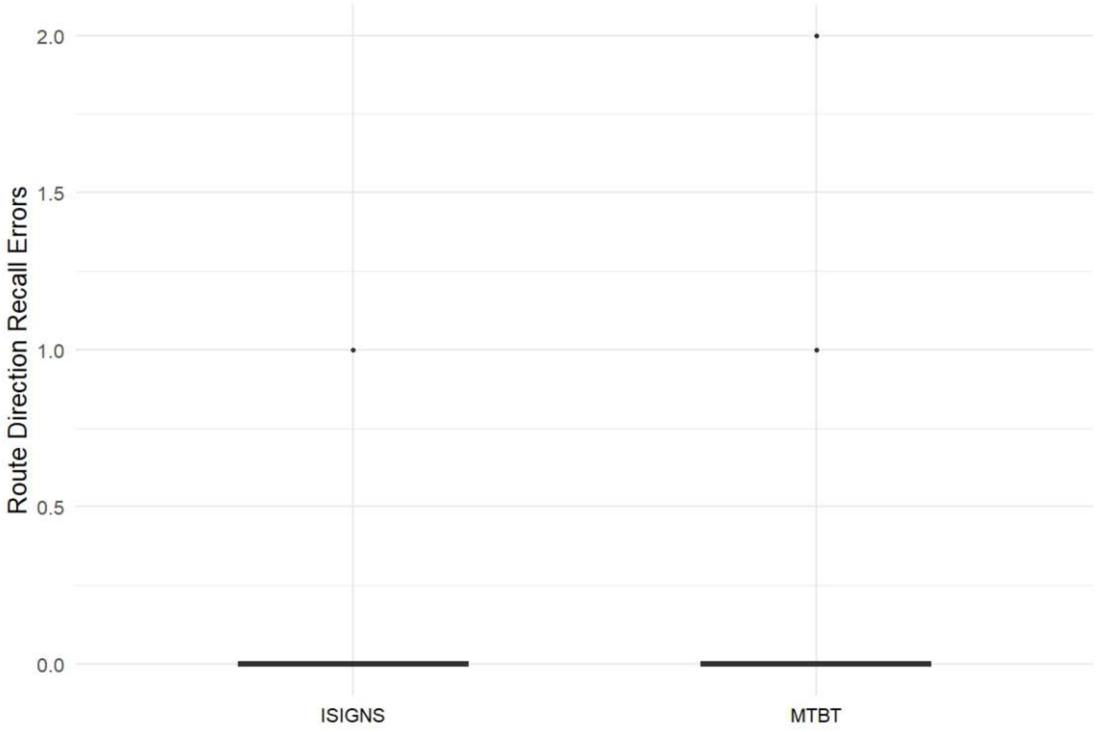


Figure 5.17 - The route direction recall errors per system.

5.3.4.2 Preference

Participants were given a preference choice between ISIGNS and MTBT, yet four participants could not decide. We accepted their justified alternatives and aggregated them into "others". Overall, 23 participants (55%) preferred ISIGNS, 18 (36%) chose MTBT, and four others (9%).

Reasons for favouring ISIGNS include: intuitive and easy (n=8), personal difficulty with metric information (n=5), helpful for learning the building (n=3), individual sensitivity to visual cues (n=2), environmental confirmation (n=2), and feeling like playing (n=1).

Justifications from participants who preferred MTBT include: similarity to conventional outdoor navigation systems (n=5), individual sensitivity to metric information (n=3), informative and precise (n=3), and signs too small (n=3).

Among the participants who could not decide, two suggested combining both instructions, which could provide more confirmation and be more informative. One participant said metric information was suitable for short route segments, as the distance was easy to estimate and more precise. At the same time, sign-based was good for long route segments, as users would be free from the phone and explore the environment. The other participant also suggested the system be adaptive, and in her opinion, to the use context and users. In terms of context, she would prefer to use ISIGNS when relaxed and in the mood for exploration and learning. When

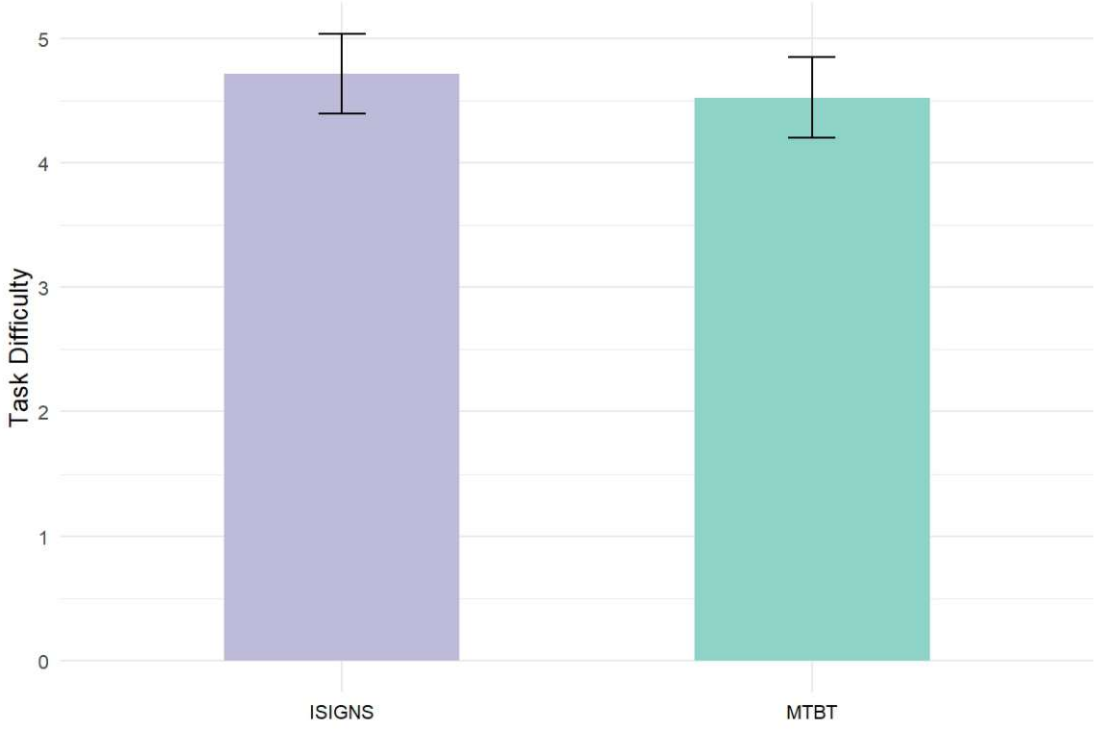


Figure 5.18 - The mean task difficulty rating per system. It ranges from 1 (very difficult) to 7 (very easy). Vertical error bars denote 95% confidence intervals.

under time pressure, she would only follow the directed path and not look at the instructions at all, but knowing metric information would be helpful. Regarding users, she would always favour ISIGNS for her children because it facilitates learning. For other users, it would be context-dependent.

5.3.4.3 Modified UEQ-S

The UEQ-S asks participants to rate semantic differential items, i.e., pair of terms with opposite meanings. Since the UEQ-S was modified according to the pilot tests, we analysed the items individually instead of aggregating them into pragmatic and hedonic qualities (Schrepp et al., 2017). Figure 5.20 shows the questionnaire items and the comparison between the systems using the Wilcoxon signed-rank test (two-tailed). Overall, participants scored more towards the positive end for ISIGNS compared with MTBT. The item pairs on the “Conventional - Inventive”, “Boring – Exciting”, and “Confusing - Clear” resulted in significant differences between the systems (Table 5.5). It indicates that participants are generally more satisfied with ISIGNS. Pragmatically, they thought ISIGNS more clear. Hedonically, they enjoyed using ISIGNS more and felt it more exciting and inventive.

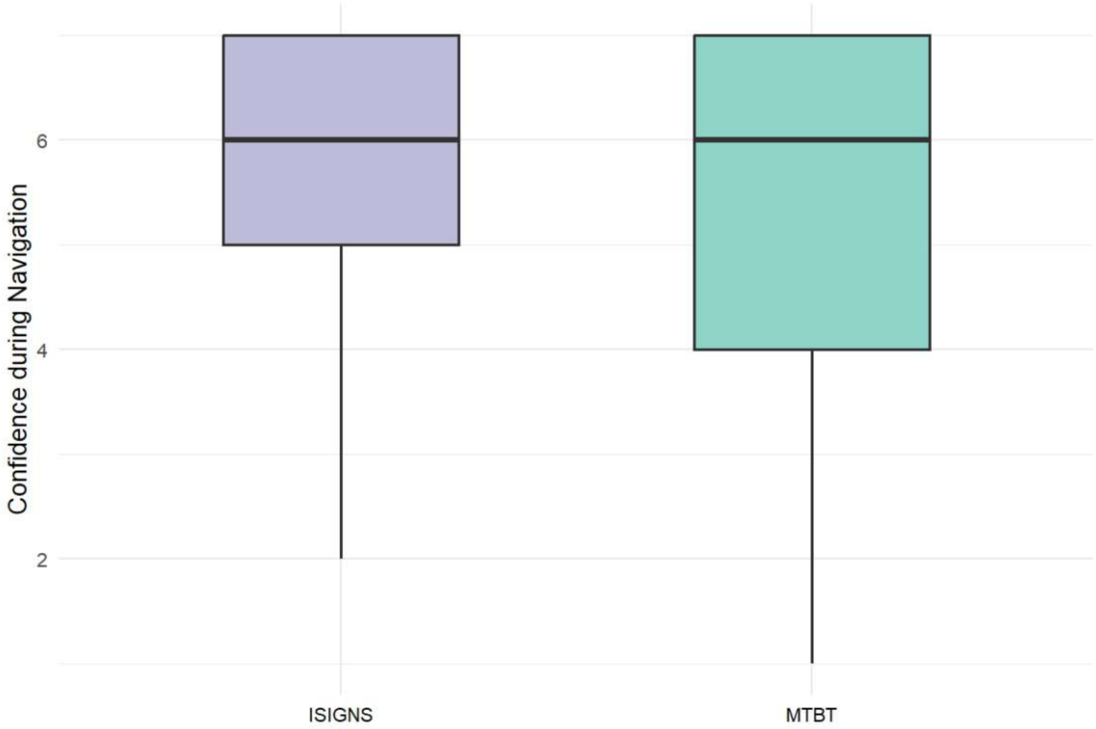


Figure 5.19 - The confidence rating per system. It ranges from 1 (strongly disagree) to 7 (strongly agree).

Table 5.5 - Comparison of the user experience items tested by the Wilcoxon signed-rank test between ISIGNS and MTBT.

Item	**ISIGNS**	**MTBT**		
	Mdn	Mdn	p	r
Uncomfortable - Comfortable	6	6	.399	-.092
Conventional - Inventive	4	4	.041*	-.223
Boring - Exciting	4	4	.006**	-.302
Confusing - Clear	6	6	.031*	-.234
Inefficient - Efficient	6	6	.312	-.110
Complicated - Easy	6	6	.524	-.069
Obstructive - Supportive	6	6	.235	-.130

* $p < .05$
** $p < .01$

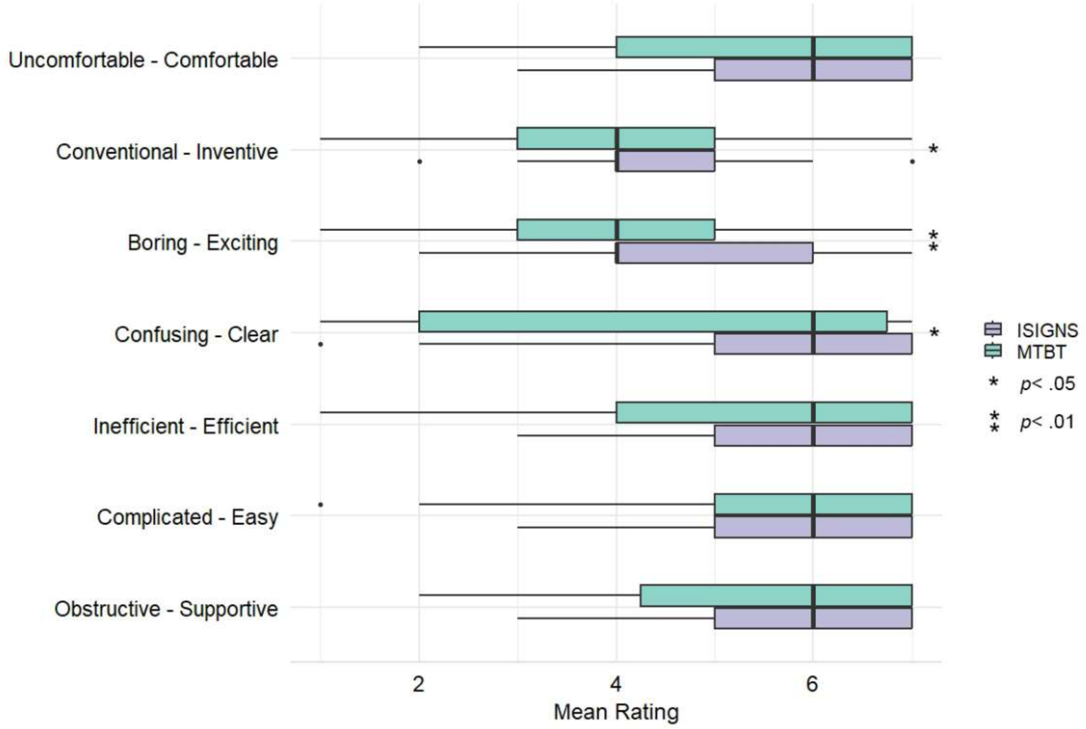


Figure 5.20 - Ratings of the user experience items per system, ranging from 1 to 7.

5.4 Discussion

5.4.1 Navigation performance

We hypothesised that in terms of efficiency and effectiveness, participants navigating with ISIGNS would perform better than navigating with the conventional navigation system. However, the results do not support this hypothesis.

Regarding efficiency, speed was used as a normalised measure. Using ISIGNS, participants walked faster, but the difference was not significant. Between signs, they could walk normally, without continually checking the phone for confirmation. As mentioned in the interview, this was helpful, especially for participants struggling with metric information. Not having a clear sense of how long a certain distance was, would stimulate them to consistently match the navigation system with reality. This leads to more frequent stops and a slower walking pace. However, being instructed to follow the signs triggered longer stops at signs, to read and comprehend the information there. At locations where several signs exist with much information to process, participants needed a longer time. Such an alternating pattern of walking fast between signs and walking slower or stopping at signs reduces the average speed. Similar walking patterns were observed by Brügger et al. (2019) in experiments comparing systems with different automation levels. Likewise, their study and Huang et al. (2021) did not find a significant difference in navigation efficiency between different navigation systems.

In terms of effectiveness, we looked into the number of errors and stops. A common error for both systems is that participants did not realise the destination when they reached it. Because there was no sign directing to the destination for the C route, the last two instructions were the same for both systems, i.e., metric-based (Table 5.1). As explained by participants, this was caused by miscalculating the distance (See Section 5.3.2.2). To prevent such confusion caused by metric-based instructions, ISIGNS could be improved by incorporating landmarks in route instructions (Richter & Winter, 2014), e.g., combing the sign semantics with landmark-based indoor route communication (Bakogiannis et al., 2019; Fellner et al., 2017). Another possible cause for such an error is the interface of experimental navigation systems. Interface design highlighting the destination may help to avoid such misunderstandings. However, this is beyond the scope of this dissertation.

Another error, although rarely occurred, is also noteworthy. Participants mistook Hörsaal 8 as the destination in the C route when guided by ISIGNS. In the interview, they explained that they had forgotten the destination. They followed the signs all the way to Hörsaal 8, hence the mistake. Despite the fact that people are more likely to remember their destination in a real navigation scenario, it indicates the possible side effect of ISIGNS. Semantic information irrelevant to the current task may increase the cognitive load and interfere with the current task. Although such information facilitates environmental learning (see Section 5.4.2) as part of the intrinsic cognitive load needed to cognise the overall environment, it might be the extraneous cognitive load for the current route (Sweller et al., 2011). Supported by our experimental findings on the K route, a potential development could be applying hierarchical modelling (Zhou, 2022) to signs, so that users are only directed to the signs at a higher hierarchical level. The signs employed for the K route instruct participants to follow the signs to the staircases, which are on a higher hierarchical level. Such a movement also aligns with the building organisation. Although it led to a detour in the experimental case, the unfamiliar participants received it well (see below). Another possible improvement could be constructing semantic relations between all nodes and only employing signs semantically relevant to the destination. To illustrate it in a scenario: if students want to find a cartography lecturer's office, instead of directing them to follow the sign leading to the secretary's office of the architecture institute, which is geometrically closer, the system guides them to follow the sign leading to the secretary's office of the cartography institute.

As expected, errors were observed during turns, such as participants turning into incorrect corridors or staircases when following the MTBT instructions. Such findings align with the qualitative comparisons made by Fellner et al. (2017) and Zhou (2022) between landmark-based instructions and MTBT. The empirical evidence further confirms their anticipation, as well as our earlier qualitative comparison conducted in Section 4.3.5.

The average number of stops mirrors the walking pattern that participants stopped more frequently but shorter for confirmation using MTBT, while they stopped fewer but longer using ISIGNS. Instructed by ISIGNS, there was a short detour in the K route, in which participants had to first reach Staircase 1 before following the sign to retrace some meters, then heading to Kuppelsaal. As mentioned in Section 5.2.2.1, this detoured route was the only possible publicly accessible route in this building that is longer in ISIGNS than the shortest path. We chose it to examine how participants perceive and reflect on such a longer distance or a detour. As expected, many participants spent significant time at the Staircase 1 signs. A few made an error, and some asked the experimenter, who only told them to follow the instructions on the phone. Surprisingly, when interviewed retrospectively, participants expressed that they initially found it counterintuitive but felt encouraged to read the signs thoroughly. By somehow being "forced" to read the signs in such a situation, they began to understand the building structure and organisation and attend more to the surroundings afterwards. They considered it a learning process and helped them with the following tasks. This was the view shared by many unfamiliar participants.

On the contrary, the only participant familiar with this route disagreed. He found it confusing when the navigation system instructed him to diverge from the path he previously knew. We agree with him that navigation systems should generally avoid detours. Whether participants positively perceive a longer distance in trade of environmental confirmation and learning should be validated in a different building.

5.4.2 Spatial knowledge acquisition

The results support the second hypothesis that navigating with ISIGNS significantly promotes spatial knowledge acquisition. In Table 5.2, we presented the spatial knowledge acquisition assessment tasks according to the type of spatial knowledge they examined. Below, we first clarify our evaluation of the sketching and verbal description tasks, and then elaborate on landmark, route, and survey knowledge acquired during the experiment.

Based on previous experience (see Section 3.5), the sketching task is greatly influenced by participants' drawing skills and the established method for analysing outdoor sketches is not all well-compatible indoors. On that account, we provided a base floor plan similar to Van Asselen et al. (2006) for the sketching task. They counted the correct recognition of the start and the end, each decision point along the way and whether the turning decision was right. Then, they weighted each of them equally (each receiving one point) to achieve an overall score, representing the survey knowledge. Their calculation utilises a combination of route and survey aspects to represent the configurational understanding. However, we think it is plausible to examine the survey knowledge by assigning the same weight to each decision point, the turning choice, and the start and end. We argue that some of these aspects reflect more survey knowledge, e.g., recognising the destination, while others more route knowledge, e.g., the turning choice at each decision point. As there is no clear evidence of how much each of the mentioned aspects contributes to the overall survey knowledge, we decided to separate the spatial awareness task meant to assess the survey knowledge from the sketching. To analyse sketch maps, we counted the landmarks depicted as a measure for free recall of landmark knowledge (Huang et al., 2021; Wunderlich et al., 2022). As the experiment route is relatively simple in respect of turns, we assessed the route knowledge by the route's overall correctness. We acknowledge that the sketching task may be biased by the spatial awareness task, as localising the destination help with route reconstruction. This was indeed observed during the experiment. Except for a few participants whose drawn route ended somewhere else, most connected the start and the end. A similar bias can exist in the verbal description task as well. Most participants either verbalised the route while looking at the sketch and detail about each turn, or directed others to follow the signs. Only a few exceptions said they could not describe the route verbally. In the interest of comparing the visual and verbal externalisations of participants' spatial knowledge, the same analysing schema was applied to the verbalisations.

5.4.2.1 Landmark knowledge acquisition

With respect to landmark knowledge, the number of landmarks drawn in sketches and mentioned in route descriptions, and the landmark recognition task are taken as estimates. The landmarks sketched and mentioned are the information retrieved from participants' memory without a specific cue. Wunderlich et al. (2022) named them free recall tasks. Likewise, we consider them as recall, to be distinguished from the recognition tasks, e.g., landmark recognition. In the recognition tasks, participants felt familiar with and identified scenes they had previously experienced. Recognition is regarded as less effortful than recall, and may induce a recognition bias (Hollingworth, 1913). All landmark knowledge assessments returned statistically significant results, with the effect size ranging from medium (the number of landmarks drawn in sketches and landmark recognition errors) to large (the number of landmarks mentioned in route descriptions). Together, they evidence ISIGNS's substantial influence on landmark knowledge acquisition. This is in line with our expectations and with research on landmark-based outdoor navigation (Gramann et al., 2017; Wunderlich & Gramann, 2018; Wunderlich et al., 2022) and landmark-augmented indoor navigation (B. Liu et al., 2021).

The improvement of landmark knowledge is likely due to the increased attention allocation to the environment (Wunderlich & Gramann, 2018, 2021). Navigating with ISIGNS, participants were explicitly instructed to follow signs. To do so, they had to look around at their surroundings to find signs before reading the sign information. If the information successfully matched their expectation, they followed the sign. Otherwise, they had to continue searching for the correct sign in the environment. During the process, participants must attend to the environment. In addition, participants knew what to anticipate between signs, i.e., the message on the sign. They always had to observe the environment, so that they could realise the intended location when reached. Conversely, using MTBT, many participants attended mainly to their phones and ignored the surrounding environment, similar to the outdoor navigation behaviour described in the literature (Brügger et al., 2019; Huang et al., 2021; Parush et al., 2007). Such behavioural contrast seemingly contributes to the substantial difference in landmark knowledge acquisition tested by recognition and recall tasks. Future studies combining spatial knowledge assessment with eye-tracking (e.g., Brügger et al., 2019; Wenczel et al., 2017) may clarify whether participants paid more attention to the environment and what they attended to.

The semantic nature of signs may also account for enhancing landmark knowledge. Signs are semantic landmarks that carry messages to guide visitors to various parts of the building. ISIGNS is a system to signal navigators where to find what message. The combination of "signal" and "message" form the mechanism of reminding (Norman, 2013). For example, we rarely remember all the schedules we enter into a calendar, but we know that if we open it, we will not miss our plan. Participants were unlikely to recall all they experienced during navigation, but remembering signs and their location was comparably easier and more effective. Just like we use a calendar and remember its location. On such grounds, participants may incidentally learn the signs' locations. This explanation is endorsed by the high occurrence of signs in the sketches and verbal descriptions.

In addition to including the signs, participants also mentioned more lecture room names and staircase names in the sketches. The cognitive load theory may clarify it. According to Sweller et al. (2011), humans tend to rely on readily available information rather than generate it themselves. When learning, humans integrate new information with their existing knowledge stored in long-term memory, creating personalised mental models known as schemas. This process follows the "borrowing and reorganising principle" (Sweller et al., 2011), whereby new information that is similar to existing knowledge is less effortful to learn. According to the experiment results in Chapter 3, people usually prefer to navigate indoors using signs when navigation systems are unavailable. Based on such habitual behaviour, learning spatial information encoded on signs is typically more straightforward than from metric-based instructions. Guided by ISIGNS, participants connected to their established navigation behaviour of following signs, during which the information on signs was also learned. Furthermore, unlike arbitrary numbers used in metric information, the room names on signs are meaningful, facilitating learning (Ausubel et al., 1968; Bretz, 2001).

Comparing the landmarks drawn and mentioned, there is not much difference for ISIGNS. But participants drew more landmarks than verbalised, when navigating with MTBT. This contrasts with results from Chapter 3 that participants verbalised more landmarks than depicted in both environments in the wayfinding scenario. One possible explanation is that people learn from and mimic what they were instructed (Sweller et al., 2011). When ISIGNS led them, they verbalised with the same information, i.e., signs. Whereas guided by MTBT, they received metric information and advised others as so. Consequently, landmarks were not very often employed in their verbal instructions.

5.4.2.2 Route knowledge acquisition

On the subject of route knowledge, we approximated it by the accuracy of the drawn and verbalised routes, landmark ordering error rate, and route direction recall errors. Similar to landmark knowledge, the accuracy of the drawn and verbalised routes is considered as recall of route knowledge, while landmark ordering and route direction recall are recognition tasks. Both recall tasks yielded statistically significant results. However, as discussed earlier in Section 5.4.2, the spatial awareness task used to assess survey knowledge can bias the correctness of the drawn and verbalised routes. This means that if ISIGNS improves survey knowledge acquisition, the significant advantage observed in route correctness may not necessarily result from an increased route knowledge acquisition. In this study, ISIGNS indeed increased participants' survey knowledge acquisition, as will be discussed later. Thus, the significant results may be biased, and the interpretation is limited.

Regarding the recognition tasks, navigating with ISIGNS, participants' average error rate was lower, but a significant difference was not observed. Regarding route direction recall, participants generally made few errors, with ISIGNS showing a statistically significant advantage. Both tasks indicate route knowledge acquisition, but their results did not converge. Several explanations may account for this. Firstly, both tasks depend on the landmark recognition task, as participants ordered and recalled the directions from the previously chosen pictures. If a participant recognised only a few correct pictures, their route knowledge implied from these tasks was limited. Using MTBT, on average, participants chose 3.5 pictures correctly. This number is lower compared to the number of pictures used for landmark ordering (Burte & Montello, 2017; Van Asselen et al., 2006; Wunderlich et al., 2022) and route direction recall (Burte & Montello, 2017; Huang et al., 2012) in similar studies, which may have limited our results. This may also explain the lack of significance in the results of the landmark ordering tasks, in contrast to the findings of Wunderlich et al. (2022). Secondly, varying the reference of route instructions from metric-based to sign-based does not influence their inherent sequential nature, upon which route knowledge may be developed. Researchers summarised that text instructions present spatial information serially, and this sequential nature is key to acquiring route knowledge (Chrastil & Warren, 2012; Pazzaglia & Cornoldi, 1999; Richter & Winter, 2014). Moreover, Van Asselen et al. (2006) suggested that a human innate system can encode route knowledge to a significant extent, by providing the bare minimum information required for orientation. As long as the instructions are sequential and participants physically traverse the environment, they should be able to acquire relatively good route knowledge regardless of whether the instructions are sign-based or metric-based.

Taking together the recall and recognition tasks for route knowledge, the current experiment can hardly conclude whether integrating signs improve route knowledge acquisition.

5.4.2.3 Survey knowledge acquisition

We assessed survey knowledge by using direction estimation, spatial awareness, and landmark placement tasks. Similar to landmark knowledge, the assessments for survey knowledge present a congruous picture. They coincide with indicating that navigating with ISIGNS considerably helps develop a configurational understanding of the environment, with all their effect size showing medium impact.

Developing survey knowledge is generally considered sophisticated in microgenetic development (Ishikawa & Montello, 2006) and requires substantial attention to relevant environmental properties and spatial relations (Chrastil & Warren, 2012). ISIGNS directed participants' attention to signs in the environment, which are salient environmental features explicitly conveying spatial relations. As with landmark knowledge acquisition, the increased attention allocation and the semantic nature of signs, may account for the improved survey knowledge acquisition.

Landmark-based outdoor navigation studies (Gramann et al., 2017; Wunderlich & Gramann, 2018; Wunderlich et al., 2022) demonstrated an enhanced landmark knowledge acquisition, whereas survey knowledge would need further environmental exposure and attention. In contrast, our study indicates the sign-integrated navigation system significantly benefits configurational spatial learning as opposed to the metric-based one. Since landmark-based navigation systems also facilitate the allocation of attention to salient environmental features, it seems more reasonable that the semantics contained in signs contributed considerably to this improvement. In addition to the placement of signs, namely important circulation locations, they are semantic landmarks designed to explicitly convey spatial structure and relations of the indoor environment (see Section 2.1.1.1). To follow sign-integrated instructions, participants needed to comprehend the messages on signs, as indicated by the long stops at signs (see Section 5.4.1). Such effort, presumably both physical (as time) and cognitive, required more attention and intensified knowledge acquisition.

At the same time, the spatial relations encoded in signs may have been "borrowed" by participants, integrated into their spatial representation of the building, and stored in memory (Sweller et al., 2011). As humans refer to signs for indoor navigation, learning spatial relations from signs may unconsciously happen. Participants' interviews supported this interpretation. They shared that being guided from one staircase to another and then to a specific room, they started comprehending the building configuration. One participant, who worked in a different building wing for two years, said she would always ask the concierge whenever she wanted to go to an unfamiliar part. However, with the navigation system, she got a sense of the building organisation and knew where to find important navigation information. This reflection was not an individual case, but confirmed by empirical research that direct experience alone is insufficient for spatial knowledge acquisition in complex indoor environments (Moeser, 1988). The summarised and readily presented spatial relation is easier to grasp than fumbling alone.

This outcome also contributes to the debate on spatial microgenesis, whether spatial knowledge develops in stages from landmark to route to survey knowledge (Siegel & White, 1975)), or in parallel (D. R. Montello, 2005) (see Section 2.2.1). Our results support the latter continuous framework, suggesting that people start to develop all three kinds of knowledge from their first environmental exposure, confirming the findings from Ishikawa and Montello (2006) and Kim and Bock (2021).

5.4.3 User experience

The third hypothesis that participants will be more satisfied with ISIGNS than MTBT is partially confirmed. In terms of confidence during navigation, participants felt confident with both systems. Although some participants mentioned extra confirmation from the environment by signs, navigating with ISIGNS did not further the high confidence level.

Regarding preference, as expected, more participants favoured ISIGNS because of its intuitiveness and environmental engagement. Moreover, the route instructions in ISIGNS use qualitative rather than quantitative relations, similar to natural language (Winter et al., 2021). Although researchers generally consider landmarks more natural and metric information complex to comprehend outdoors (Rehrl et al., 2010) and indoors (Bakogiannis et al., 2019; Fellner et al., 2017), it appeared to be a controversy from the interview. We consider it an individual trait, as some participants articulated difficulties with metric information while others enjoyed it. Between them likely lie several interesting alternatives. First, to always provide both for cross-confirmation and for users to choose individually. Second, to adapt the instructions according to the length of the route segments. Third, to further adapt to the use context and user groups.

Concerning the aspects of pragmatic and hedonic qualities, ISIGNS received positive feedback. It was perceived as significantly more satisfying than metric-based instructions, in the hedonic quality aspects, like novelty and enjoyment to use. This is in line with the findings supporting landmark-based instructions (Bakogiannis et al., 2019).

As remarked by participants, the sign system design influences user preference as well as the general experience. Unlike indoor landmark-based instructions, which consider landmarks' visual and structural saliency (Dong et al., 2020; Lyu et al., 2015; C. Wang et al., 2020). Sign-based instructions mainly focus on semantics while assuming signs are visually salient by their designed nature. On the one hand, the emphasis on semantics facilitates spatial learning due to the borrowing and reorganising principle (Sweller et al., 2011) (see Section 5.4.2). On the other hand, it is highly dependent on the building's existing signage system and treating all signs indifferently may influence user experience. In the case of a poorly designed signage system, like in this study, user experience and performance are negatively affected.

5.5 Summary and conclusions

We conducted a real-world navigation experiment comparing the proposed ISIGNS with the conventional navigation system using metric-based turn-by-turn instructions (MTBT), to evaluate the performance of ISIGNS and test whether it prompts spatial learning. We hypothesised that participants navigating with ISIGNS would perform better than with MTBT, in terms of efficiency and effectiveness (H1). Additionally, navigating with ISIGNS would promote participants' spatial learning (H2). Further, participants would be more satisfied with ISIGNS than MTBT, in terms of preference and overall user experience (H3).

The experiment consisted of two route-following tasks, each followed by a set of spatial knowledge acquisition assessment tasks. It ended with a semi-structured interview guided by a questionnaire (see Figure 5.5 for the detailed procedure). We recruited 52 participants for the experiment. After a familiarity screening, the experiment data of 42 unfamiliar participants was used for quantitative analysis, while all participants' interview was qualitatively analysed and employed for results interpretation.

Contrary to H1, the results reveal a tendency for faster speed and fewer stops using ISIGNS, but the difference was not significant. In general, participants made few errors. They stopped fewer but longer using ISIGNS, while they stopped more frequently but shorter for confirmation using MTBT.

As expected, the results support H2 that navigating with ISIGNS improves spatial learning. All assessments, either recognition or recall, concur to indicate the enhanced landmark and survey knowledge acquisition, possibly due to the encouraged environmental attention allocation and the semantic nature of signs. Specifically, signs explicitly convey spatial relations, which may substantially benefit configurational learning. Regarding route knowledge, the assessments allow open interpretation. Restricted by the study design, whether integrating signs facilitate route knowledge acquisition remains for further investigation.

With regard to user experience, H3 that participants will be more satisfied with ISIGNS than MTBT is partially confirmed. Participants felt more confident with and favoured ISIGNS, but not to a significant extent. Interestingly, they proposed several alternatives for combing both. Concerning the aspects of pragmatic and hedonic qualities, participants perceived ISIGNS notably more novel and enjoyable to use. Also worth noting is that the building's existing signage system influences user experience.

Chapter 6

General discussion and future research

In this chapter, we engage in a comprehensive reflection on our study and discuss its main aspects. We have organised the discussion by topic in Sections 6.1, 6.2, and 6.3, beginning with our contributions and their potential implications. Subsequently, in each section, we delve into a critical reflection on the limitations of our study and outline avenues for future research. Then we critically reflect on the general limitations of this research in Section 6.4 and summarise the key recommendations for indoor navigation service providers in Section 6.5.

Throughout the chapter, we aim to provide a thorough analysis and thoughtful interpretation of our findings. By structuring the discussion in this manner, we hope to present a cohesive and coherent narrative that enhances the understanding of our study's significance and sheds light on areas that warrant further investigation.

6.1 Indoor wayfinding theory

It is essential to comprehensively understand wayfinders' information needs during indoor wayfinding at different decision levels to facilitate indoor navigation. While previous research has examined indoor wayfinding strategies as the hierarchical decision plan (Passini, 1984b) and at the general planning level (Hölscher et al., 2006), the specific focus on decision points, which are critical locations where wayfinders must evaluate information and make choices, failed to receive sufficient attention (Best, 1970). Existing literature has investigated factors that influence indoor decision-making, such as decision point complexity (M. O'Neill, 1991; M. J. O'Neill, 1991), environmental features (Hughes et al., 2020; Vilar et al., 2012), and group and individual differences (Davis et al., 2008; Kuliga et al., 2019). However, a systematic overview of the decision-making and reasoning processes, specifically at decision points, still calls for contribution. Previous reviews on indoor wayfinding by Hirtle and Bahm (2015) and Jamshidi et al. (2020) have emphasised the need for exploratory studies to identify and categorise factors that influence wayfinding in order to develop a comprehensive understanding of indoor wayfinding theory.

Based on previous literature and our explorative study, we have summarised and categorised the factors influencing wayfinders' decision-making at decision points into indoor wayfinding tactics. Our categorisation focuses on decision points and distinguishes between two decision-making scenarios: Scenario_Aided and Scenario_Unaided. This differentiation is based on whether relevant wayfinding support information is explicitly accessible and perceived by individuals. It focuses on human perception rather than what the environment affords. By focusing on human information needs, our categorisation bridges the gap between general wayfinding planning strategies and the detailed decision-making and reasoning processes at decision points.

The proposed indoor wayfinding tactics and their influencing factors have significant implications for architecture design, building management, and indoor navigation system design. As demonstrated in Section 3.5.5 and Chapter 4, our recommendations for the wayfinding system in the TU and the proof-of-concept ISIGNS serve as practical examples. Despite the recommendations, we agree with Arthur and Passini (1992) that wayfinding difficulties can be relieved but can hardly be entirely compensated by the wayfinding system, if the architecture lacks clarity. After all, architects should create space for humans rather than building matters. It is important to note that our theory does not explicitly inform the graphic design of building signage systems, but it implicitly highlights their importance. A poorly designed and placed sign can transform a decision point from the aided scenario to the unaided scenario, if wayfinders cannot perceive the signs.

While our recommendations and proof-of-concept focus on university buildings, the implications of our theory extends to other public buildings with enclosed indoor structures. This generalizability stems from conducting our exploratory experiment in two buildings with different functions and structures. However, further studies are needed to validate our theory for partially enclosed built environments, such as transitional spaces (Kray et al., 2013).

In addition to its implications for wayfinding design, the categorisation of indoor wayfinding tactics provides a structured theoretical framework for systematically exploring the factors that influence wayfinding. As discussed in Section 3.5, our study represents an initial attempt to observe and identify potential influencing factors for the choice of indoor wayfinding tactics at decision points. Conducting future experiments that manipulate one or several of these factors can help uncover their interactions and mechanisms. For instance, we observed a tendency for participants to turn right, which is supported by research on human behaviour (Bitgood, 2006). However, this tendency may be influenced by the cultural norm of right-hand traffic. It would be intriguing to investigate how culture affects this tendency and determine if it is a cultural trait specific to populations accustomed to right-hand traffic. This is crucial for ensuring appropriate implications in cultures otherwise and warrants careful consideration.

One area for future exploration relates to familiarity and the memory tactic. We observed participants relying on their memory and disregarding other information at decision points, which we associated with the dominance of familiarity leading to the use of the memory tactic over other tactics, including the ones in the aided scenario (see Section 3.5.1). However, previous theory (Passini, 1984b) suggests that tactics involving perceived information are often preferred and more accurate. It would be interesting to explore the interaction between the memory tactic and other tactics in the aided scenario, particularly among participants familiar with a specific environment.

Regarding the selection and utilisation of existing navigational aids, it is worth noting that our observation revealed a preference for signs over floor plans, which can be attributed to the higher cognitive cost associated with processing and comprehending floor plans. However, we recognise that this preference for signs is individualised and may be influenced by the description of a wayfinding task. Our analysis suggests the target descriptions that include spatial relations (e.g., "A close to B") motivate wayfinders to find configurational representations, i.e., floor plans. To further explore this aspect, future studies could investigate whether wayfinding task instructions that include spatial relations prompt a preference for floor plans, while tasks worded without spatial relations lead to a greater reliance on signs. Such findings would contribute to a more nuanced understanding of how and when to support wayfinders in complex indoor environments effectively.

Furthermore, our findings in the indoor wayfinding strategies highlighted the influence of building structure and existing wayfinding aids on the choice between vertical first or horizontal first strategies. In the area bearing an explicit order, wayfinders prefer to follow the pre-defined order. It suggests that different indoor environments may possess distinct characteristics in terms of wayfinding strategies and navigational needs. For instance, transport hubs may prioritise efficient wayfinding to help people reach their destinations quickly. At the same time, shopping malls may aim to encourage longer stays, and museums may seek to guide visitors in a specific order for an optimal viewing experience. Categorising indoor environments based on their function and structure, and developing a taxonomy and corresponding ontologies, can contribute to both theoretical advancements and practical implications. Similarly, developing a landmark categorisation according to building function could facilitate creating and implementing landmark-based indoor navigation systems, making them easier to develop and apply in practical settings.

Overall, our study provides valuable insights into indoor wayfinding tactics and the factors influencing their selection. By offering a theoretical framework, practical implications for wayfinding design, and proposing future research directions, we contribute to advancing indoor wayfinding theory and its applications.

6.2 The Indoor Sign InteGrated Navigation System: implications, limitations, and future improvements

To realise and evaluate our concept of integrating signs into indoor navigation services, we proposed a workflow and developed ISIGNS. The proposed ISIGNS requires only a navigation graph and a sign dataset as input, which can be derived from most existing indoor spatial databases. The attributes of the semantic edges can be easily adapted to the specific building context (see Section 4.4). Hence, this approach readily applies to constructing sign integrated navigation systems for various indoor environments where graph-based modelling is suitable.

One of the advantages of integrating signs is that physical signs in the environment can be equipped with sensors. As ISIGNS refer to them, it can "communicate" with the signs through sensors, enabling functionalities such as monitoring and dynamically manipulating the flow of people. For instance, Bluetooth tracking can be used to analyse human movement (Versichele et al., 2012). By setting thresholds for the flow in sign nodes, ISIGNS can dynamically adjust attributes of the connecting edges, thus modifying navigation routes based on the number of people present. This can be particularly useful during large public events to manage crowd flow and ensure safety.

While this study focuses on signs and their semantics, the concept of semantic edges can be extended to other forms of semantics. Given a dataset with nodes and the semantic context, the algorithm could generate semantic edges fulfilling specific criteria. This way, a semantic layer can be created and used in navigation. This node dataset can be a separate input or the output of other processes within the same building (e.g., other infrastructure linked to navigation in a holistic system proposed byWang et al., 2019). For example, in a museum setting, artworks with common themes can be connected by semantic edges, allowing visitors to follow personalised routes based on their interests. An application scenario can be: one visitor is interested in landscape paintings and wants to go from *The Harvesters* by Pieter Bruegel to the *Poppy Fields near Argenteuil* by Claude Monet, most likely in different exhibition halls. Based on the theme, the navigation system prioritises the semantic edges with the theme of landscape painting, and guides navigators through a route covering most such artworks.

Additionally, ISIGNS can function as a tool to evaluate the quality of a building's existing signage system. By simply performing ISIGNS without user testing, the type of instructions it generates can indicate the quality of the existing signage system. If the signage system is comprehensive, ISIGNS will predominantly generate instructions based on signs. Otherwise, ISIGNS will offer more metric-based turn-by-turn instructions. As demonstrated in Chapter 5, a user study provides more insights than qualitative comparisons. Evaluating users' experiences while following ISIGNS instructions can further reveal the completeness and consistency of the building's signage system. Instances where users experience confusion or take detours following the instructions, may indicate that the building wayfinding design needs iteration and improvements. The detoured K route in Chapter 5 serves as such an example.

While ISIGNS offers valuable implications, it is important to acknowledge the limitations of the current design. In Chapter 4, our focus was on integrating directional signs into the ISIGNS. However, it is important to note the significance of orientation signs, which provide an overview of various points of interest within specific building areas (such as the entire building, a section, or a level). These signs play a crucial role in navigation and spatial learning by helping users maintain their orientation and obtain an overview. Moreover, they can assist in guiding users across different floor levels or sections. By modelling orientation signs into the navigation graph, we can establish semantic connections that bridge building sections and floor levels. One approach is to add an edge from an orientation sign to a directional sign, if the destination is indicated on both signs and associated with a specific hierarchical level (e.g., building section or level). An instruction could be generated to go to the particular hierarchical level and follow the directional sign there. This way, route instructions reflect the building hierarchy encoded in the signage system and guide the navigators accordingly. However, further exploration is needed to consider additional scenarios.

As discussed in Section 4.4, the current implementation of semantic edges in ISIGNS connects to the centroids of rooms, overlooking the decision point at the room's entrance. This can be improved by assigning room semantics to portal nodes and connecting edges exclusively to these portal nodes, enabling more accurate door-to-door indoor navigation.

Regarding routing, the current algorithm does not take into account the semantic relevance of the semantic edge to the requested route. As revealed in Chapter 5, when the destination was E242 for the C route, the system instructed participants to first go to Hörsaal 8. Although this approach promotes spatial learning, the lack of semantic relevance can confuse participants, as discussed in Section 5.4.1. One potential improvement could involve applying hierarchical modelling (Zhou, 2022) to signs so that users are directed only to signs at a higher hierarchical level. Another possible improvement could be constructing semantic relations between all nodes and only employing signs semantically relevant to the destination.

Another shortcoming is that the current system does not consider the presence of intermediate signs between a sign and its destination. For instance, there may be confirmation signs along a long corridor or signs indicating changes in direction (as described in Section 4.3.4.1). However, in the current system, as long as a semantic edge is selected, the system instructs users to follow the sign directly to the destination without accounting for these intermediate signs. It is left to the users themselves to look for confirmation. In the future, the inclusion of confirmation signs could be considered in the generation of route instructions.

The most critical limitation for ISIGNS sits in its reliance on the building signage system. This reliance can be interpreted in two layers: the functional layer, which pertains to the overall building circulation, and the aesthetic layer, which involves the graphic design and placement of individual signs. In Section 3.5.5, we critically reflected on the current wayfinding design of the TU Wien main building. As revealed in Chapter 5, the signage system influenced the wayfinding performance and user experience of ISIGNS. The detour corresponds to the imperfection in the functional layer, while the user feedback regarding difficulties in sign visibility relates to issues in the aesthetic layer. In such cases, user experience and performance are negatively affected. To practically apply ISIGNS, it is worthwhile to first use it as an instrument for evaluating the building signage system, as discussed previously. Then apply it according to the assessment.

For future research, it would be interesting to explore the integration of indoor landmark-based instructions (Fellner et al., 2017) into ISIGNS route instructions. This integration could potentially reduce the system's reliance on the signage system and enhance its effectiveness. With the benefits of landmark-based instructions on spatial learning outdoors, such a combination may further promote indoor spatial learning. As suggested by participants (see Section 5.3.4.2), offering context-aware adaption can be another promising future direction. Such context can be time, building function, as well as user characteristics (Huang et al., 2018).

Additionally, while the current proof-of-concept of ISIGNS focuses on route instructions, future research should also consider the interface design of the navigation system. We used a minimalist base floor plan imitating the style of Google Indoor Maps for the in-situ experiment evaluating the system. However, as an essential part of navigation systems, it would be crucial to investigate how the visualisation design could be coupled with route instructions and best support wayfinding performance, spatial learning, and user experience. The timing of instructions is another aspect to consider. While for the semantic edges, ISIGNS generates the same instruction for the edge as the second part of the instructions for the current node. In our experiment, we incorporated the advice from participants in the pilot study on the timing of transitioning instructions. However, for the actual use of the system, the timing of the transition between instructions can impact usability. Close proximity turns, as depicted in Figure 4.8, highlight the importance of timing in guiding navigators accurately. Incorporating recent advances in the timing of route instructions could further enhance the navigation system's usability (Giannopoulos et al., 2017; Golab et al., 2022).

6.3 Towards cognitive mechanisms underlying mobile navigation systems and spatial learning

We identified the influence of environmental information sources (i.e., direct experience or external representations of the environment) on the levels of spatial knowledge as one of our research challenges. We analyse two empirical studies to shed light on this ongoing discussion and propose future research avenues.

In a study comparing the cognitive economy of signs and floor plans, Hölscher et al. (2007) suggested that using floor plans, which provide overall configurational information, leads to greater survey knowledge acquisition. On the other hand, signs offer sequential point-to-point information, supporting route knowledge. In Chapter 3, we correlated participants' reliance on floor plans and signs with the survey-likeness and route-likeness of their sketches. Our results showed a weak tendency towards this theory. Yet, we had reservations about this observation due to the limitations of using sketch map analysis methods developed for outdoor environments (Krukar et al., 2018), which are not necessarily suitable for indoor environments.

In Chapter 5, through a controlled experiment, we found that integrating signs into navigation systems facilitated survey knowledge acquisition significantly, in addition to landmark knowledge acquisition, compared to similar studies incorporating landmarks either outdoors (Gramann et al., 2017; Wunderlich & Gramann, 2018, 2021; Wunderlich et al., 2022) or indoors (B. Liu et al., 2021). Since instructing wayfinders with landmarks also draw their attention to the environment, it seems reasonable to attribute this survey knowledge enhancement to the semantics contained in signs. The information on signs is non-arbitrary, thus offering a relevant connection between the new information and participants' existing knowledge, where meaningful learning occurs (Ausubel et al., 1968). Participants confirmed this interpretation during interviews, stating that signs helped and encouraged them to learn about the building's structure.

These findings highlight the positive impact of integrating semantics into navigation guidance on spatial learning. It emphasises the importance of meaningful learning, which involves connecting new information to an individual's existing knowledge in a coherent manner (Ausubel et al., 1968; Bretz, 2001). The implications of these findings extend beyond indoor navigation for unfamiliar individuals. The concept of associating navigation instructions with meaning can also be applied to outdoor landmark-based navigation, if it is not already being utilised. Specifically, greater importance can be placed on semantic landmarks, particularly those that have established associations with specific user groups or individuals. Implementing this approach requires user modelling, which can be derived from user profiles or their previous spatial footprints (W. Wang, 2015).

Moreover, cognitive theories support our interpretation that participants learned spatial relations encoded in signs through the borrowing and reorganising principle (Sweller et al., 2011). Although this spatial relation is not explicitly presented in a graphic format like a floor plan, it is implicitly encoded in the signage system. Importantly, it is not the sign alone but the combination of signs with direct experience that facilitated participants' configurational understanding of the space. The spatial relation implicitly coded in signs structured participants' spatial sensing from direct experience, thus influencing the levels and structure of their acquired spatial knowledge. In Section 6.2, we proposed further incorporating landmarks into the ISIGNS. A comparison between the landmark-incorporated ISIGNS with a landmark-based navigation system could uncover the mechanism of this survey knowledge improvement and may empirically validate this interpretation.

These findings contribute to our understanding of how different environmental information sources influence the levels and structure of spatial knowledge acquisition. After all, spatial cognition is valuable not for its own sake but for accomplishing various spatial tasks, such as navigation and spatial reasoning (D. R. Montello & Raubal, 2013). Different spatial tasks require different levels of spatial knowledge, which are not constant but context-dependent (Ruginski et al., 2022). For example, route knowledge can be sufficient to retrace the same route in case we have lost something on the way. However, to be able to find a shortcut, survey knowledge is needed. Understanding the interplay between environmental information sources and spatial knowledge acquisition, as well as the required spatial knowledge for specific tasks within particular contexts, can maximise the effects of spatial learning. Considering that humans have limited working memory (Cowan, 2010) and learning inherently induces cognitive load, future research must investigate the cognitive mechanisms for mobile navigation systems and spatial learning components.

To unveil these cognitive mechanisms, it is necessary to differentiate cognitive processes, which can be achieved through a combination of methods for measuring cognitive load (Schmälzle & Grall, 2020), such as eye-tracking (Kiefer et al., 2016; Krejtz et al., 2018) and EEG (Keskin & Ooms, 2018). Additionally, spatial knowledge assessment methods deserve research attention. While we aim to measure spatial knowledge accurately to reflect the construct (D. Montello & Sutton, 2012), it is important to consider whether the tests we use help individuals exhibit their spatial knowledge and if the assessment methods are appropriate. Sketch map quality, for example, can be hindered by participants' drawing abilities, and analysing indoor sketch maps using outdoor analysis methods may further this inaccuracy. As another example, the limitations of the route knowledge assessment tasks used in our study were discussed in Section 5.4.2.2. The landmark ordering error and route direction recall error depend on the previous landmark knowledge assessment task. Although they are the shared assessment methods by previous literature (Burte & Montello, 2017; Huang et al., 2012; Van Asselen et al., 2006; Wunderlich et al., 2022)), their appropriateness, especially indoors, is still debatable. It would be worthwhile to re-evaluate and validate outdoor assessment methods in indoor environments to increase the validity of indoor spatial studies. Developing a dedicated set of spatial knowledge assessment methods for the indoor environment, taking into account its specific characteristics, would contribute to our understanding of spatial learning.

As a final critical reflection, we would like to return to our discussion on the negative impact of mobile navigation systems. Many studies argue that mobile navigation systems negatively affect spatial learning as they offload too much cognition. Still, this is naturally desirable considering the limited cognitive capacity of humans (Risko & Gilbert, 2016). While we label this a negative impact, it is not entirely unfavourable. In certain situations, such as emergencies, where working memory is already at its capacity limit for more vital activities, prioritising the task at hand over spatial learning is necessary. Therefore, it is crucial to understand the potential costs and benefits of cognitive offloading by navigation systems and explore possible interventions to increase or reduce individuals' inclination to engage in cognitive offloading. This understanding will enable future navigation systems to strike a balance between offloading unnecessary cognitive load and empowering individuals in spatial tasks.

6.4 General limitations

In Section 6.2, we outlined the shortcomings of ISIGNS. Here, we critically reflect on the general limitations of this research. This research studied indoor navigation, while conducting an explorative experiment in a museum and a university building and subsequently implemented and evaluated ISIGNS in the same university building. It is important to note that the generalisability and transferability of the findings may be limited due to the specific selection of these indoor environments.

Despite identifying shortcomings in the signage system of the university building in Chapter 3, we continued using it as our study area in Chapters 4 and 5. On the one hand, this choice showcases the potential of ISIGNS as a tool for assessing the quality of building signage systems. On the other hand, it was due to the convenience sampling of the study area. University buildings generally offer easy access to researchers. Similarly, convenience sampling was used to recruit participants for the evaluation of ISIGNS, with a majority of participants being geodesy and cartography students. The other participants recruited through volunteering groups were mainly researchers. Thus, we must recognise that our findings may be limited to highly educated young adults.

Another limitation lies in the evaluation of ISIGNS. In both Chapters 4 and 5, we used metric-based turn-by-turn instructions as a benchmark for comparison. However, we must acknowledge the availability of other types of route instructions, such as landmark-based instructions, and the comparison results may vary or be influenced by the choice of benchmark.

6.5 General recommendations

Throughout this dissertation, we have provided various suggestions to indoor navigation service providers. We present a summary of the key recommendations in a progressive manner below:

- Consistently provide signs at each decision point and floor plans at crucial building circulation points. This fundamental requirement ensures effective wayfinding.
- Provide mobile navigation systems, and consider integrating signs into the services. Integrating signs into mobile navigation services offers confirmation from the physical signage to mobile navigation services, enhances navigation experiences, and promotes spatial learning.
- Provide alternative choices for users, and consider the system's adaptivity to the use context and users. Allowing users to customize their navigation preferences and offering adaptive features can optimise the navigation experience.

By incorporating these recommendations progressively, indoor navigation service providers can offer effective and efficient wayfinding, enhance the overall navigation experience, and facilitate users' spatial learning.

Chapter 7

Conclusions

Navigating indoor spaces can present significant challenges, especially in large-scale public buildings. Conventional mobile navigation systems often rely on metric-based turn-by-turn instructions, which fail to account for the rich semantic cues, such as existing navigational aids, essential for effective indoor wayfinding. Moreover, the reliance on such navigation systems is suggested to affect spatial learning negatively.

This dissertation aims to address the challenges of indoor wayfinding and foster spatial learning, by proposing an integrated indoor navigation system that considers existing navigational aids. In the following, we summarise our main research findings in relation to the research questions identified in the introductory chapter.

RQ 1 *What factors influence navigators' decision-making at decision points, and how are the selection and utilisation of existing navigational aids affected?*

In Chapter 3, an explorative indoor wayfinding study was conducted to investigate the nature of human indoor wayfinding and the relevance of existing navigational aids. In response to **RQ 1**, we provide a systematic overview of indoor wayfinding tactics in Section 3.3, addressing how humans make wayfinding decisions under different conditions at decision points. The choice of tactics was influenced by various factors, including the wayfinding task, availability of navigational aids, environmental features, familiarity with the environment, human movement patterns, cultural background, and individual experiences and preferences. The sign tactic emerged as the most popular, regardless of the building structure and function.

Regarding existing navigational aids, wayfinders generally favoured signs, which is likely because processing information on signs is less cognitively demanding compared to floor plans. Nevertheless, this preference for signs is subjective and can be influenced by the description of a wayfinding task. Our analysis indicates that when the wayfinding task description includes spatial relations, such as "A close to B," it motivates wayfinders to seek the configurational representation in floor plans.

Our study setting in two buildings, which differ in structure and function, allowed us to find out whether and how building characteristics shape indoor wayfinding behaviour. We discovered that building characteristics did not affect unfamiliar wayfinders' preference for the central point strategy. However, the decision to follow a vertical-first or horizontal-first approach was influenced by the building structure and the availability of wayfinding aids. In two-dimensional spaces with a pre-defined order, such as museum exhibitions, wayfinders tended to follow the specified order, possibly because of the relatively low cognitive load and social considerations.

Concerning features for depicting and describing indoor environments, participants verbally instructed with semantic landmarks (signs and floor plans) more frequently than others, while functional landmarks (staircases, elevators, etc.) were the most drawn. We interpret these findings as a result of semantic landmarks' high visual and semantic saliency, which aligns with the employed wayfinding tactics.

RQ 2 *How do we integrate existing navigational aids into indoor navigation services?*

Wayfinders' dependence on signs and their high occurrence in human verbal instructions encouraged us to integrate them and their semantics into indoor navigation services. Consequently, we have modified our research question **RQ 2** to focus on integrating signs into indoor navigation services in Chapter 4. Specifically, our proposed solution is the Indoor Sign InteGrated Navigation System (ISIGNS).

ISIGNS operates by first modelling signs and their semantics into an indoor navigation model. It then generates routes and route instructions that consider sign semantics. Its implementation and evaluation have demonstrated its ability to automatically generate a navigation graph incorporating semantic information from signs, plan routes and provide route instructions accordingly. A quantitative evaluation of the readability indicates that the generated route instructions are easy to understand. Furthermore, a qualitative comparison has revealed multiple advantages of ISIGNS over metric-based turn-by-turn instructions, such as fewer instructions, utilising qualitative information, and addressing confusion at turns.

RQ 3 *Compared with conventional mobile navigation services, how do navigators' wayfinding performance, spatial learning, and user experience differ when navigating with the integrated indoor navigation service?*

Chapter 5 addresses **RQ 3**, in which we conducted a real-world navigation experiment comparing the proposed ISIGNS with the conventional navigation system using metric-based turn-by-turn instructions (MTBT) to evaluate the performance of ISIGNS and test whether it prompts spatial learning.

In terms of wayfinding performance, the results indicate a tendency for faster speed and fewer stops when using ISIGNS, although the difference was not statistically significant. Notably, using ISIGNS, participants made fewer but longer stops, whereas they stopped more frequently but for shorter durations using MTBT, typically for confirmation purposes.

As expected, navigating with ISIGNS led to improved spatial learning. The assessments for spatial knowledge acquisition, whether through recognition or recall, consistently demonstrated enhanced acquisition of landmark and survey knowledge, possibly due to the encouraged environmental attention allocation and the semantic nature of signs. Specifically, signs explicitly convey spatial relations, which may substantially benefit configurational learning.

However, regarding route knowledge, the assessments allow for varying interpretations, and further investigation is required to determine whether integrating signs facilitates route knowledge acquisition.

With regard to user experience, participants expressed a slightly higher level of confidence and preference for ISIGNS, although the difference was not statistically significant. They also suggested several alternatives for combining both systems adapting to the use context and user characteristics. Additionally, participants perceived ISIGNS as notably more novel and enjoyable to use in terms of both pragmatic and hedonic qualities. It is worth noting that the existing signage system within the building influenced user experience.

To summarise, this dissertation provides valuable insights into indoor human wayfinding behaviour and its influencing factors. We have provided a systematic overview of indoor wayfinding decision-making tactics, enriching the existing wayfinding theory and practically informing architecture design, building management, and indoor navigation system design.

Building upon these insights, we propose a computational framework for integrating signs into indoor navigation systems, prioritising sign semantics and utilising them to guide navigators. Through an in-situ experiment involving human participants, the evaluation of this framework reveals its potential for enriching navigation experiences and improving usability. Most importantly, the proposed approach has also significantly enhanced human spatial learning, particularly regarding landmark and survey knowledge acquisition.

In conclusion, this dissertation contributes to our understanding of indoor human wayfinding behaviour, sheds light on how different environmental information sources influence spatial knowledge acquisition, and presents ISIGNS, a practical and spatial-learning-promoting indoor navigation solution. We hope these findings and the ISIGNS framework will inspire further advancements in indoor navigation and support human spatial learning.

Please allow us to bring you back to the opening scenario. Imagine using the ISIGNS this time. As you followed the instructions, ISIGNS would have guided you to refer to the signs en route. At the same time, you would have noticed that information screens often accompany these signs. After purchasing the flowers, you could use your spatial knowledge to locate one of these information screens and obtain the platform information for your connecting train. Then, you could confidently navigate to the correct platform, thanks to the spatial knowledge you just acquired.

As we end this journey, we would like to return to where "wayfinding" started and echo Lynch (1960) concluding remarks in The Image of the City. In a similar vein, we aspire for a future where humans and technology thrive together within an environment enriched by technology. Through this dissertation, we aim to sow a seed that will nurture our confidence in a future where technology supports human spatial capabilities.

Appendix A

Appendix A.1: ISIGN graph generation algorithm

```
# ISIGN graph generation
# first, we add the sign node to its nearest point on the
    nearest edge, and split the edge into two. The signs and
    their semantics are modelled in the nodes.

G_sem_undi = G.copy()
new_edges_sem = new_edges.copy()
all_nodes_sem = all_nodes.copy()

for i, sign in signs.iterrows():
    min_distance = float("inf")
    nearest_edge_id = None
    # get the distance as a geoseries of all edges to the
        current sign node, then get the minimum
    distance = new_edges_sem.distance(sign['geometry'])
    min_dist = distance.min()
    if min_dist < min_distance:
        nearest_edge_id = new_edges_sem.loc[distance.idxmin(),
            'Edge_ID']
        nearest_edge = new_edges_sem.loc[new_edges_sem['Edge_ID
            '] == nearest_edge_id]
        min_distance = min_dist
    # Create a buffer around the sign with the minimum distance
    buffer_distance = min_distance + 0.01 # because using min-
        distance may end up with no intersection, i.e., just
        missed, so add a bit value.
    buffered_sign = signs.buffer(buffer_distance)
    # Find the intersection of the buffer with the edges
    intersection = nearest_edge['geometry'].intersection(
        buffered_sign.iloc[i])
    intersection_line = intersection.iloc[0]
```

```
intersection_point = intersection_line.interpolate(0.5,
    normalized=True) # using interpolation to find the mid-
    point

# Create a geodataframe for the intersection point and add
    it to original nodes geodataframe
sign_semantics = sign['Semantics']
node_id = all_nodes_sem['Node_ID'].max() + 1
intersection_dict = {
     'Node_ID': node_id,
     'OBJECTID': None,
     'Room_code': None,
     'Code': None,
     'Area': None,
     'Level': sign['Level'],
     'Level_ID': sign['Level_ID'],
     'Class': sign['Class'],
     'Construction': 'No',
     'Height': sign['Height'],
     'Room_name': sign['Room_name'],
     'Edge_ID': None,
     'Edge_ID_2': None,
     'Semantics': sign_semantics,
     'geometry': intersection_point
     }
intersection_gdf = gpd.GeoDataFrame([intersection_dict],
    geometry = 'geometry', crs=all_nodes_sem.crs)
all_nodes_sem = all_nodes_sem.append(intersection_gdf,
    ignore_index=True)

# split the edge into two edges, first: start to
    intersection, second: intersection to end
start_pt = Point(nearest_edge.iloc[0]['geometry'].coords
    [0])
end_pt = Point(nearest_edge.iloc[0]['geometry'].coords[1])
new_edge1 = LineString([start_pt, intersection_point])
new_edge2 = LineString([intersection_point, end_pt])
edge1_start = nearest_edge.iloc[0]['Start_Node_ID']
edge1_end = node_id
edge2_start = node_id
edge2_end = nearest_edge.iloc[0]['End_Node_ID']

# update the edges by adding two edges and delete the
```

```
    original one (be aware that the mapping in the nodes
    dataframe will not work, if not updated accordingly)
new_row1 = {
        'Start_Node_ID': nearest_edge.iloc[0]['Start_Node_ID'],
        'End_Node_ID': node_id,
        'Edge_ID': new_edges_sem['Edge_ID'].max() + 1,
        'Semantic_edge': 'No',
        'Oneway': 'No',
        'OBJECTID': None,
        'Level': nearest_edge.iloc[0]['Level'],
        'Level_ID': nearest_edge.iloc[0]['Level_ID'],
        'Height': nearest_edge.iloc[0]['Height'],
        'Shape_Length': None,
        'Shape': None,
        'length': new_edge1.length,
        'geometry': new_edge1
}
new_row1_gdf = gpd.GeoDataFrame([new_row1], geometry = '
    geometry', crs = new_edges_sem.crs)
# add the new edges to the graph
G_sem_undi.add_edge(edge1_start, edge1_end, geometry=
    new_edge1, length=new_edge1.length, edge_id=
    new_edges_sem['Edge_ID'].max() + 1, semantic_edge='No',
    oneway='No', level_id=nearest_edge.iloc[0]['Level_ID'],
    level=nearest_edge.iloc[0]['Level'], height=nearest_edge
    .iloc[0]['Height'])

# create a new row for the second segment
new_row2 = {
        'Start_Node_ID': node_id,
        'End_Node_ID': nearest_edge.iloc[0]['End_Node_ID'],
        'Edge_ID': new_edges_sem['Edge_ID'].max() + 2,
        'Semantic_edge': 'No',
        'Oneway': 'No',
        'OBJECTID': None,
        'Level': nearest_edge.iloc[0]['Level'],
        'Level_ID': nearest_edge.iloc[0]['Level_ID'],
        'Height': nearest_edge.iloc[0]['Height'],
        'Shape_Length': None,
        'Shape': None,
        'length': new_edge2.length,
        'geometry': new_edge2
}
```

```
    new_row2_gdf = gpd.GeoDataFrame([new_row2], geometry = '
       geometry', crs = new_edges_sem.crs)
    G_sem_undi.add_edge(edge2_start, edge2_end, geometry=
       new_edge2, length=new_edge2.length, edge_id=
       new_edges_sem['Edge_ID'].max() + 2, semantic_edge='No',
       oneway='No', level_id=nearest_edge.iloc[0]['Level_ID'],
       level=nearest_edge.iloc[0]['Level'], height=nearest_edge
       .iloc[0]['Height'])

    # append the new rows to the edges geodataframe
    new_edges_sem = new_edges_sem.append(new_row1_gdf,
       ignore_index=True)
    new_edges_sem = new_edges_sem.append(new_row2_gdf,
       ignore_index=True)
    # drop the original row corresponding to the edge that was
       split
    new_edges_sem.drop(new_edges_sem[new_edges_sem['Edge_ID']
       == nearest_edge_id].index, inplace=True) # Without
       inplace=True, the operation will return a new DataFrame
       with the modifications applied, leaving the original
       DataFrame unchanged.

# add a semantic edge in the graph from the mapped sign
   location to the destinations on the sign (and the sign at
   the destination). Modelling the semantics
G_sem = G_sem_undi.to_directed()
for idx, row in all_nodes_sem.iterrows():
    if row['Class'] == 'Sign':
        destinations = row['Semantics']
        destinations_list = destinations.split(",␣")
        for destination in destinations_list:
            for j, node in all_nodes_sem.iterrows():
                if node['Class'] == 'Sign': # distinguish
                   whether the node is a sign node.
                    # extract the sign location from the sign
                       name
                    sign_name = node['Room_name']
                    sign_name_parts = sign_name.split("at")
                    location_part = sign_name_parts[1]
                    sign_location = location_part.strip()
                        sem_edge_line = LineString([row['
                           geometry'], node['geometry']])
                        sem_edge_start = row['Node_ID']
```

```
sem_edge_end = node['Node_ID']
sem_edge_length = nx.
    shortest_path_length(G_sem_undi,
    source=sem_edge_start, target=
    sem_edge_end, weight='length')
# Calculate the shortest path between
    start and end, and get the last edge
     of the shortest path
shortest_path = nx.shortest_path(
    G_sem_undi, source=sem_edge_start,
    target=sem_edge_end)
sem_edge_last_edge = (shortest_path
    [-2], shortest_path[-1])
sem_edge = {
     'Start_Node_ID': row['Node_ID'],
     'End_Node_ID': node['Node_ID'],
     'Edge_ID': new_edges_sem['Edge_ID'
         ].max() + 1,
     'Semantic_edge': 'Yes',
     'Oneway': 'Yes',
     'OBJECTID': None,
     'Level': 'Not␣applicable',
     'Level_ID': None,
     'Height': None,
     'Shape_Length': None,
     'Shape': None,
     'length': sem_edge_length,
     'geometry': sem_edge_line,
     'last_edge': sem_edge_last_edge
}
sem_edge_gdf = gpd.GeoDataFrame([
    sem_edge], geometry = 'geometry',
    crs = new_edges_sem.crs)
G_sem.add_edge(sem_edge_start,
    sem_edge_end, geometry=sem_edge_line
    , length=sem_edge_length, edge_id=
    new_edges_sem['Edge_ID'].max() + 1,
    semantic_edge='Yes', oneway='Yes',
    level_id='Not␣applicable', level=
    None, height=None, last_edge=
    sem_edge_last_edge)
new_edges_sem = new_edges_sem.append(
    sem_edge_gdf, ignore_index=True)
```

```
else:
    if node['Room_name'] == destination:
        sem_edge_line = LineString([row['
           geometry'], node['geometry']])
        sem_edge_start = row['Node_ID']
        sem_edge_end = node['Node_ID']
        sem_edge_length = nx.
           shortest_path_length(G_sem_undi,
           source=sem_edge_start, target=
           sem_edge_end, weight='length')
        shortest_path = nx.shortest_path(
           G_sem_undi, source=sem_edge_start,
           target=sem_edge_end)
        sem_edge_last_edge = (shortest_path
           [-2], shortest_path[-1])
        sem_edge = {
            'Start_Node_ID': row['Node_ID'],
            'End_Node_ID': node['Node_ID'],
            'Edge_ID': new_edges_sem['Edge_ID'
               ].max() + 1,
            'Semantic_edge': 'Yes',
            'Oneway': 'Yes',
            'OBJECTID': None,
            'Level': 'Not␣applicable',
            'Level_ID': None,
            'Height': None,
            'Shape_Length': None,
            'Shape': None,
            'length': sem_edge_length,
            'geometry': sem_edge_line,
            'last_edge': sem_edge_last_edge
        }
        sem_edge_gdf = gpd.GeoDataFrame([
           sem_edge], geometry = 'geometry',
           crs = new_edges_sem.crs)
        G_sem.add_edge(sem_edge_start,
           sem_edge_end, geometry=sem_edge_line
           , length=sem_edge_length, edge_id=
           new_edges_sem['Edge_ID'].max() + 1,
           semantic_edge='Yes', oneway='Yes',
           level_id='Not␣applicable', level=
           None, height=None, last_edge=
           sem_edge_last_edge)
```

```
                        new_edges_sem = new_edges_sem.append(
                            sem_edge_gdf, ignore_index=True)
```

Appendix A.2: ISIGN routing

```
# ISIGN routing

# find the shortest path between nodes source and target
source = input("Please␣enter␣your␣start:␣")
target = input("Please␣enter␣your␣destination:␣")
node1_id = room_to_node[source]
node2_id = room_to_node[target]
shortest_path = nx.shortest_path(G_sem, source=node1_id, target
    =node2_id, weight="length")
# set the maximum length for candidate paths
max_length = int((1+delta) * len(shortest_path))

# find all simple paths that are at most max_length nodes long
def k_shortest_paths(G, source, target, k, weight=None):
    return list(
        islice(nx.shortest_simple_paths(G, source, target,
            weight=weight), k)
    )

k_candidate_paths = k_shortest_paths(G_sem, node1_id, node2_id,
    20, weight="length")
candidate_paths = [path for path in k_candidate_paths if len(
    path) <= (1+delta) * len(shortest_path)]

# calculate the path with max coverage of semantic egdes
max_coverage = 0
sem_path = None
for path in candidate_paths:
    semantic_edges = [(u, v) for u, v in zip(path, path[1:]) if
        G_sem[u][v]["semantic_edge"] == "Yes"]
    semantic_length = sum(G_sem[u][v]["length"] for u, v in
        semantic_edges)
    total_length = sum(G_sem[u][v]["length"] for u, v in zip(
        path, path[1:]))
    coverage = semantic_length / total_length
    if coverage >= max_coverage:
        max_coverage = coverage
        sem_path = path
```

```
print(sem_path)
```

Appendix A.3: ISIGN route instructions generation

```
#ISIGN ROUTE INSTRUCTION GENERATION

# Create a transformer object to transform from original CRS to
    cartesian CRS
original_crs = {'init': 'epsg:3045'}
cartesian_crs = {'init': 'epsg:3857'}
transformer = pyproj.Transformer.from_crs(
    original_crs,
    {"proj": "utm", "zone": "32N", "ellps": "WGS84", "datum": "
       WGS84", "units": "m"},
    always_xy=True,
)

def get_turn_direction(prev_angle, curr_angle):
    angle = prev_angle -curr_angle
    if angle > 180:
        angle -= 360
    elif angle < -180:
        angle += 360

    # determine turn direction based on the angle
    if -165 < angle <= -120:
        return "sharp␣left"
    elif -120 < angle <= -60:
        return "left"
    elif -60 < angle < -20:
        return "slightly␣left"
    elif -20 <= angle <= 20:
        return "straight"
    elif 20 < angle < 60:
        return "slightly␣right"
    elif 60 <= angle < 120:
        return "right"
    elif 120 <= angle < 165:
        return "sharp␣right"
    else:
        return "back"
```

```
def extracting_sign_location(sign_name):
    sign_name_parts = sign_name.split("at")
    location_part = sign_name_parts[1]
    sign_location = location_part.strip()
    return sign_location

def get_spatial_relation(node, egde, nodes_gdf):
    edge_vector = np.array(edge['end_node']) - np.array(edge['
       start_node'])
    edge_direction = edge_vector / np.linalg.norm(edge_vector)
    start_node = edge['start_node']
    edge_start = Point(nodes_gdf.loc[start_node, 'geometry'].x,
        nodes_gdf.loc[start_node, 'geometry'].y)
    end_node = edge['end_node']
    edge_end = Point(nodes_gdf.loc[end_node, 'geometry'].x,
       nodes_gdf.loc[end_node, 'geometry'].y)
    node_coords = Point(nodes_gdf.loc[node, 'geometry'].x,
       nodes_gdf.loc[node, 'geometry'].y)
    if nodes_gdf.loc[node, 'Node_ID'] == edge['start_node']:
        node_vector = np.array(node_coords) - np.array(
           edge_start)
    else:
        node_vector = np.array(node_coords) - np.array(edge_end
           )
    dot_product = np.dot(edge_direction, node_vector)
    if dot_product > 0:
        node_relation = "right"
    elif dot_product < 0:
        node_relation = "left"
    else:
        node_relation = "unknown"
    return node_relation

def get_spatial_relation2(prev_angle, curr_angle):
    angle = prev_angle -curr_angle
    if angle > 180:
        angle -= 360
    elif angle < -180:
        angle += 360
    # determine the relation right or left
    if angle < 0:
        return "left"
    elif angle > 0:
```

```
        return "right"
    else:
        return "unknown"

def get_location_name(node, nodes_gdf):
    node_idx = nodes_gdf.index[nodes_gdf['Node_ID'] == node][0]
    if nodes_gdf.loc[node_idx, 'Class'] == 'Sign': #
        distinguish whether the node is a sign node or other
        node with a name.
        sign_name = nodes_gdf.loc[node_idx, 'Room_name']
        sign_location = extracting_sign_location(sign_name)
        location_name = sign_location
    else:
        location_name = nodes_gdf.loc[node_idx, 'Room_name']
    return location_name

def calculate_angle(current_node_idx, next_node_idx, nodes_gdf)
    :
    curr_point = Point(nodes_gdf.loc[current_node_idx, '
        geometry'].x, nodes_gdf.loc[current_node_idx, 'geometry'
        ].y)
    next_point = Point(nodes_gdf.loc[next_node_idx, 'geometry'
        ].x, nodes_gdf.loc[next_node_idx, 'geometry'].y)
    curr_point_proj = transformer.transform(curr_point.x,
        curr_point.y)
    next_point_proj = transformer.transform(next_point.x,
        next_point.y)
    dx = next_point_proj[0] - curr_point_proj[0]
    dy = next_point_proj[1] - curr_point_proj[1]
    curr_angle = math.degrees(math.atan2(dy, dx))
    return curr_angle

def generate_semnatic_route_instructions(route, G, nodes_gdf):

    #initialise
    prev_angle = 0
    prev_direction = None
    prev_distance = 0
    direction = None
    distance = 0
    instructions = []
    previous_edge = {
        'semantic_edge': None,
```

```
    'geometry': None,
    'start_node': None,
    'end_node': None
}

for i in range(len(route)-1):
    current_node = route[i]
    current_node_idx = nodes_gdf.index[nodes_gdf['Node_ID']
         == current_node][0]
    next_node = route[i+1]
    next_node_idx = nodes_gdf.index[nodes_gdf['Node_ID'] ==
         next_node][0]
    path_type = "path"  # As our data does not have path
        type, we assume path type by default.

    # considering different situation for the NODES. Two
        actions: where they are, and next move.
    if previous_edge['geometry'] is not None:
        if nodes_gdf.loc[current_node_idx, 'Room_name'] !=
            'unknown': # distinguish whether the current
            node has a name. always tell people where they
            are.
             location_name = get_location_name(current_node,
                  nodes_gdf)
             instructions.append(f"Now␣you␣are␣at␣{
                 location_name}.")
        if G[current_node][next_node]['semantic_edge'] == '
            Yes': # tell people about the next move. if next
             edge is semantic edge
             location_name = get_location_name(next_node,
                 nodes_gdf)
             instructions.append(f"Follow␣the␣sign␣pointing␣
                 to␣{location_name}.")
        else: # metric_based tbt, at node, only turn
            information
             curr_angle = calculate_angle (current_node_idx,
                  next_node_idx, nodes_gdf)
             direction = get_turn_direction(prev_angle,
                 curr_angle)
             if direction == "straight" and len(instructions
                 ) > 0 and prev_direction == None:
                  instructions.append(f"Go␣straight.")  #
                      just want "Go straight." to be printed
```

```
               once.
        elif direction == "straight" and len(
           instructions) > 0 and prev_direction != None
           :
            instructions.pop() # delete the previous
               item in the list, which is "Go along the
                {path_type} for {distance}m."
        else:
            instructions.append(f"Turn␣{direction}.")

# generate instruction for the EDGES.
if G[current_node][next_node]['semantic_edge'] == 'Yes'
   :
    location_name = get_location_name(next_node,
       nodes_gdf)
    instructions.append(f"Follow␣the␣sign␣pointing␣to␣{
       location_name}.")
    # initialise the information for tbt, everytime one
        passes a semantic edge, angle calculated based
       on the last_edge
    direction = None
    source_node = G[current_node][next_node]['last_edge
       '][0]
    target_node = G[current_node][next_node]['last_edge
       '][1]
    curr_angle = calculate_angle (source_node,
       target_node, nodes_gdf)
    distance = 0
else:
    curr_angle = calculate_angle (current_node_idx,
       next_node_idx, nodes_gdf)
    direction = get_turn_direction(prev_angle,
       curr_angle)
    distance = G[current_node][next_node]['length']
    if direction == "straight" and len(instructions) >
       0 and prev_direction == None:
        instructions.append(f"Go␣along␣the␣{path_type}␣
           for␣{round(distance)}m.")
    elif direction == "straight" and len(instructions)
       > 0 and prev_direction != None:
        distance = distance + prev_distance
        instructions.append(f"Go␣along␣the␣{path_type}␣
           for␣{round(distance)}m.")
```

```
     else:
         instructions.append(f"Go␣along␣the␣{path_type}␣
             for␣{round(distance)}m.")

# handle last leg of the route
 destination = route[-1]
 destination_idx = nodes_gdf.index[nodes_gdf['Node_ID']
    == destination][0]
 if current_node == route[-2]:
     side = get_spatial_relation2(prev_angle, curr_angle
        )
     if G[current_node][next_node]['semantic_edge'] == '
        Yes':
         instructions.append(f"The␣{path_type}␣leads␣to␣
             your␣destination␣{nodes_gdf.loc[
             destination_idx,␣'Room_name']}.")
     elif side == 'right' or side == 'left':
         destination_name = nodes_gdf.loc[
             destination_idx, 'Room_name']
         if destination_name != 'unknown':
             instructions.append(f"Your␣destination␣{
                nodes_gdf.loc[destination_idx,␣'
                Room_name']}␣is␣located␣on␣the␣{side}␣
                side␣of␣the␣{path_type}.")
         else:
             instructions.append(f"Your␣destination␣is␣
                located␣on␣the␣{side}␣side␣of␣the␣{
                path_type}.")
     else:
         instructions.append(f"The␣{path_type}␣leads␣to␣
             your␣destination␣{nodes_gdf.loc[
             destination_idx,␣'Room_name']}.")

 previous_edge['semantic_edge'] = G[current_node][
    next_node]['semantic_edge']
 previous_edge['geometry'] =  G[current_node][next_node
    ]['geometry']
 previous_edge['start_node'] = current_node
 previous_edge['end_node'] = next_node
 #prep for metric-based tbt, update
 prev_angle = curr_angle
 prev_direction = direction
 prev_distance = distance
```

```
        return instructions

sem_instruction = generate_semnatic_route_instructions(sem_path
    , G_sem, all_nodes_sem)
sem_instruction
```

Appendix B

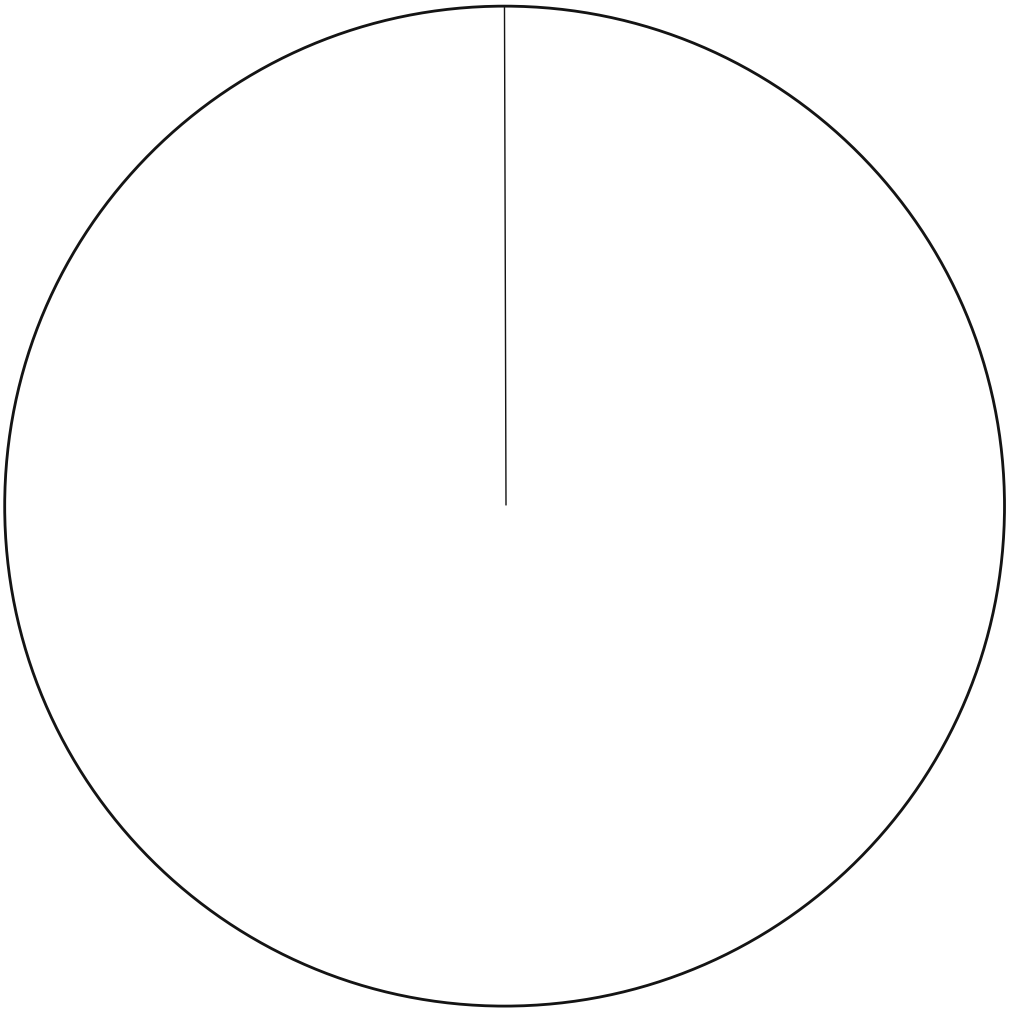
Appendix B.1: Tasks

The content of the following pages are the tasks handed out to the participants of the study.

Participant ID:

The line in the circle indicates the direction you are facing.

Please draw a line from the center of the circle to indicate the direction to the starting point.



1. How confident you are with the direction?

1	2	3	4	5	6	7
not at all						very sure

5. Please write down the IDs of all pictures that you think were along the current route, e.g., X, X, X.

6. Please write down the picture IDs, according to the order you encountered them along the route, e.g., X-X-X.

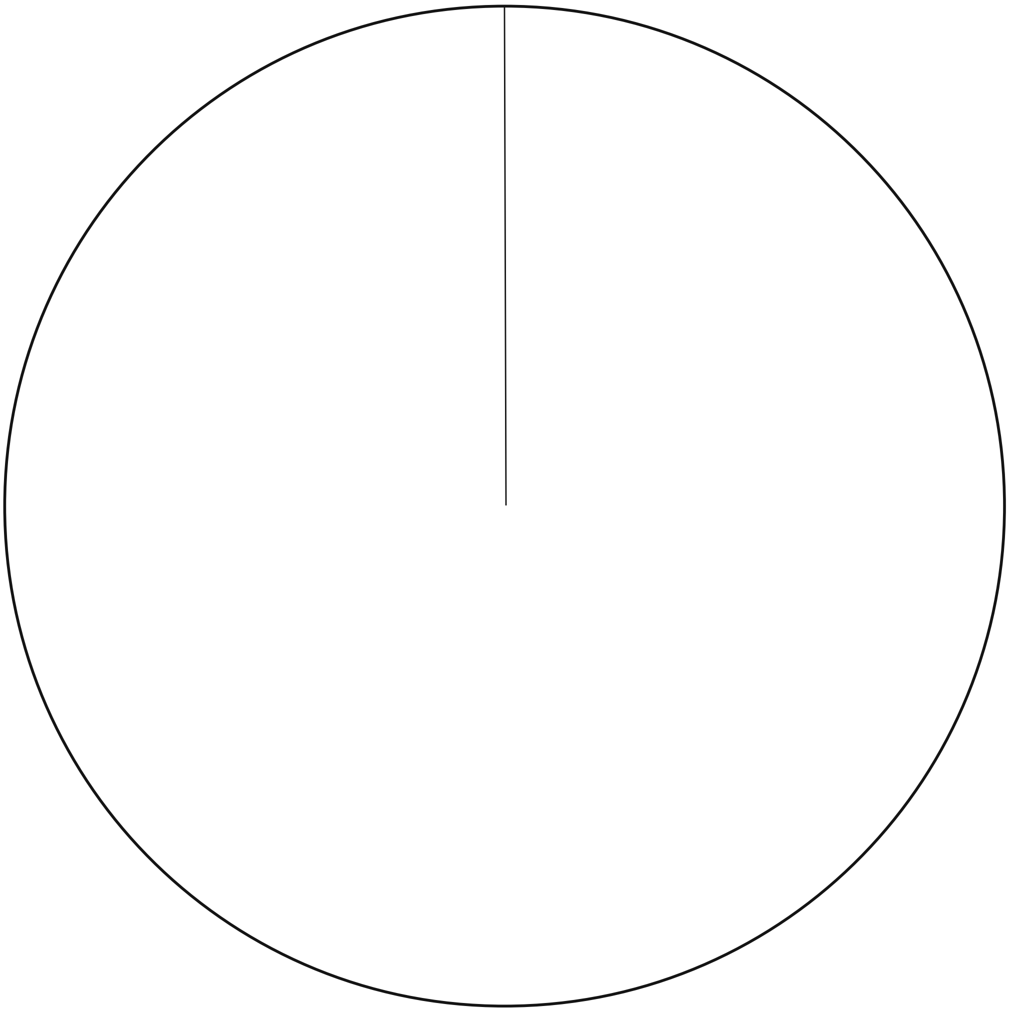
8. Please write down the IDs of the turns, e.g., X-1.

K

Participant ID:

The line in the circle indicates the direction you are facing.

Please draw a line from the center of the circle to indicate the direction to the starting point.



1. How confident you are with the direction?

1 2 3 4 5 6 7

not at all very sure

5. Please write down the IDs of all pictures that you think were along the current route, e.g., X, X, X.

6. Please write down the picture IDs, according to the order you encountered them along the route, e.g., X-X-X.

8. Please write down the IDs of the turns, e.g., X-1.

Please draw your current location (with a circle ○) and orientation (with an arrow ⬆) on the floor plan.

The starting point is marked as ●.

Please draw the route you have taken on the floor plan, and describe the characteristics of the route as detailed as you can (in the floor plan).

If there is another new student asking you how to come here from the starting point, how will you direct them? Please describe it to me. (I will record it.)

Please write down the IDs of all pictures that you think were along the current route.

(Please write on the first sheet, e.g., X, X, X)

Please order the pictures you have chosen, according to the order you encountered them along the route. Please write down the IDs in the order.

(Please write on the first sheet, e.g., X-X-X)

Please place the pictures you have chosen, by writing their IDs on the corresponding locations on the floor plan.

In your chosen pictures, these are intersections. Please indicate the turn you have taken, by writing down the IDs.

(Please write on the first sheet, e.g., X-1)

Appendix B.2: Questionnaire

The content of the following pages are the questionnaire handed out to the participants of the study.

Participant ID: Gender: Age:

Education background (e.g., Cartography):

1. How familiar are you with this building?

not familiar familiar very familiar

2. How familiar are you with the first route?

not familiar familiar very familiar

3. How familiar are you with the second route?

not familiar familiar very familiar

4. Have you ever used mobile navigation services for outdoors?

YES ☐ NO ☐

5. If yes, how often do you use them?

once a year every few month once a month every two weeks weekly several times a week daily

6. Have you ever used mobile navigation services for indoors?

YES ☐ NO ☐

7. If yes, how often do you use them?

once a year every few month once a month every two weeks weekly several times a week daily

8. How difficult were the tasks after the first route?

very difficult neutral very easy

9. I felt confident navigating using the first route instruction during the experiment.

strongly disagree neutral strongly agree

10. I felt the first route instruction:

obstructive	1	2	3	4	5	6	7	supportive
complicated	1	2	3	4	5	6	7	easy
inefficient	1	2	3	4	5	6	7	efficient
clear	1	2	3	4	5	6	7	confusing
boring	1	2	3	4	5	6	7	exciting
conventional	1	2	3	4	5	6	7	inventive
uncomfortable	1	2	3	4	5	6	7	comfortable

11. How difficult were the tasks after the second route?

very difficult neutral very easy

12. I felt confident navigating using the second route instruction during the experiment.

strongly disagree neutral strongly agree

13. I felt the second route instruction:

obstructive	1	2	3	4	5	6	7	supportive
complicated	1	2	3	4	5	6	7	easy
inefficient	1	2	3	4	5	6	7	efficient
clear	1	2	3	4	5	6	7	confusing
boring	1	2	3	4	5	6	7	exciting
conventional	1	2	3	4	5	6	7	inventive
uncomfortable	1	2	3	4	5	6	7	comfortable

14. Which route instructions do you prefer?

first ☐ second ☐

Please comment:……………………………………………………………………

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