UMEÅ UNIVERSITY

Escaping 'Death By GPS': Foundations For Adaptive Navigation Assistance

Fateme Teimouri

Doctoral Thesis, May 2023
Department of Computing Science
Umeå University
Sweden

Department of Computing Science
Umeå University
SE-901 87 Umeå, Sweden

teimouri@cs.umu.se

ISBN 978-91-8070-024-5 (print)
978-91-8070-025-2 (digital)
ISSN 0348-0542
UMINF

Printed by Cityprint i Norr AB, Umeå, 2023

“All our dreams can come true if we have the courage to pursue them.”

Walt Disney

Abstract

Navigating through physical environments has evolved over time from using stars and maps to support the wayfinding, to employing Global Positioning Systems and navigation services. Turn-by-turn guidance of navigation services is an effective way to support wayfinding, but it may not align with the way humans naturally navigate. Over-reliance on navigation services can lead to confusion, frustration, and even dangerous situations. Humans use environmental cues to support their navigation decisions and understand their position, orientation, and surroundings. Navigation services prioritize efficient route planning and may not consider factors such as complexity that can impact travel. This discrepancy between navigation services and human navigation highlights the importance of incorporating principles of human wayfinding into navigation systems to enhance the overall wayfinding experience.

This thesis aims to improve navigation services by exploring their adaptive capabilities and addressing the discrepancies between navigation services and human wayfinding. The research focuses on identifying difficult-to-navigate intersections and prominent locations along a route that are important for successful navigation, and developing automated ways to identify them. The thesis also explores adapting instruction giving to the route and its surrounding.

The research included in this thesis analyzed geographic data, developed models and measures that extended existing research, and conducted empirical human subject studies. This work developed models that optimize route search for specific criteria, including traffic and social costs. It also proposes approaches to identifying and simplifying prominent locations along a route that define the relationship between the route and the environment. Results show that people tend to prefer less complex routes with fewer prominent locations. Results also indicate that incorporating route-defining locations in route directions can aid wayfinders in forming useful spatial memory of the environment. Additionally, the studies identified the language used and spatial reasoning mechanisms over direction change as sources of mismatches between navigation instructions and human understanding of a given wayfinding situation, which may provide insights into improving the generation of instructions.

Sammanfattning

Preface

This thesis includes the following five papers.

Paper I	**F. Teimouri**, and K. F. Richter. You are not alone: Path search models, traffic, and social costs. *GIScience 2021; 11th International Conference on Geographic Information Science*, Schloss Dagstuhl–Leibniz-Zentrum für Informatik, 177, pp. 1-14, 2020.
Paper II	**F. Teimouri**, H. H. Hochmair, and K. F. Richter. Analysis of route choice based on path characteristics using GeoLife GPS trajectories. *Submitted*, 2023.
Paper III	**F. Teimouri**, and K. F. Richter. Abstracting routes to their route-defining locations. *Computers, Environment and Urban Systems*, Elsevier, 91, 101732, 2022.
Paper IV	**F. Teimouri**, and K. F. Richter. Supporting spatial knowledge acquisition by automated augmentation of route directions with route-defining locations. *Submitted*, 2023.
Paper V	**F. Teimouri**, and K. F. Richter. ‘Straight? What straight?’ Investigating navigation instructions’ applicability. *Journal of Location Based Services*, Taylor & Francis, 1–25, 2021.

Financial support for this work is provided by the Swedish Research Council (Vetenskapsrådet) under grant 2018-05318.1.

Acknowledgements

Contents

Chapter 1

Introduction

Wayfinding, the process of navigating through the physical environment from one location to another, is a common activity in our daily lives. This process involves selecting the best route to reach a destination, monitoring progress to ensure the correct path is being followed, and finally recognizing the destination once reached. Humans have used various means of guidance throughout history, including the stars, compasses, and maps, to aid in wayfinding. However, in recent years, Global Navigation Satellite Systems (GNSS), in particular the Global Positioning System (GPS), have become ubiquitous, providing users with real-time information on their location and destination with the helpf of mobile computing devices and geographic data sources.

One of the most common features of navigation services is turn-by-turn guidance, which breaks down the overall journey into smaller segments connected by decision points. Turn-by-turn guidance has proven to be an effective way to support wayfinding, allowing wayfinders to reach their destination successfully most of the time. This has led to a significant increase in demand for these services. However, these services may not align with the way humans naturally navigate. Wayfinders often rely on heuristics and a variety of factors when making navigation decisions, whereas navigation services prioritize efficient route planning. This discrepancy can lead to confusion or frustration for users, especially in unfamiliar environments.

Over-reliance on navigation services can even lead to dangerous situations, resulting in the phenomenon of “Death by GPS” [Mil16]. Blindly following instructions provided by navigation services can lead people astray and into unsafe areas. What was once a complex process involving active information search, spatial updating, and decision-making has now been reduced to a simple task of passively following a path and carrying out a series of turn instructions. This highlights the discrepancy between how navigation services operate and how people naturally navigate, which can cause confusion or frustration for wayfinders.

The way humans navigate and the way navigation services operate can differ in several ways. Firstly, navigation services rely on predetermined routes that prioritize minimizing travel time, whereas wayfinders use heuristics to simplify their navigation decisions and may take alternative routes based on factors such as complexity or social preferences. For instance, a navigation service may suggest the shortest route without considering the complexity of intersections, leading to delays and frustration for users. In contrast, a wayfinder may choose a slightly longer route to avoid complex intersections and reduce the risk of potential delays due to difficulties in navigating. These discrepancies can result in confusion and frustration, particularly when navigation services do not consider the factors that can impact travel.

Secondly, environmental embedding is critical for correct navigation, as it allows wayfinders to use environmental cues to understand their position and orientation within the environment. However, navigation services often do not take into account the environmental context when generating route instructions. As a result, there can be mismatches between the instructions provided by the service and how a wayfinder understands the given wayfinding situation. Wayfinders use a variety of cues to augment their route instructions with an environmental context, such as points of interest and orientation. Removing this environmental context can lead to negative effects on wayfinding and spatial knowledge acquisition, resulting in confusion and disorientation for wayfinders.

Lastly, spatial learning is a crucial aspect of navigation, as it enables individuals to create cognitive maps of their surroundings and building a mental representation of their environment. Navigation systems that rely on turn-by-turn route instructions may hinder this spatial learning process by providing users with step-by-step directions without contextual information about the environment. This can result in wayfinders struggling to remember the route taken or understand how it relates to the broader surroundings, which can be problematic in the short and long run. These discrepancies between navigation services and human navigation highlight the importance of considering human navigation tendencies and incorporating them into navigation systems to enhance the overall wayfinding experience.

1.1 Research Problem and Objectives

While previous research has identified both technological and cognitive reasons for navigation failure and the lack of environmental learning when using navigation services, limited exploration has been conducted on how to address their negative effects. Previous studies have mainly focused on manipulating device interaction or instruction giving to alter human behavior and spatial learning, overlooking the adaptive potential of navigation services and their ability to provide assistance in any environment. Therefore, it is essential to examine the interaction triangle of environment, service, and user to enhance navigation services and their ability to address the negative effects of navigation.

The objective of this thesis is to improve navigation services by exploring their adaptive capabilities and addressing the discrepancies between navigation services and human navigation. A significant aspect of this research involves identifying difficult-to-navigate intersections that require additional attention and careful instructions. These intersections may pose unique challenges to users, such as complex spatial layouts or the need to perform specific wayfinding actions. By developing means to identify and address these intersections, the thesis aims to enhance the overall reliability and ease of use of navigation services.

In addition to identifying complex intersections, the thesis focuses on identifying the specific locations along a route that are important for users to understand and remember to navigate successfully. This includes determining the specific features of these locations and developing automated ways to identify them. The thesis also explores ways of adapting instruction giving to reflect the differing information needs of users along a route, utilizing data on the characteristics of the environment to generate instructions that provide users with the necessary information to navigate successfully. By developing these adaptive instruction-giving strategies, the thesis aims to provide the crucial foundations for the development of automated navigation assistance that can adapt to any environment.

This research focuses on the following key research questions:

RQ1 How to design route search models to optimize for a specific aspect and mitigate unwanted effects?

RQ2 How to analyze a route regarding its embedding in the environment, thereby identifying those locations along the route that define the relation between route and environment which are crucial to navigate correctly?

RQ3 How to generate instructions for a route that help wayfinders with route-finding and route-learning?

1.2 Approach

We have utilized theories and methods from computer science, cognitive science, and geographic information science, including spatial reasoning and analysis methods, to identify situations where information provision needs to change. We have developed models and measures that draw upon and significantly extend existing research. Some of these models and measures have been evaluated through empirical human subject studies. To calculate differences in the importance and complexity of different locations, we have analyzed geographic data about the environment, making use of freely available data sources such as OpenStreetMap as much as possible. Empirical human subject studies provide important insights into whether the developed measures accurately capture how people experience wayfinding situations and whether the aims of adaptive navigation assistance are achieved.

As a first step to answer **RQ1**, we developed a comprehensive analytical model of decision point complexity (**Paper I**). Decision points are locations along a route where a wayfinder must choose which direction to take. To develop this model, we started by analyzing and comparing existing models of route complexity to understand which factors of complexity they considered, how these factors were measured, and how they were integrated into an overall measure of decision point complexity. Based on this analysis, we created a new, comprehensive model that included all factors of complexity that could be extracted or inferred from geographic data, taking into account how these factors interacted with each other.

We then compared our new model with existing models by calculating different routes in various environments (e.g., urban vs. suburban, historic vs. modern) and analyzing the differences in decision point complexity produced by each model. This allowed us to assess the performance of our new model.

Additionally, we took a more naturalistic approach to understanding how individuals navigate in the real world. We utilized GPS trajectory data from individuals navigating in the real world and analyzed their heuristics for route selection. This top-down approach allowed us to examine how people naturally navigate and make decisions about their routes, providing valuable insights into the cognitive processes involved in wayfinding.

To address **RQ2**, which aims to identify significant locations along a route and understand their relation to the overall environment and spatial knowledge acquisition, we developed methods to abstract routes to these key locations, which we term *route-defining locations*. These methods take into account the overall shape of the route, such as major changes in direction, as well as highly salient locations in the environment near the route, such as major streets or landmarks. By abstracting the route to these locations, we have produced a set of locations that define the route. Highlighting these locations for wayfinders in an appropriate manner can improve their ability to understand the relationship between the route and the overall environment, stay oriented while following the route, and remember the route more effectively.

As with our approach to **RQ1**, we have also adopted a naturalistic approach to understanding how individuals process and use information about their environment. To accomplish this, in the same study as for **RQ1** we analyzed GPS trajectories data from individuals navigating in the real world with a focus on the number of important locations along their selected routes. This allows us to examine how people naturally make decisions about information along a route and gain valuable insights into their cognitive processes involved in wayfinding.

To address **RQ3**, we first investigated whether the instructions provided by current navigation services always match with human understanding of a given wayfinding situation. We presented participants with screenshots of various wayfinding situations, along with corresponding instructions, and asked them to indicate to what degree they agreed that the given instructions accurately described the depicted situation. They were also given the opportunity to provide an alternative instruction that might fit the situation better in their view. The data collected through this questionnaire provided some empirical support for the anecdotal evidence that sometimes the instructions generated by a navigation service do not seem to match with how a wayfinder understands the given wayfinding situation. It also helped to identify patterns of when and how a service's instructions may not match with people's understanding of the situation.

We then conducted an empirical study using a virtual reality (VR) setting, which allowed for controlled conditions and eliminated external factors that may affect navigation, such as positioning errors or weather conditions. Participants were asked to follow four routes through a campus environment, with one group receiving instructions from the prototype system and the other group receiving standard instructions commonly provided by contemporary navigation services. During the route-following task, errors were measured to assess the performance of the different instruction-giving systems. Additionally, participants were asked to find their way from the starting point to the destination on their own to determine the amount of spatial knowledge acquired during the route-following task. Finally, participants were asked to draw a mental map of the environment, which provided further insights into the spatial knowledge acquired and the ability to remember the route. This study provided valuable information on the effectiveness of the developed measures and instruction-giving system in improving navigation performance and spatial knowledge acquisition.

1.3 Thesis Outline

The thesis is structured into four main chapters. In Chapter 2, an overview of human wayfinding heuristics and navigation service wayfinding heuristics is provided, emphasizing the importance of incorporating human principles of route planning and the cognitive complexity of traveling through a network in route search models. This chapter also discusses the limitations of current navigation services and the necessity to develop new, more effective approaches. Chapter 3 explores the reasons why the use of navigation services impairs spatial learning and suggests mechanisms for re-establishing spatial learning. The challenges of defining significant locations along a route and abstracting routes to these key locations are discussed, and existing research on methods to improve spatial learning is reviewed. Chapter 4 concentrates on the ambiguities and errors of current route directions generated by navigation services and reviews existing literature on how to overcome these challenges by considering both the structure of the environment and the route. Chapter 5 concludes the thesis by summarizing the research contributions, discussing its limitations, and future directions. Additionally, the thesis includes the five papers related to the research.

Chapter 2

Human Route Search and Route Search Models

Every day, people navigate their way through the world, moving from one location to another to get to work, education, entertainment, and other activities. While the act of getting from point A to point B may seem straightforward, it is actually a complex task that requires making choices among a multitude of potential routes. Traditionally, geographic routing has been focused on finding the shortest or fastest route between two points. However, in recent years, researchers and practitioners have started to explore alternative routing criteria that take into account other factors such as simplicity. This chapter aims to investigate the various heuristics used by wayfinders to select routes and the models that have been developed to explain these heuristics.

2.1 Wayfinding

The process of wayfinding involves navigating from one location to another. It may seem simple on the surface, but it is actually a complex set of processes that involve multiple variables and cognitive processes [Far+12]. Humans have historically used various means of guidance such as stars, compasses, and maps to navigate. With the advent of technology, global positioning systems (GPS) have also become a common wayfinding tool [Few01]. The term "wayfinding" was first coined by Lynch [Lyn64], who defined it as the consistent use and organization of sensory cues from the environment, which led to the association of wayfinding with spatial orientation [AP92]. Over time, the definition of wayfinding has evolved to encompass the process of moving through space with the goal of reaching a specific destination [Cas+00]. Specifically, it involves identifying one's current location and determining the most efficient and effortless route to a desired destination [BLA10]. While different research fields may have slightly different definitions of wayfinding, they all share common elements. For

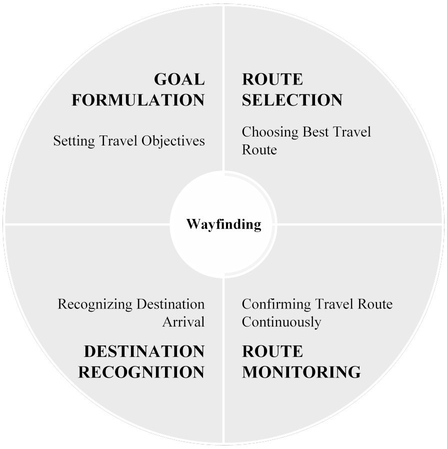


Figure 2.1: Key steps in the wayfinding process, which may occur simultaneously and not in a linear fashion, as wayfinders navigate through their environment.

instance, Allen et al. [All+04] and Brunyé et al. [BLA10] defined wayfinding as destination-guided motion, which results from the combination of spatial and environmental cognition [Kit94]. It allows individuals to make a series of decisions using cognitive and behavioral abilities to navigate through the built or natural environment, with or without the use of external representations such as maps, signs, or GPS [Cas+00].

The process of wayfinding can be broken down into several key steps that individuals go through when navigating through their environment [DS73; Van16] (see Figure 2.1). To begin with, goal formulation is the first step, in which individuals identify their desired destination and the purpose of their journey. This step involves considering various factors such as accessibility, distance, and personal preferences. The second step is route selection, in which the individual chooses the most suitable path to reach the destination. Different options are evaluated, taking into account factors such as estimated travel time, distance, and potential obstacles. Route monitoring is the third step, in which individuals continually check that they are on the correct path using cues such as cognitive maps and landmarks. Finally, destination recognition is the last step, where the individual recognizes that they have reached the desired destination by using visual and semantic cues.

It is important to note that these steps are not necessarily linear and may occur simultaneously. Additionally, wayfinding is a dynamic process that requires the integration of various cognitive and physical abilities, such as spatial perception, memory, decision-making, and motor skills. By understanding the different steps involved in wayfinding, researchers can gain insights into how individuals navigate through the environment and make decisions. In this chapter, the focus is on the second step of wayfinding, which is route selection.

2.2 Human Wayfinding Heuristics

Planning routes to destinations is a common task that humans engage in, whether it be through the use of printed maps, digital mapping services, or memory of past experiences. The traditional approach to route planning assumes that people will choose the shortest or fastest route between an origin and destination[GG88]. However, recent research has shown that this is not always the case [Chr95; HK05; Pin10]. Instead, people use various heuristics to simplify the decision-making process. One such study, conducted by Shao et al. [Sha+14], investigated way-finder's preference between the easiest-to-reach destinations and the nearest-to-reach destinations. They found that way-finders prefer easiest-to-reach destinations rather than nearest-to-reach ones. This section explores some of the most common heuristics used in human wayfinding.

The Longest Leg First Heuristic also known as the initial segment heuristic, involves basing decisions disproportionately on the straightness of the initial segments of the routes [BSU00]. This means that pedestrians choose longer and straighter initial segments to reach as close as possible to their destination, without taking a "turn" and thereby reducing cognitive effort. This heuristic is based on the assumption that a route with a straight segment leaving an origin is shorter than other route options.

The Shortest Leg First Heuristic involves taking turns in the initial portion of the route to keep the latter portions as straight as possible [HK05]. This allows pedestrians to explore further alternatives quickly at the next decision point and reduces the cost of potentially required backtracking when compared to long initial segments.

The Least-Angle Heuristic is a heuristic that describes the tendency for route planners to disproportionately select routes that deviate least from a destination's overall direction [HF00]. This heuristic is based on the assumption that a route that begins by heading in the general direction of a destination will be more efficient than other route options.

The Southern Route Preference is the tendency for route planners to disproportionately select paths that go generally south rather than north between an origin and destination pair[BLA10]. This preference is largely outside of conscious awareness and has been found to be consistent across different regions and cultures[Bru+12]. Research suggests that this preference may be driven by implicit associations between cardinal directions and elevation, which may be due to the common practice of depicting maps with north-up and patterns of linguistic use[Bru+12].

The Fewest Turns Heuristic is a popular wayfinding heuristic that involves choosing routes involving the fewest number of turns[Gol95; Zho+14]. This results in simpler routes since turns involve decision making and increased cognitive effort. The heuristic involves reaching a set of decision points from the origin that do not require taking a turn, and then selecting from that set the decision points closest to the destination. This process is repeated at every turn until the destination is reached.

2.3 Wayfinding Heuristics in Navigation Services

When it comes to automated navigation services, the most commonly used heuristics are based on the geometric properties of the road network, such as the length of the path and the estimated time to travel it [RD08]. However, recent research has shown that incorporating human principles of path planning and cognitive complexity can improve the overall quality of these services [Sch+17; LKS19; KAS20]. In particular, there are three main categories of heuristics that have emerged to achieve this: 1) Easiest to Navigate Routes; 2) Easiest to Describe Routes; and 3) Easiest to Follow Routes based on Spatial Abilities.

2.3.1 Easiest to Navigate Routes

Wayfinding, which refers to the ability to navigate and find one's way to a destination [Mon05], is affected by a range of factors. One such factor is the complexity of the environment [Gia+14], which can affect how individuals navigate and make decisions while wayfinding [Ric09]. In complex environments, it can be more difficult for individuals to create a mental map of the area [Kim01], resulting in longer travel times and increased likelihood of mistakes [DE00]. The complexity of an environment can be influenced by various factors as follows.

The theory of Intersection Density (ICD) [ONe91] posits that the higher the number of branching options at an intersection, the more difficult it becomes to navigate the area accurately. This is due to the increased potential for taking a wrong turn and the higher likelihood of wayfinding errors [Kli03]. Moreover, intersections with many streets converging on one point can be more intricate, as they require individuals to process more information and make decisions accordingly.

Research has shown that people have a typical understanding of turning actions in wayfinding [Kli03], and street configurations that deviate from these typical angles can be challenging to incorporate into their mental representation of the environment [Mon91]. Intersections with oblique turns, which deviate from the typical angles of 90 and/or 45 degrees, are considered more complex from a functional perspective of wayfinding, and are harder to understand, integrate, and navigate as compared to intersections with prototypical angles. This is because oblique angles do not conform to people's preconceptions of how streets should be configured, making them harder to mentally map and navigate.

Decision points are the places along a route where wayfinders must choose which direction to take next [DD98]. Decision points are also where wayfinding errors are most likely to occur. Therefore, areas with longer segments, which have fewer decision points, are generally less complex for wayfinding as there are fewer options and opportunities for errors to occur [Ric09]. In contrast, areas with shorter segments have a higher density of decision points, making wayfinding more complex. Hence, it is essential to consider the number and distribution of decision points when assessing the complexity of an area for wayfinding.

Overall, Richter proposed an algorithm for path planning that considers both the layout complexity and decision points in order to plan routes [Ric09]. The algorithm uses three key factors to calculate a normalized measure of combined wayfinding complexity (CWC) for each intersection: the number of branching options, the average deviation of street angles from typical angles (90 and 45 degrees), and the average segment length. This algorithm takes into account the specific characteristics of the environment and clusters intersections into two groups based on their CWC values: complex and easy regions. Any intersection not assigned to a region is placed in the easy region. Finally, the algorithm uses the shortest path algorithm for easy regions and the simplest path algorithm for complex regions.

The formula for CWC is as follows:

$$\text{CWC} = w1 * \text{numOfBranch} + w2 * \text{AvgDeviation} + w3 * \text{AvgLength}$$

Here, numOfBranch refers to the number of branching options at an intersection, AvgDeviation is the average deviation of street angles from typical angles (90 and 45 degrees), and AvgLength is the average segment length. The weights $w1$, $w2$, and $w3$ are assigned to each factor to reflect their relative importance in determining the overall complexity of an intersection.

2.3.2 Easiest to Describe Routes

When people navigate through unfamiliar environments, they often prioritize simplicity over the shortest route[DK03]. This is because they prefer a path that is easy to explain, understand, and memorize. For instance, tourists visiting a foreign city for the first time might receive directions to a hotel or attraction that is easiest to understand. The path that people choose can vary based on whether it is shared with others, intended for personal use, or actually followed through [Wie+08]. They tend to direct way-finders with easy-to-understand instructions, which minimize the amount of memorization required by them. People also tend to use phrases such as “this is the tricky part” to ease difficulty navigating a specific portion of the route [Hir+10], based on their personal experiences and the assumed knowledge and abilities of the person receiving the directions.

In this regard, Mark [Mar86] introduced a novel method to improve shortest-path algorithms by considering the *instruction complexity*, which refers to the number of items a way-finder needs to remember during navigation. As an example, turning at a T-junction requires remembering three items, such as the distance to the turn, the direction of the turn, and the name of the street to turn onto (Table 2.1).

Table 2.1: Frame for a turn at a T-junction [Mar86].

Left or Right Instruction:	Drive for {x.x} miles to a T-junction and turn {left / right} onto {street_name}.
Summary Instruction:	Remember, it's {x.x} miles to your {left / right} turn onto {street_name}.

Mark suggested a change to the A* shortest-path algorithm by introducing a new factor called the instruction complexity to the cost function. He determined the cost by adding the length of the path and a weight multiplied by the instruction complexity. The formula for the cost function is:

$$\text{Cost} = \text{length} + \text{Weight} * \text{InstructionComplexity}$$

Duckham and Kulik [DK03] developed a method called "Simplest Paths" for determining the easiest routes to follow in unfamiliar surroundings. Although Mark's work influenced their approach, they view instruction complexity from a different perspective. Rather than relying on a distance metric, Duckham and Kulik convert the path graph to a line graph and assign weights to the line graph's edges. In the line graph, nodes represent path graph edges showing instructions, and edge weights represent instruction complexity. The conversion works by equating the search for the shortest paths in the line graph with that of finding the simplest paths in the path graph. Duckham and Kulik's weight function is based on Mark's, but the algorithm differs from Mark's in that it identifies the simplest path from an origin to all other destinations without using any distance metric.

Haque et al. [HKK06] proposed a novel algorithm, the shortest most reliable path algorithm, which builds upon Dijkstra's shortest path algorithm but also considers the concept of *instruction equivalence*. Instruction equivalence measures the number of turns at a decision point that can be described with the same linguistic label. To address this issue, the algorithm attempts to minimize both distance and unreliability cost functions. The unreliability cost function assigns an unreliability weight "r" to each "turn", represented by a pair of connected edges in the path graph, based on instruction equivalence. The algorithm then identifies competing edges, or edges with the same minimum unreliability, from the origin. These competing edges are then assigned a weight "w" based on distance, and the algorithm seeks to identify the edge set with the minimum distance from the origin.

Haque et al. introduced the idea of a trade-off between reliability and distance in finding an optimal route based on a way-finder's preferences. They proposed a formula to compute the optimal route, which is a combination of the distance and the unreliability weight. By adjusting the weights, the algorithm can find the most reliable route (minimum w1 and maximum w2), which leads to less ambiguous but longer routes, or the shortest route (maximum w1 and minimum w2), which leads to more ambiguous but shorter routes. In essence, the shortest most reliable path algorithm aims to find the optimal path by taking into account the trade-off between reliability and distance and assigns weights to each instruction based on its ambiguity, as measured by instruction equivalence. The algorithm is a modified version of Dijkstra's shortest path algorithm, and the optimal route is calculated as follows:

$$\text{Opimal}(e, e') = w1 * \text{distance}(e') + w2 * r(e, e')$$

Numerous studies on spatial cognition have consistently shown that landmarks play a crucial role in how people conceptualize and navigate their surroundings. This concept was first explored in Lynch's influential work on "the image of the city" in 1960 [Lyn64], which investigated how long-term residents perceive the layout and social structure of their cities. Landmarks are important in various contexts, such as learning environments [SW75] and forming mental representations of environments [HJ85]. When providing directions, people often rely on landmarks as a point of reference or confirmation that they are on the correct route [MD01]. It is therefore not surprising that landmarks are highly desired features in automated navigation services, with users frequently requesting their inclusion [May+03]. Studies have demonstrated that the incorporation of landmarks in these systems enhances users' performance and satisfaction [May+03; RMT04].

Caduff and Timpf proposed the landmark spider method [CT05] as a means to improve wayfinding by considering potential landmarks. They presented an algorithm that determines a route through a network while taking into account point-like landmarks at decision points. The goal of the algorithm is to guide the wayfinder along a route that includes a landmark at every decision point. The landmark spider algorithm operates similarly to shortest path algorithms, but each edge in the path graph (representing an instruction) is assigned a weight that we call *landmark complexity.* The weight is calculated based on the distance between the landmark and the navigator, the direction between the landmark and navigator, and the salience of the landmark. Edges with a high amount of landmark information are assigned a low weight, and vice versa. This way, by finding the shortest path, we identify instructions with a high amount of landmark information. This idea is supported by other research, such as Klippel et al. [KW05], who found that people tend to use landmarks as reference points when receiving route directions, and that the more salient a landmark is, the more likely it is to be used as a reference point.

The weight for each edge is calculated as follows:

$$\text{Weight} = a * \text{Distance} + b * \text{Orientation} + c * \text{Salience}$$

2.3.3 Easiest to Follow Routes based on Spatial Abilities

Individuals may differ in their navigation abilities or an innate sense of direction. For some people it is easier to find their way around than for others. Sense of direction refers to a person's perception of their location or orientation with regards to their environment [KB77] and knowledge of the person's location and orientation in relation to permanent landmarks on the earth [Sho+00]. This ability can be measured through self-report surveys, such as the 15-item Santa Barbara Sense of Direction Scale developed by Hegarty et al. [Heg+06]. Hegarty et al. generally believe that sense of direction is a stable individual trait, and self-assessments of this ability have been proven to be reliable predictors of an individual's wayfinding performance [KT03; Heg+06].

Giannopoulos et al. [Gia+14] proposed a new path planning algorithm in their study that goes beyond the traditional approach of simply finding the shortest path. This algorithm accounts for environmental adaptation, spatial cognition, and the reliability of instructions based on landmarks. The objective of the algorithm is to minimize a cost function that incorporates three factors: the complexity of the environment, an individual's spatial cognition, and the cost of following instructions. The environmental factor is determined by the number of branches, while the spatial cognition factor is based on data obtained from the Santa Barbara Sense of Direction Scale. The cost of following instructions is a weighted sum of the advance visibility of landmarks used in the given instruction and the ease of landmark matching.

The cost function can be represented as:

$$c(e,u,i) = w1 * \text{numOfBranch} + w2 * \text{Landmarks} + w3 * \text{SBSODS}$$

where numOfBranch represents the number of branching options at an intersection, landmarks represents the advance visibility of landmarks and landmark matching, and SBSOD represents the Santa Barbara Sense of Direction Scale. The weights $w1$, $w2$, and $w3$ are assigned to each factor to reflect their relative importance. This algorithm considers multiple factors to provide an accurate and adaptable route-finding approach, making it a valuable tool for navigating complex environments.

As discussed in this chapter, people use various heuristics to simplify the decision-making process when planning routes to destinations. However, existing models have mostly focused on one aspect, either the environment (Section 2.3.1), the instructions (Section 2.3.2), or the user (Section 2.3.3) (See Figure 2.2). These models are not comprehensive enough to account for all factors affecting navigation. As mentioned in Chapter 1, ensuring the safety, reliability, ease of use, and cognitive effectiveness of navigation services involves considering the interdependence and interplay between the environment, service, and user. To achieve a more comprehensive understanding of the wayfinding experience, an integrated approach that considers all three factors is necessary. Although Giannopoulos et al. [Gia+14] proposed an integrated model, it has limitations

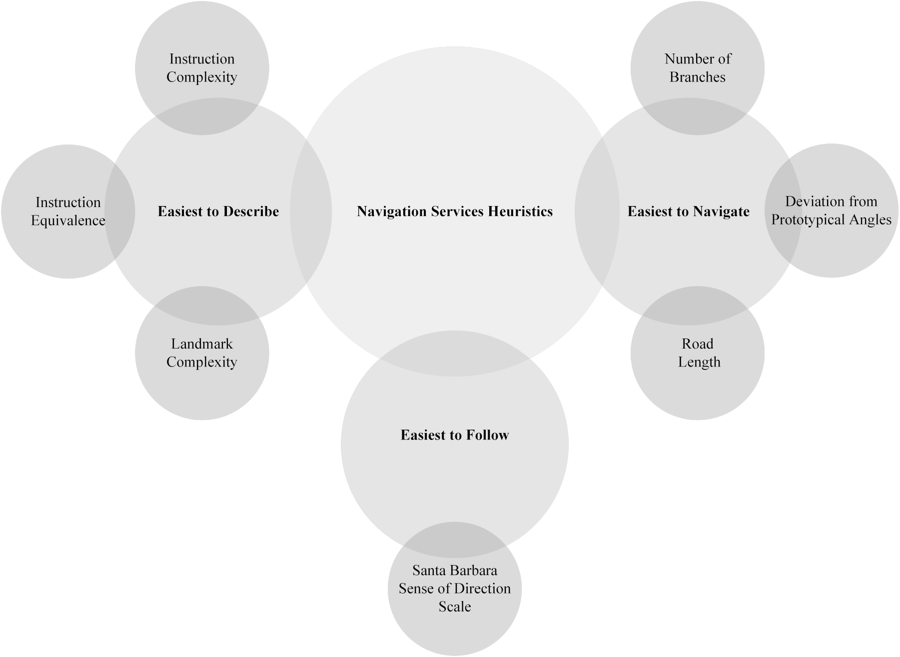


Figure 2.2: Various wayfinding heuristics employed by current navigation services.

as it mainly focuses on a limited set of factors and parameters, and neglects the complexity and variability of real-world scenarios.

To overcome these limitations and gain a more nuanced understanding of the navigation process, in my work (**Paper I**), I proposed a complexity model that combines the three elements of environment, instructions, and user into a single model. Additionally, I proposed a combined model that considers the complexity, traffic, and social costs simultaneously, adopting a more integrated and comprehensive approach. By doing so, I aim to mitigate unwanted effects and provide a more effective and satisfying navigation experience for users.

Chapter 3

Route Defining Locations

With the advent of automated systems that can display a user's position and route in real-time, wayfinding and navigation have become simpler. While automation has made the task of wayfinding easier by reducing the cognitive load, it can also lead to several issues. Relying solely on automated systems may cause individuals to be less attentive to their environment, leading to a lack of wayfinding and orientation skills and insufficient spatial knowledge. This can be particularly problematic when the automated system fails, leaving the user disoriented and unable to navigate effectively. This chapter seeks to address this issue by exploring ways to engage users in the wayfinding task and facilitate the acquisition of spatial knowledge, even when using automated navigation assistance. By combining automated systems with active cognitive processing, individuals can still develop wayfinding and orientation skills, improve spatial knowledge, and be better equipped to navigate effectively in the event of automation failure.

3.1 Spatial Knowledge Through Wayfinding

People acquire knowledge about their surroundings, such as a city, through various means, including wayfinding. Over time, as people become more familiar with a place, they develop a mental "image of the city" [Lyn64] by remembering landmarks, learning routes between them, and integrating this information into a coherent understanding of the environment [SW75; Mon98]. According to Siegel and White [SW75], spatial knowledge is sequentially developed in three stages (See Figure 3.1) that are hierarchically ordered. The first stage is landmark knowledge, which involves memorizing distinctive objects along the way. The second stage is route knowledge, which involves learning the sequence of direction choices at decision points. Finally, the third stage is survey knowledge, which involves forming a cognitive map of the environment. Survey knowledge allows individuals to find new routes and shortcuts, and it is

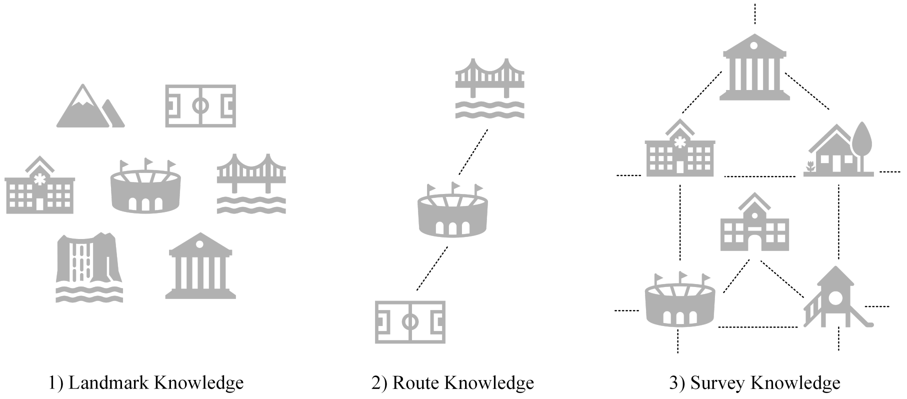


Figure 3.1: Three Stages of Spatial Knowledge Acquisition: Landmark Knowledge, Route Knowledge, and Survey Knowledge.

independent of their own position [Pas79]. However, the previously accepted idea that spatial knowledge is acquired sequentially has been challenged. It is now believed that this information is constructed simultaneously with differences among individuals in the process [Mon98; IM06]. Some individuals may acquire survey knowledge on their initial exposure to a new environment, while others may rely on route knowledge even after repeated visits [IM06].

3.2 Downsides of Navigation Services

Wayfinding refers to the ability of individuals to reach their desired locations in space, which is influenced by their spatial knowledge and learning [Gol+99]. Orientation and navigation from any source to any destination requires these abilities [WM03]. However, the use of navigation services can decrease the acquisition of spatial knowledge when compared to traditional methods, such as paper maps [Rug+19; Ish19]. Studies on the effects of navigation services on spatial learning suggest that users of such systems struggle to acquire accurate spatial knowledge, while paper map users perform better in terms of remembering locations and directions [Mün+06]. Additionally, users of navigation services tend to travel longer distances, stop more frequently [Ish+08], and have difficulty remembering their surroundings compared to those who use paper maps [IT13]. Navigation systems have transformed wayfinding into a passive task, where one simply follows a predetermined series of turns at decision points, eliminating the need for active information search, spatial updating, and decision making [Sch+17; Kru+18; Ben21]. This shift has a negative impact on spatial learning and people's ability to orient themselves in the environment [KAZ04; MZB12; Rug+19]. Although providing directions can enhance wayfinding performance [LC08], this comes at a cost to spatial learning

[MZB12]. It is important to consider this issue, as wayfinders need to be able to make spatial decisions and adjust their orientation in the case of technology failures or environmental changes that are not reflected in the service's database. The reasons why navigation services negatively impact spatial learning are multi-faceted [Gar+13].

3.2.1 Decrease in Environmental Engagement

Navigation services are designed to provide a passive experience for users, reducing the need for active engagement in the wayfinding task. This results in poor spatial knowledge acquisition as individuals do not gather information from their surroundings, process the information, or make decisions [Mün+06; PAE07]. The lack of environmental engagement in the navigation process means that individuals do not encode, process, and memorize spatial information actively. This problem is further compounded by map-based, augmented reality-based, and voice-based navigation services that provide a limited visual representation of the environment, hindering the development of spatial knowledge [HSG12].

3.2.2 Decrease in Spatial Decision Making

Navigation services don't involve users as active decision-makers [Ric13], leading to poor spatial knowledge acquisition. Research shows that individuals who actively decide on their navigation path acquire higher spatial knowledge compared to those who simply follow the navigation system's instructions [BLP08]. Automated systems may result in over-reliance on the system and disregard of spatial decision making, preventing users from developing spatial orientation and wayfinding skills.

3.2.3 Issues with Interface Design

Navigation services currently provide information through a combination of verbal and non-verbal cues, dividing attention and drawing visual focus away from the environment. This may lead to cognitive overload and poor spatial learning [Dic12; Gar+13]. Tactile display navigation systems, such as belt-based systems, built-in actuators of smartphones, and shoe-based systems, have shown promise in reducing visual demand and improving spatial learning [Ber+17]. These systems do not require a display at all and instead use tactile cues to provide navigation information. However, despite these advantages, the limited size of current systems still presents challenges. The "keyhole problem" occurs when users must choose between viewing an overview with limited detail or zooming in to see more detail, but losing the overview [Bar+95; Ric13]. The fragmentation and regionalization of views further limit the visibility of the whole route, dividing the user's attention between the navigation system and their surroundings, resulting in poor performance and poor spatial learning [Wil+09; Ish+08].

3.3 Re-establishing Spatial Knowledge

Parush et al. [PAE07] presented a three-step model for navigation service automation that replaces human perception, cognition, and decision-making with information gathering, processing, and problem-solving. While the aim of automation is to eliminate the need for human intervention, it can result in decreased spatial learning. To organize the various approaches for enhancing spatial learning, we will adopt Parush et al.'s model and categorize the mechanisms into the three steps of information gathering, processing, and problem-solving. Although there may be some overlap between categories, each approach will be classified under the most relevant category.

3.3.1 Improving Information Gathering

This category is centered on enhancing the presentation of environmental information to improve spatial learning. Münzer et al. [Mün+06] proposed a navigation system that featured a visual animation to display the current path from the last intersection to the present one, and its continuation to the next intersection. However, this system did not significantly improve spatial learning, as the survey information presented was not utilized during wayfinding. Huang et al. [HSG12] designed and compared the effects of three navigation interfaces on spatial knowledge acquisition. These were a map-based interface that displayed the entire route, a voice-based interface that issued a verbal instruction at each intersection, and an augmented reality (AR) based interface that overlaid a virtual route and landmarks on the real-world camera view. However, the results did not show a significant difference in spatial learning among the three interfaces. Oliver and Burnett [OB08] proposed a learning-oriented user interface with landmarks, compass bearings, and previously driven routes, which resulted in better cognitive map development and lower visual demand based on eye glance assessment. The subjective feedback from participants suggested that landmarks were most beneficial in promoting spatial learning. Gramann et al. [GHK17] modified navigation instructions by adding landmark and personal relevant information associated with landmarks. Their results showed that these modifications improved wayfinders' spatial knowledge acquisition. Bertel et al. [Ber+17] compared two types of pedestrian navigation assistance systems: a visual display condition and a tactile display condition that provides route directions via a tactile display that vibrates on the wayfinder's left or right foot. Their results showed that the tactile display improved route knowledge, while the visual display helped in acquiring survey knowledge. Tactile display is less visually demanding, which helps wayfinders pay more attention to the environment.

3.3.2 Improving Information Processing

Research in this category is focused on increasing wayfinders' engagement in the process of acquiring spatial knowledge during wayfinding. Parush et al. [PAE07] proposed the idea of "keeping the wayfinder in the loop," which allows wayfinders to access spatial information only when they choose to and to indicate their position by pointing and clicking on a displayed map at random times and distances during wayfinding. This approach resulted in the highest level of acquired spatial knowledge, but it also comes with the challenge of increasing user effort, which decreases usability [Wen+14]. The main question is that whether wayfinders care about spatial knowledge acquisition during wayfinding. It may not be reasonable to force occasional travelers to be more active in the wayfinding task to gain better spatial knowledge. However, tourists may appreciate the ability to remember visited places as a wayfinding experience without any memory of the places visited may not be enjoyable [IT13].

To increase the effort invested in wayfinding and improve spatial learning, Wen et al. [Wen+14] proposed an interactive AR-based navigation system with a focus on usability. They created two modes: a simple mode showing the AR path without a landmark quiz and a work mode that required the wayfinder to answer a landmark quiz before viewing the AR path. The landmark identification question involved matching one of three images to a highlighted landmark. Their results showed that the added spatial cognition feature may be welcomed as long as the purpose is clear. Richter [Ric13] suggested combining user-generated content (volunteered geographic information) and gamification to increase engagement among wayfinders in navigation assistance systems. This approach aims to make wayfinding more enjoyable and interactive, potentially leading to better information processing and a more memorable experience.

3.3.3 Improving Problem Solving

The objective of this category is to enhance wayfinders' participation in decision-making during navigation. Ishikawa and Takahashi [IT13] proposed a navigation system that provides only directional information, leaving the specific route to the wayfinder's choice. Their study showed that this approach can be helpful for tourists or those exploring, as it allows them to discover new routes and places. Brügger et al. [BRF19] conducted a study to investigate the effects of different levels of automation in navigation systems on attention allocation and self-localization, and the subsequent impact on spatial knowledge acquisition and retention. Allocation of attention is the process of directing a person's focus toward a specific feature, such as a landmark, in the environment. Self-localization is the process of determining one's current position in the environment using visual cues. The study found that participants who used navigation systems with higher levels of automation did not acquire enough spatial knowledge to reverse the route without making navigation errors. According to the authors, this result is likely due to the fact that automated navigation systems reduce human effort in self-localization and path planning, which can negatively affect attention to environment properties and spatial knowledge acquisition. Additionally, the authors suggest that designing navigation systems with lower levels of automation, where the decision of when and where to execute the cognitive processes is left to the navigator, may increase spatial knowledge acquisition without harming navigation performance.

3.4 Hierarchical Spatial Knowledge

The idea that people living in urban environments have a heightened familiarity with their surroundings is based on the concept of environmental learning, which refers to the process by which individuals acquire knowledge about their surroundings. This process is ongoing, and as individuals continue to interact with their environment, their mental representation of that environment becomes more accurate and comprehensive [SW75]. One important aspect of environmental learning is the hierarchical arrangement of spatial information. This means that people organize their knowledge of the environment in a way that allows for efficient organization and retrieval of information [HJ85]. For example, a person may have a mental representation of their city that is organized hierarchically, with general information about the city at the top of the hierarchy, and increasingly specific and local information further down the hierarchy. This hierarchical arrangement of spatial information is also evident in hierarchical place and route descriptions, which provide a gradual progression from general to highly specific and local references to city elements [TW06].

3.4.1 Reference Points

The ability to understand and navigate through the surrounding environment is a fundamental aspect of human cognition. Our spatial knowledge is largely organized around reference points, which serve as key anchors for our understanding of space. The anchor point theory[Gol97] proposes that prominent or personally significant locations play a critical role in forming our spatial memory. This theory suggests that humans process and retrieve spatial information in a relational manner, where the location of an object is considered in relation to reference points. For example, we may use landmarks, such as a distinctive building or a natural feature like a mountain, to orient ourselves and understand the layout of the surrounding environment. These anchor points can have a strong influence on our spatial memory and can be used to guide navigation and decision-making in the future. Understanding the role of reference points in spatial cognition is important for developing effective navigation strategies and aiding individuals with spatial impairments. By recognizing the importance of anchor points, we can improve our ability to navigate through complex environments and form accurate mental representations of the spaces around us.

Landmarks

The role of landmarks as key reference points in organizing human spatial knowledge is well-established [RW14; Cou+87]. These distinctive objects play a fundamental role in the construction of mental representations of space and improve navigation efficiency [Cou+87]. The definition of landmarks initially referred to noticeable objects that act as external points of reference [Lyn64], but anything that stands out from its surroundings can be considered a landmark [PM88]. A landmark's salience, or ability to stand out, is influenced by factors such as uniqueness, spatial prominence, and cultural significance [SH99]. Various methods have been developed to account for these factors when calculating landmark salience values.

Raubal and Winter proposed a landmark saliency model that considers four important attributes of building facades for determining the salience of an object [RW02]. These attributes are facade area, shape, color, and visibility. The size of the facade plays a significant role in determining how noticeable a building is, as buildings that are larger or smaller than their surroundings tend to stand out. The shape of a building also contributes to its salience, particularly if it deviates from the typical rectangular form. A building's color can also make it more prominent, such as a red building among gray ones. Lastly, the visibility of a building is its location's prominence, and it is measured by the area covered by the visibility cone of the front side of the building. To calculate the salience of individual buildings, the model uses a weighted sum of these attributes, and the weights were determined through a user survey to adjust for differences between day and night conditions [WRN05].

Winter [Win03] developed a method to measure the visibility of building façades along a specific route, while disregarding other urban features. He focused on the visibility of building façades from a distance, and developed a computational approach to assess the prominence of relevant façades at each decision point, taking into account both their visibility and salience. The most suitable façade for wayfinding was selected based on the best combination of the two factors, rather than just the most salient one. This method can be used along with a measure of salience to identify façades that are both noticeable and visible from a distance. Façades with a good balance of salience and visibility are preferred, while those with high salience but poor visibility receive lower rankings, and those without salience are not considered.

Caduff and Timpf [CT08] proposed a framework to assess the salience of spatial or geographical features in navigation. They argued that the relevance of a feature is not solely determined by the feature itself, but rather by the interaction between the observer, the environment, and the geographical feature. According to their framework, during navigation, the observer perceives the environment through sensory input and is able to distinguish salient spatial features that serve as landmarks based on this perception and the task at hand. To evaluate the salience of a feature, they proposed a three-component framework comprising Perceptual Significance, Cognitive Significance, and Contextual

Significance. Perceptual Significance refers to the observer's direct interpretation of sensory input. Cognitive Significance encompasses decision-making, problem-solving, memory, and other integrative processes that influence the assessment of significance. Contextual Significance modifies the significance assessment based on available resources. The overall salience of a geographical feature is viewed as a variable that can be decomposed into these three components and represented as a Saliency Vector, indicating the potential of a spatial feature to draw the navigator's attention.

Streets

Geographic features play a crucial role in our spatial knowledge and navigation. These features can take various forms, including districts, barriers or edges, rivers or lakes, and recognizable objects [CT08]. Streets, in particular, are highly impactful in spatial knowledge as their connectivity affects the flow of urban movement and can determine the extent to which individuals learn and remember the urban layout. Prominent streets that are frequently experienced tend to be highly ranked in the hierarchical mental representation of spatial information [TWC08]. Tomko et al. [TWC08] introduced a novel method to reconstruct the hierarchy of streets in an urban network based on the interactions of wayfinders with streets in the city. They suggested that the intensity of experience of a street is related to its functional and structural significance in the network. In other words, the more prominent a street is, the more likely it is to be recognized by the wayfinder.

To rank streets in a street network and determine their hierarchical importance in the city network, Tomko et al. proposed using the network measure of betweenness centrality. This measure determines the likelihood that a street lies on a shortest path between two other streets in the city. With more trips made by a wayfinder in the city, the betweenness centrality is expected to better approximate the wayfinder's experience of the urban environment. In this way, the betweenness centrality can provide a useful tool for ranking streets and determining their importance in the city's street network.

Major Turns

Major turns along a route are crucial for acquiring spatial knowledge. These turns indicate significant changes in direction along the path, making them critical reference points for navigation. They provide users with a sense of progress and direction, allowing them to mentally organize the route and make predictions about what lies ahead. To effectively identify these crucial direction changes, shape simplification can be employed. The objective of shape simplification is to reduce the complexity of the route by eliminating any irrelevant geometric details and simplifying it to its essential geometric form [LL99; BLR00]. This simplification facilitates spatial learning by making it easier to remember and recognize the essential features of a route. One method for shape simplification is the discrete curve evolution algorithm [BLR00], which iteratively removes the least important kinks from the geometric figure. This algorithm aims to simplify the route to its most basic geometric form while preserving its essential features.

In conclusion, reference points such as landmarks, streets, and major turns play a crucial role in navigation and orientation. These points serve as anchors for individuals to orient themselves in any environment and can aid in the development of cognitive maps. The use of reference points has been shown to be an effective strategy for improving navigation and wayfinding, particularly in complex environments. Furthermore, the ability to identify and remember reference points is essential for spatial memory. In my work (**Paper III**), I focused on identifying these locations along a route that define its characteristics, and termed them as route-defining locations. The identification of these locations can aid in simplifying the route while maintaining its essential features, and thus, can be useful in designing effective navigational aids and wayfinding strategies.

Chapter 4

Route Directions

There is a significant difference between the navigation instructions provided by computers and those given by humans. While computer-based navigation services typically provide turn-by-turn instructions for a given route, human directions are much more comprehensive, including information on local and global orientation, non-turning actions for confirmation, and descriptions of the surrounding environment. Despite the common use of turn-by-turn instructions in navigation systems, these limited spatial descriptors may not be as effective as the strategies humans use to naturally acquire, store, retrieve, and communicate spatial information. One of the major drawbacks of navigation systems is that they tend to direct people's attention solely to the route and its turning points, which can hinder their ability to take in other important contextual information. Numerous studies have demonstrated that relying on turn-by-turn directions in navigation systems can be ineffective for supporting spatial learning, which can lead to difficulties in remembering the route taken or understanding how it relates to the broader surroundings. This lack of spatial knowledge can be problematic in the short and long run, especially in the event of automation failure, where individuals may not have acquired enough spatial knowledge to continue navigating the environment without assistance. Thus, there is a pressing need for a new type of navigation system that provides more comprehensive route instructions to support effective spatial learning and navigation.

4.1 Death by GPS

Navigation services have become ubiquitous in today's world, helping individuals navigate from point A to point B. However, despite the convenience and widespread use, these systems are prone to errors and ambiguities like all computer systems. This is evident in the term "Death by GPS" [Mil16], which refers to incidents that occur due to reliance on personal navigation technologies such as GPS devices, mobile map apps, or SatNavs. These incidents can range from getting lost in unfamiliar areas to more serious events, such as driving a car into a body of water, ending up in a different country, or becoming stranded in the wilderness [Lin+17]. Although most often not resulting in loss of life, these incidents often involve people endangering themselves or others or causing property damage.

While it is easy to blame the user for these mistakes, it is important to also consider the role of the technology and its limitations. Witnesses and observers often question why the driver didn't notice warning signs or question seemingly incorrect directions. To understand how these errors can occur, it's important to be familiar with the five main components of a navigation system [KRK11].

4.1.1 Navigation Services Modules

Navigation services consist of several modules that work together to provide accurate and reliable guidance to users. Understanding the different modules of navigation services is essential to identify potential sources of errors and improve the accuracy and reliability of these systems [KRK11].

Map Database

This module serves as the foundation for the navigation system by providing essential information for other modules to function correctly. This includes information about the road network, which is crucial for the geocoding, positioning, map matching, and routing/direction modules. It is essential to ensure the accuracy of this data to avoid errors in other modules.

Geocoding

Geocoding is the process of converting a description of a location, such as a place name or address, into geographic coordinates (latitude and longitude) that can be used to display the location on a map or to calculate directions to it. The Geocoding module in the navigation services is responsible for assigning geographic coordinates to a place name. It allows users to specify their destination through various methods, such as placing a point on the map, providing an address or intersection name, or selecting a Point of Interest (POI) from directories placing a point on the map, providing an address or intersection name, or selecting a Point of Interest (POI) from directories. There are two ways in which POIs can be geocoded: pre-geocoding and on-the-fly geocoding. Pre-geocoded POIs have their coordinates stored in a database, while on-the-fly geocoding finds the coordinates of an address when it is provided. The positioning module in the navigation service constantly determines the location of the wayfinder, estimating its geographic coordinates.

Positioning Module

This module constantly determines the location of the wayfinder by estimating their geographic coordinates.

Map Matching Module

This module uses the coordinates data to place the wayfinder on the map accurately, enabling the navigation service to perform various functions, such as calculating a route from the wayfinders's current location to a desired destination, adjusting the route if necessary, providing step-by-step directions, and searching for nearby points of interest in the vicinity. Map matching involves determining the precise location of a wayfinder on a road network by using their geographic coordinates obtained from the positioning module. This process usually consists of two steps: identifying the correct road segment the wayfinder is on and pinpointing its exact location on that segment. The map matching algorithm relies on onboard data, including position data and road network information, which may contain inaccuracies.

Routing/Direction Module

This module calculates preferred routes and provides instructions for travel. Navigation services use different algorithms to solve the optimization problem of finding the best route between two addresses. These algorithms have been discussed in Chapter2.

4.2 Effective Route Directions

The provision of turn-by-turn instructions at intersections by current navigation services aims to assist individuals in decision-making while following a route. However, this approach of providing step-by-step instructions, also known as "route directions," [Den+99] converts active processes of spatial interaction and decision-making into a passive task of following instructions [Gar+13; Sch+17], ultimately hindering the acquisition of crucial spatial knowledge required for navigation. This knowledge is particularly essential in situations where automated systems fail [Lin+17; BRF19]. Therefore, this thesis aims to create route directions that not only support route following but also facilitate route learning. Route following involves decision-making at intersections to determine the next direction [DD98], while route learning involves gaining knowledge of the sequence of direction choices at intersections [SW75]. The route directions should be easy to process and understand, as comprehensibility is a prerequisite for effective use [DGP03].

In order to generate effective route directions, it is important to take into account the structure of the environment where the route is being followed. This includes the path itself, the spatial arrangement in the surrounding area, and identifiable landmarks, all of which play a significant role in determining the type of directions that can be provided. The nature of the route directions is dependent on the interplay between the route, its surrounding spatial structure, and identifiable features along the way [RK04]. There are three types of elements that can be utilized to provide effective route directions: global references, environmental structure, and route elements [RK04].

4.2.1 Global References

The concept of global references refers to elements that exist outside of the immediate surroundings in which an action is taking place. These references are based on an absolute reference system, which means that their direction remains consistent and does not vary with the wayfinder's position. One of the most common types of global references is the cardinal directions, including north, south, east, and west. For example, if someone is told to go north, they will always be moving towards the same direction, regardless of their current position. In addition to cardinal directions, global landmarks also fall under this category if their references remain constant throughout the environment. These landmarks can be easily identified as they are visible from multiple locations within the environment, or their location is widely known, making them useful as reference points[SH99]. For instance, a mountain or a river could serve as a global landmark, providing a reliable and unambiguous way to direct movement and actions within an environment.

The advantage of using global references is that they provide a consistent frame of reference for navigation, especially in larger environments where local landmarks may not be sufficient. By using global references, individuals can orient themselves and navigate to their destination with greater ease and accuracy.

Schwering et al. [Sch+17] proposed the Wayfinding Through Orientation approach, which emphasizes the use of landmarks to promote global orientation. Landmarks play a crucial role in determining the relative position of features within an environment [GA06]. The approach provides instructions in a more comprehensive manner, with a higher level of abstraction. Instead of solely communicating individual turns, the approach seeks to relate the immediate route information to the larger environmental context and define larger segments of the route, comprising a meaningful sequence of turn instructions. For example, instructions might include "go towards the city center" and "turn left at the supermarket, circumnavigate the city center" (p. 284). This approach replaces or modifies traditional turn-by-turn instructions with information about the surrounding environment, spatial relationships to landmarks, and other information that helps the user construct a cognitive map. By incorporating orientation into the wayfinding process, users can gain both survey knowledge, allowing them to understand the overall route and surrounding environment, and route knowledge, which is gained through turn-by-turn wayfinding and entails the sequence of turns required.

Löwen et al. [LKS19] investigated the impact of highlighting different types of environmental features on the incidental acquisition of both route knowledge and survey knowledge during the wayfinding process. The study focused on two types of environmental features: (1) local features along the route and at decision points, and (2) global features such as landmarks, network structures, and structural regions. The findings suggested that accentuating local features enhances an individual's route knowledge, while accentuating global features promotes survey knowledge.

Krukar et al. [KAS20] proposed a novel approach that blends route and survey information seamlessly into a route description without impairing the ability to recall the route information. The approach is based on human-generated instructions and incorporates landmarks at key decision points[KW05], landmarks along the route[IN12], and global landmarks not on the route[LFS14]. This approach aims to provide a richer and more contextually relevant description of the route that can enhance both route and survey knowledge.

Overall, these studies highlight the importance of using landmarks and global references to promote global orientation and construct cognitive maps. By providing users with more comprehensive information about their surroundings, they can gain a better understanding of the overall route and surrounding environment, in addition to the sequence of turns required. The use of these approaches has the potential to improve wayfinding efficiency and accuracy, and enhance the overall wayfinding experience.

4.2.2 Environmental Structure

Environmental structure refers to the physical components that shape the environment and create distinctive segments within it. These environmental elements can take on various forms, including natural elements such as hills, trees, or waterways, as well as man-made structures such as buildings or roads. The distinct nature of these elements provides clear and specific information that can be used for orientation and navigation. An example of such a component is slopes [RK04]. Slopes are changes in elevation that can have a significant impact on the surrounding environment, and create a unique segment of the environment that can be used as a reference point for navigation. For instance, if one needs to navigate upward or downward a slope, this can provide a clear and concise direction of travel. By identifying and utilizing environmental components to establish a sense of direction, wayfinding becomes easier and more accurate.

4.2.3 Routes Elements

In wayfinding, the elements that make up a route are crucial for guiding wayfinders along their intended path. These elements can take the form of landmarks, decision points, and annotations placed along a path to unequivocally identify it, such as street names, street signs, or markers. Lovelace et al. [LHM99] categorize landmarks into four types: decision point landmarks, potential decision point landmarks, route marks, and distant landmarks, each with its own function in the navigation process.

Decision point landmarks are those that are encountered at intersections where a choice must be made in order to continue on the intended route. These landmarks are crucial for successful navigation as they signal that a re-orientation is necessary. Potential decision point landmarks, on the other hand, are encountered at locations where a turn could be made to deviate from the current route, and passing by these landmarks without turning is also considered a choice. For example, not turning left or right, but continuing straight at an intersection can still be considered a decision that maintains the current route. These landmarks may be visually distinct and memorable, but they are not useful for re-orientation. Route marks are landmarks that confirm that the traveler is still on the correct path. These landmarks may include signage, distinctive architecture, or other recognizable features that serve as evidence of progress and success in the journey. Distant landmarks are particularly useful for establishing a sense of overall orientation within a larger environment. As noted by Lynch [Lyn64], these landmarks can be seen from a great distance and provide a reliable reference point for travelers. Local landmarks, on the other hand, are encountered along a specific path and serve as routemarks [Kri+98; RK04] that guide travelers towards their destination. These routemarks can be located at decision points or along path-segments connecting two decision points, and may be visible at a distance from the path. By paying attention to these routemarks, travelers can ensure that they are making progress towards their destination and avoid getting lost.

Humans tend to rely on landmarks rather than numerical values when generating turn-by-turn route instructions. In fact, a study by Daniel and Denis [DD98] found that only a small percentage of instructions (15%) do not involve landmarks. Landmarks can serve two important functions in route instructions, according to Duckham et al. [DWR10]. Firstly, landmarks can act as a reference point to anchor navigation actions. For example, instructions to "turn left at the gas station" provide a specific location for the turn based on the landmark, rather than relying solely on numerical distances or angles. This can help the traveler understand their current location in relation to a decision point. Secondly, landmarks can provide confirmation that the traveler is on the correct route. By referring to landmarks along the route segment, travelers can ensure that they are staying on track even if they are not at a decision point. For instance, instructions to "continue straight until you reach the blue building" help the traveler confirm their progress and location along the route. Therefore, landmarks play a crucial role in providing navigational guidance and ensuring successful wayfinding.

Numerous studies have highlighted the importance of landmarks in enhancing the effectiveness of route directions. One such model, proposed by Raubal and Winter [RW02], provides a comprehensive framework for incorporating local landmarks as reference points in wayfinding instructions. The model divides a route into a series of decision points (nodes) and edges. At each node, travelers require information about their next move - whether to continue in the same direction or turn. This is where landmarks play a critical role. They serve as anchors to help travelers orient themselves and confirm their location along the route. Furthermore, the model recognizes that the selection of landmarks can be context-dependent. Therefore, it includes a landmark saliency model to identify the most appropriate landmarks to use as reference points at each node. Along the edges, where no orientation is required, the traveler simply moves from one decision point to the next. In addition, landmarks along the route (route marks) can be used to provide travelers with further confirmation that they are on the correct path. To facilitate navigation, the model integrates both landmarks and egocentric cardinal orientations (front, back, left, right). This combination of reference points allows for a more intuitive wayfinding experience, making it easier for travelers to navigate unfamiliar environments. Raubal and Winter's model provides a practical and effective approach to enhance the clarity of route directions and help travelers reach their destinations with greater ease.

Gramann et al. [GHK17] conducted a study that investigated the effects of incorporating landmarks in navigation instructions to support spatial knowledge acquisition. They proposed two types of modifications to the traditional turn-by-turn instructions: “contrast modifiers” and “personal-relevant modifiers.” Contrast modifiers provided explicit information about the identity and affordance of specific landmarks at decision points, (e.g., “Please turn right at the concert hall. Here you can attend concerts.”; [GHK17], p. 3), while personal-relevant modifiers incorporated personal information about a landmark, such as a favorite movie, to make the landmark more salient and memorable, (e.g., “Please turn right in front of the movie theater. There you can watch your favorite movie, Zoolander.”, [GHK17], p$\dot{3}$). These modifications were personalized for each participant based on information collected in a questionnaire. The results of the study showed that incorporating landmarks in navigation instructions can enhance spatial knowledge acquisition and retention, especially when the landmarks are personally relevant to the traveler. The use of contrast modifiers and personal-relevant modifiers in navigation instructions provides a more engaging and memorable experience for the traveler, making it easier for them to recall and use the information in the future. This has implications for designing effective navigation instructions for both familiar and unfamiliar environments, as well as for enhancing spatial learning and memory in educational and training contexts.

In conclusion, effective route directions are determined by several critical parameters, as depicted in the Figure 4.1. By taking into account the structure of the environment, including the path, spatial arrangement, and identifiable landmarks, wayfinders can receive route directions that are accurate and useful. The figure shows that global references, environmental structure, and route elements all play an important role in providing effective route directions. Global references help wayfinders orient themselves and identify landmarks,

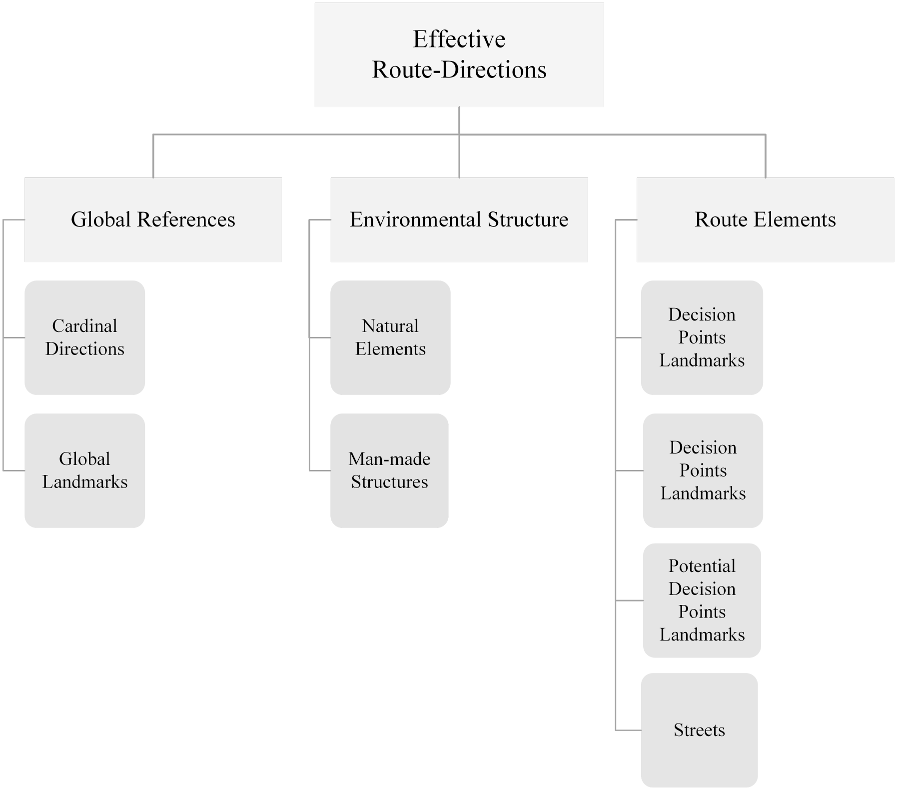


Figure 4.1: Critical Parameters for Effective Route Directions: Global References, Environmental Structure, and Route Elements.

while environmental structure provides natural and man-made cues to guide them. Route elements, such as decision points, landmarks, and streets, enable wayfinders to navigate unfamiliar environments with greater ease and confidence. Through my research (**Paper IV**), I demonstrated that augmenting turn-by-turn instructions with route-defining locations can enhance wayfinders' performance in both route-finding and route-learning tasks, providing a promising approach to address the limitations of conventional navigation services.

Chapter 5

Summary of Contributions

The thesis focused on enhancing navigation services by addressing discrepancies between them and human navigation, and by exploring their adaptive capabilities. The research aimed to answer three main research questions:

RQ1 How to design route search models to optimize for a specific aspect and mitigate unwanted effects?

RQ2 How to analyze a route regarding its embedding in the environment, thereby identifying those locations along the route that define the relation between route and environment which are crucial to navigate correctly?

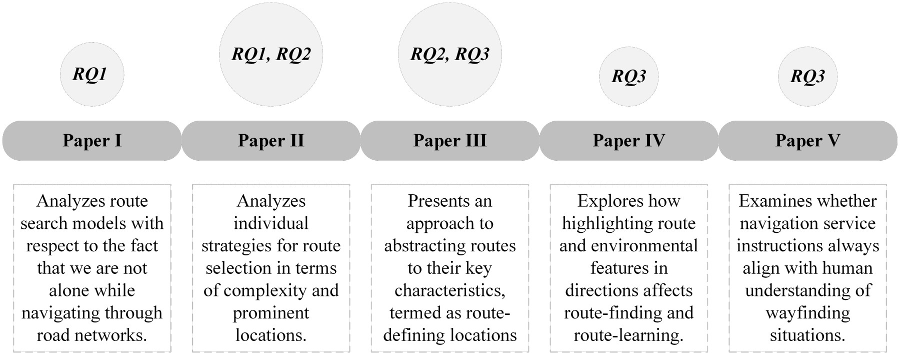
RQ3 How to generate instructions for a route that help wayfinder with route-finding and route-learning?

To answer these questions, the thesis proposed a combined model that takes into account the complexity, traffic, and social costs of routes. This model can simultaneously optimize route search models and mitigate unwanted effects. The thesis also identified prominent locations along a route, termed as "route-defining locations", that can aid in accurate wayfinding and better spatial learning. Moreover, the thesis generated route-defining location instructions that can help wayfinders successfully navigate a route and form spatial memory of the environment.

In this chapter, an overview of the papers included in the thesis is presented, along with their relevance to the research questions. Figure 5.1 summarizes the main contributions of the thesis, which are then discussed in more detail, including the individual authors' contributions.

5.1 Paper I

F. Teimouri, and K. F. Richter. You are not alone: Path search models, traffic, and social costs. *GIScience 2021; 11th International Conference on Geographic*



Analyzes route search models with respect to the fact that we are not alone while navigating through road networks.

Analyzes individual strategies for route selection in terms of complexity and prominent locations.

Presents an approach to abstracting routes to their key characteristics, termed as route-defining locations

Explores how highlighting route and environmental features in directions affects route-finding and route-learning.

Examines whether navigation service instructions always align with human understanding of wayfinding situations.

Figure 5.1: Overview of Thesis Papers and Related Research Questions.

Information Science, Schloss Dagstuhl–Leibniz-Zentrum für Informatik, 177, pp. 1-14, 2020.

The main objective of **Paper I** is to develop route search models that optimize for specific criteria in order to address **RQ1**. Current route-search models do not take into account traffic and social costs, which can greatly impact navigation. While some commercial navigation services consider traffic, they may overlook social costs which is avoiding routing through residential areas not meant for higher traffic volumes. The paper investigates the impact of these assumptions on computed routes and found that neglecting traffic or social costs can lead to traffic congestion or routing through unsuitable areas. To address these issues, the paper proposed a combined model that takes into account the complexity, traffic, and social costs simultaneously. This model aims to optimize route search models to mitigate unwanted effects and answer the **RQ1**.

Author contributions

As the main author, I contributed in formulating the problem, proposing and implementing the algorithm, conducting experiments, and writing the initial draft of the paper. Dr. Kai-Florian Richter provided valuable guidance and support throughout the process, including discussions on problem formulation, methodology, experiments, presentation of results, and editing of the paper.

5.2 Paper II

F. Teimouri, H. H. Hochmair, and K. F. Richter. Analysis of route choice based on path characteristics using GeoLife GPS trajectories. *Submitted to Journal of Location Based Services*, 2023.

The primary objective of **Paper II** is to investigate the factors that shape people's route selection while navigating their surroundings through GPS-based trips. To accomplish this objective, the study examines a vast sample of such trips using the Geolife dataset, focusing on the individual approaches people use when selecting their routes based on complexity and prominent locations. The findings of the research indicate that individuals tend to prefer less complex routes (**RQ1**) with fewer prominent locations (**RQ2**). This result provides researchers with valuable insights that can be used to develop navigation services that align more closely with people's natural navigation strategies. With this understanding, researchers can create more effective and intuitive navigation systems that help people reach their destinations efficiently and safely.

Author contributions

In my role as the primary author of the paper, I undertook a number of essential tasks, including formulating the problem, implementing the data analysis steps, and drafting the initial version of the paper. Dr. Hartwig Hochmair contributed to the research by providing the dataset, and both Dr. Kai-Florian Richter and Dr. Hartwig Hochmair played an instrumental role in providing invaluable guidance throughout the entire research process. Their guidance included discussions on problem formulation, methodology, presentation of results, and paper reviewing and commenting.

5.3 Paper III

F. Teimouri, and K. F. Richter. Abstracting routes to their route-defining locations. *Computers, Environment and Urban Systems*, Elsevier, 91, 101732, 2022.

Paper III proposes an approach to identifying and simplifying key characteristics of a route, which are referred to as route-defining locations. These are major changes in direction along the route, as well as prominent streets and landmarks. The approach allows for different levels of abstraction, and an agent-based simulation shows that the approach is effective as long as the level of abstraction matches the agent's knowledge level. The paper suggests that this approach can be used to provide personalized instructions for wayfinders and improve spatial learning. This paper has successfully addressed **RQ2**, which involves analyzing the embedding of a route in the surrounding environment. Specifically, the paper proposes a method for identifying critical locations along a route that define the relationship between the route and the environment. This approach could be used to provide personalized instructions for individual wayfinders and could lead to accurate wayfinding as well as better spatial learning (**RQ3**).

Author contributions

As the primary author, I worked on shaping the research problem, devising and implementing the algorithm, carrying out experiments, and drafting the initial manuscript. Throughout the course of the project, Dr. Kai-Florian

Richter provided invaluable advice and assistance, offering insights on problem formulation, methodology, experiment design, presentation of findings, and editing of the paper.

5.4 Paper IV

F. Teimouri, and K. F. Richter. Supporting spatial knowledge acquisition by automated augmentation of route directions with route-defining locations. *Submitted*, 2023.

Paper IV compares the effectiveness of turn-by-turn instructions and route-defining location instructions in aiding wayfinding performance in a virtual environment, with the aim of addressing **RQ3**: "How to generate instructions for a route that help wayfinders with route-finding and route-learning?" A total of 36 participants were recruited to traverse four routes in the virtual environment, with half of the participants receiving turn-by-turn instructions and the other half receiving route-defining location instructions. The results of the paper indicate that participants who received route-defining location instructions performed better in both route-finding and route-learning compared to those who received turn-by-turn instructions. The participants who received turn-by-turn instructions were more likely to make wayfinding errors and fail to reach their destination. The paper's findings suggest that incorporating route-defining locations in route directions can aid wayfinders in forming useful spatial memory of the environment, which can be useful for general navigation services.

Author contributions

I was responsible for formulating the research problem, developing and implementing the empirical study, and producing the first draft of the paper. Dr. Kai-Florian Richter provided invaluable guidance and support in areas such as problem definition, experimental design, result analysis and presentation, as well as editing and commenting on the paper.

5.5 Paper V

F. Teimouri, and K. F. Richter. 'Straight? What straight?' Investigating navigation instructions' applicability. *Journal of Location Based Services*, Taylor & Francis, 1–25, 2021.

In **paper V**, the issue of discrepancies between navigation instructions generated by navigation services and human understanding of a given wayfinding situation is explored. We utilized both quantitative and qualitative data to comprehend the level of agreement between people and navigation instructions. Two primary sources for the mismatches were identified: the language used in the instructions and the representation of and reasoning about the wayfinding situation by the navigation service. These findings directly relate to **RQ3**, which investigates how to generate route directions that assist wayfinders in route-finding and route-learning. The paper's approach of collecting both quantitative and qualitative data to uncover these mismatches can aid in developing more effective route directions that align with how wayfinders approach a given situation. The study's identification of language and reasoning as sources of mismatches can provide insights into improving the generation of instructions. In summary, this paper can serve as a valuable resource in developing more effective instructions for wayfinding.

Author contributions

As the lead author, my responsibilities included defining the research problem, designing and conducting the empirical study, and drafting the initial manuscript. Dr. Kai-Florian Richter provided the initial idea, and crucial guidance and support throughout the project, offering expert advice on problem formulation, experiment design, result presentation, and paper review and editing.

5.6 Conclusion

RQ1 asks *How to design route search models to optimize for a specific aspect and mitigate unwanted effects?*

Existing cognitively motivated route-search models assume that roads are empty and ignore the presence of fellow travelers. On the other hand, commercial navigation systems take into account traffic and delays but may ignore social conventions that dictate certain roads are not meant for general public use. To address the effects of "not being alone" on route search models, we analyzed its impact on fastest roues and least complex routes. The results showed that accounting for traffic has a negative effect on social costs, as it may redirect wayfinders into areas not built for taking larger amounts of traffic. Additionally, simply accounting for social costs drastically increases average traffic load. To mitigate these unwanted effects, we proposed a combined model that considers all aspects, including complexity, traffic, and social costs simultaneously. The combined model allows for the optimization of a specific aspect by adjusting the weights assigned to each one.

RQ2 asks *How to analyze a route regarding its embedding in the environment, thereby identifying those locations along the route that define the relation between route and environment which are crucial to navigate correctly?*

To achieve this, we proposed a method that simplifies the route to major heading change locations and identifies prominent landmarks and streets. The resulting list of route-defining locations allows for varying levels of abstraction in route description. The method was evaluated using an agent-based simulation where agents navigate from origin to destination using route-defining locations at different levels of abstraction. The simulation showed that agents with more knowledge perform better in navigation, and that the level of abstraction in route information affects the deviations from the shortest path taken by agents.

RQ3 asks *How to generate instructions for a route that help wayfinder with route-finding and route-learning?*

We conducted a human-subject experiment to assess the effectiveness of an algorithm that incorporates route-defining locations in generating navigation instructions for wayfinders. The study involved 36 participants who were divided into two groups: one group received standard turn-by-turn instructions while the other group received instructions with route-defining locations. Both groups navigated through an unfamiliar virtual environment to a predetermined destination. The results showed that participants who received instructions generated by the route-defining locations algorithm performed better in both route-finding and route-learning tasks compared to those who received standard route instructions.

Bibliography

[All+04] Gary L Allen, Kathleen C Kirasic, Matthew A Rashotte, and Daniel BM Haun. "Aging and path integration skill: Kinesthetic and vestibular contributions to wayfinding". In: *Perception & psychophysics* 66 (2004), pp. 170–179.

[AP92] Paul Arthur and Romedi Passini. *Wayfinding: people, signs, and architecture.* 1992.

[Bar+95] Lyn Bartram, Albert Ho, John Dill, and Frank Henigman. "The continuous zoom: A constrained fisheye technique for viewing and navigating large information spaces". In: *Proceedings of the 8th annual ACM symposium on User interface and software technology.* 1995, pp. 207–215.

[Ben21] Eran Ben-Elia. "An exploratory real-world wayfinding experiment: A comparison of drivers' spatial learning with a paper map vs. turn-by-turn audiovisual route guidance". In: *Transportation Research Interdisciplinary Perspectives* 9 (2021), p. 100280.

[Ber+17] Sven Bertel, Thomas Dressel, Tom Kohlberg, and Vanessa von Jan. "Spatial knowledge acquired from pedestrian urban navigation systems". In: *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services.* 2017, pp. 1–6.

[BLA10] Caroline Brunyé Tad T.and R. Mahoney, Aaron L. Gardony, and Holly A. Taylor. "North is up (hill): Route planning heuristics in real-world environments". In: *Memory & cognition* 38 (2010), pp. 700–712.

[BLP08] Jonathan Z Bakdash, Sally A Linkenauger, and Dennis Proffitt. "Comparing decision-making and control for learning a virtual environment: Backseat drivers learn where they are going". In: *Proceedings of the human factors and ergonomics society annual meeting.* Vol. 52. 27. SAGE Publications Sage CA: Los Angeles, CA. 2008, pp. 2117–2121.

[BLR00] Thomas Barkowsky, Longin Jan Latecki, and Kai-Florian Richter. "Schematizing maps: Simplification of geographic shape by discrete curve evolution". In: *Spatial Cognition II.* Springer, 2000, pp. 41–53.

[BRF19] Annina Brügger, Kai-Florian Richter, and Sara Irina Fabrikant. "How does navigation system behavior influence human behavior?" In: *Cognitive research: principles and implications* 4 (2019), pp. 1–22.

[Bru+12] Tad T Brunyé, Elena Andonova, Chiara Meneghetti, Matthijs L Noordzij, Francesca Pazzaglia, Rasmus Wienemann, Caroline R Mahoney, and Holly A Taylor. "Planning routes around the world: International evidence for southern route preferences". In: *Journal of Environmental Psychology* 32.4 (2012), pp. 297–304.

[BSU00] Jeremy N Bailenson, Michael S Shum, and David H Uttal. "The initial segment strategy: A heuristic for route selection". In: *Memory & Cognition* 28.2 (2000), pp. 306–318.

[Cas+00] Hernan Casakin, Thomas Barkowsky, Alexander Klippel, and Christian Freksa. "Schematic maps as wayfinding aids". In: *Spatial cognition II.* Springer, 2000, pp. 54–71.

[Chr95] Nicholas Christenfeld. "Choices from identical options". In: *Psychological Science* 6.1 (1995), pp. 50–55.

[Cou+87] Helen Couclelis, Reginald G Golledge, Nathan Gale, and Waldo Tobler. "Exploring the anchor-point hypothesis of spatial cognition". In: *Journal of environmental psychology* 7.2 (1987), pp. 99–122.

[CT05] David Caduff and Sabine Timpf. "The Landmark Spider: Representing Landmark Knowledge for Wayfinding Tasks." In: *AAAI spring symposium: Reasoning with mental and external diagrams: Computational modeling and spatial assistance.* 2005, pp. 30–35.

[CT08] David Caduff and Sabine Timpf. "On the assessment of landmark salience for human navigation". In: *Cognitive processing* 9 (2008), pp. 249–267.

[DD98] Marie-Paule Daniel and Michel Denis. "Spatial descriptions as navigational aids: A cognitive analysis of route directions". In: *Kognitionswissenschaft* 7.1 (1998), pp. 45–52.

[DE00] Ufuk Dogu and Feyzan Erkip. "Spatial factors affecting wayfinding and orientation: A case study in a shopping mall". In: *Environment and behavior* 32.6 (2000), pp. 731–755.

[Den+99] Michel Denis, Francesca Pazzaglia, Cesare Cornoldi, and Laura Bertolo. "Spatial discourse and navigation: An analysis of route directions in the city of Venice". In: *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition* 13.2 (1999), pp. 145–174.

[DGP03] Robert Dale, Sabine Geldof, and Jean-Philippe Prost. "CORAL: Using natural language generation for navigational assistance". In: *Twenty-Sixth Australasian Computer Science Conference (ACSC2003).* Vol. 16. 2003, pp. 35–44.

[Dic12] Frank Dickmann. "City maps versus map-based navigation systems–an empirical approach to building mental representations". In: *The Cartographic Journal* 49.1 (2012), pp. 62–69.

[DK03] Matt Duckham and Lars Kulik. ""Simplest" paths: automated route selection for navigation". In: *Spatial Information Theory. Foundations of Geographic Information Science: International Conference, COSIT 2003, Kartause Ittingen, Switzerland, September 24-28, 2003. Proceedings 6.* Springer. 2003, pp. 169–185.

[DS73] Roger M Downs and David Stea. *Cognitive maps and spatial behavior: Process and products.* na, 1973.

[DWR10] Matt Duckham, Stephan Winter, and Michelle Robinson. "Including landmarks in routing instructions". In: *Journal of location based services* 4.1 (2010), pp. 28–52.

[Far+12] Anna Charisse Farr, Tristan Kleinschmidt, Prasad Yarlagadda, and Kerrie Mengersen. "Wayfinding: A simple concept, a complex process". In: *Transport Reviews* 32.6 (2012), pp. 715–743.

[Few01] Rodney Fewings. "Wayfinding and airport terminal design". In: *The journal of navigation* 54.2 (2001), pp. 177–184.

[GA06] Glenn Gunzelmann and John R Anderson. "Location matters: Why target location impacts performance in orientation tasks". In: *Memory & cognition* 34.1 (2006), pp. 41–59.

[Gar+13] Aaron L Gardony, Tad T Brunyé, Caroline R Mahoney, and Holly A Taylor. "How navigational aids impair spatial memory: Evidence for divided attention". In: *Spatial Cognition & Computation* 13.4 (2013), pp. 319–350.

[GG88] TOMMY Gärling and E Gärling. "Distance minimization in downtown pedestrian shopping". In: *Environment and Planning A* 20.4 (1988), pp. 547–554.

[GHK17] Klaus Gramann, Paul Hoepner, and Katja Karrer-Gauss. "Modified navigation instructions for spatial navigation assistance systems lead to incidental spatial learning". In: *Frontiers in psychology* 8 (2017), p. 193.

[Gia+14] Ioannis Giannopoulos, Peter Kiefer, Martin Raubal, Kai-Florian Richter, and Tyler Thrash. "Wayfinding decision situations: A conceptual model and evaluation". In: *Geographic Information Science: 8th International Conference, GIScience 2014, Vienna, Austria, September 24-26, 2014. Proceedings 8.* Springer. 2014, pp. 221–234.

[Gol+99] Reginald G Golledge et al. *Wayfinding behavior: Cognitive mapping and other spatial processes.* JHU press, 1999.

[Gol95] Reginald G Golledge. "Path selection and route preference in human navigation: A progress report". In: *International conference on spatial information theory.* Springer. 1995, pp. 207–222.

[Gol97] Reginald G Golledge. *Spatial behavior: A geographic perspective.* Guilford Press, 1997.

[Heg+06] Mary Hegarty, Daniel R Montello, Anthony E Richardson, Toru Ishikawa, and Kristin Lovelace. "Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning". In: *Intelligence* 34.2 (2006), pp. 151–176.

[HF00] Hartwig Hochmair and Andrew U Frank. "Influence of estimation errors on wayfinding-decisions in unknown street networks–analyzing the least-angle strategy". In: *Spatial Cognition and Computation* 2 (2000), pp. 283–313.

[Hir+10] Stephen Hirtle, Kai-Florian Richter, Samvith Srinivas, and Robert Firth. "This is the tricky part: When directions become difficult". In: *Journal of Spatial Information Science* 1 (2010), pp. 53–73.

[HJ85] Stephen C Hirtle and John Jonides. "Evidence of hierarchies in cognitive maps". In: *Memory & cognition* 13.3 (1985), pp. 208–217.

[HK05] Hartwig H Hochmair and Victoria Karlsson. "Investigation of preference between the least-angle strategy and the initial segment strategy for route selection in unknown environments". In: *Spatial Cognition IV. Reasoning, Action, Interaction: International Conference Spatial Cognition 2004, Frauenchiemsee, Germany, October 11-13, 2004, Revised Selected Papers 4.* Springer. 2005, pp. 79–97.

[HKK06] Shazia Haque, Lars Kulik, and Alexander Klippel. "Algorithms for reliable navigation and wayfinding". In: *International Conference on Spatial Cognition.* Springer. 2006, pp. 308–326.

[HSG12] Haosheng Huang, Manuela Schmidt, and Georg Gartner. "Spatial knowledge acquisition with mobile maps, augmented reality and voice in the context of GPS-based pedestrian navigation: Results from a field test". In: *Cartography and Geographic Information Science* 39.2 (2012), pp. 107–116.

[IM06] Toru Ishikawa and Daniel R Montello. "Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places". In: *Cognitive psychology* 52.2 (2006), pp. 93–129.

[IN12] Toru Ishikawa and Uiko Nakamura. “Landmark selection in the environment: Relationships with object characteristics and sense of direction”. In: *Spatial Cognition & Computation* 12.1 (2012), pp. 1–22.

[Ish+08] Toru Ishikawa, Hiromichi Fujiwara, Osamu Imai, and Atsuyuki Okabe. “Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience”. In: *Journal of environmental psychology* 28.1 (2008), pp. 74–82.

[Ish19] Toru Ishikawa. “Satellite navigation and geospatial awareness: Long-term effects of using navigation tools on wayfinding and spatial orientation”. In: *The Professional Geographer* 71.2 (2019), pp. 197–209.

[IT13] Toru Ishikawa and Kazunori Takahashi. “Relationships between methods for presenting information on navigation tools and users’ wayfinding behavior”. In: *Cartographic Perspectives* 75 (2013), pp. 17–28.

[KAS20] Jakub Krukar, Vanessa Joy Anacta, and Angela Schwering. “The effect of orientation instructions on the recall and reuse of route and survey elements in wayfinding descriptions”. In: *Journal of environmental psychology* 68 (2020), p. 101407.

[KAZ04] Antonio Krüger, Ilhan Aslan, and Hubert Zimmer. “The effects of mobile pedestrian navigation systems on the concurrent acquisition of route and survey knowledge”. In: *Mobile Human-Computer Interaction-MobileHCI 2004: 6th International Symposium, MobileHCI, Glasgow, UK, September 13-16, 2004. Proceedings 6*. Springer. 2004, pp. 446–450.

[KB77] Lynn T Kozlowski and Kendall J Bryant. “Sense of direction, spatial orientation, and cognitive maps.” In: *Journal of Experimental Psychology: human perception and performance* 3.4 (1977), p. 590.

[Kim01] Young Ook Kim. “The role of spatial configuration in spatial cognition”. In: *Proceedings of the Third International Space Syntax Symposium, Ann Arbor, University of Michigan*. 2001, pp. 49–1.

[Kit94] Robert M Kitchin. “Cognitive maps: What are they and why study them?” In: *Journal of environmental psychology* 14.1 (1994), pp. 1–19.

[Kli03] Alexander Klippel. “Wayfinding choremes”. In: *Spatial Information Theory. Foundations of Geographic Information Science: International Conference, COSIT 2003, Kartause Ittingen, Switzerland, September 24-28, 2003. Proceedings 6*. Springer. 2003, pp. 301–315.

[Kri+98] Bernd Krieg-Brückner, Thomas Röfer, Hans-Otto Carmesin, and Rolf Müller. “A taxonomy of spatial knowledge for navigation and its application to the Bremen autonomous wheelchair”. In: *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (1998), pp. 373–397.

[KRK11] Hassan A Karimi, Duangduen Roongpiboonsopit, and Piyawan Kasemsuppakorn. “Uncertainty in personal navigation services”. In: *The Journal of Navigation* 64.2 (2011), pp. 341–356.

[Kru+18] Jakub Krukar, Stefan Münzer, Lucas Lörch, Vanessa Joy Anacta, Stefan Fuest, and Angela Schwering. “Distinguishing sketch map types: A flexible feature-based classification”. In: *Spatial Cognition XI: 11th International Conference, Spatial Cognition 2018, Tübingen, Germany, September 5-8, 2018, Proceedings 11.* Springer. 2018, pp. 279–292.

[KT03] Yoshinobu Kato and Yoshiaki Takeuchi. “Individual differences in wayfinding strategies”. In: *Journal of environmental psychology* 23.2 (2003), pp. 171–188.

[KW05] Alexander Klippel and Stephan Winter. “Structural salience of landmarks for route directions”. In: *Spatial Information Theory: International Conference, COSIT 2005, Ellicottville, NY, USA, September 14-18, 2005. Proceedings 7.* Springer. 2005, pp. 347–362.

[LC08] Wen-Chen Lee and Bor-Wen Cheng. “Effects of using a portable navigation system and paper map in real driving”. In: *Accident Analysis & Prevention* 40.1 (2008), pp. 303–308.

[LFS14] Rui Li, Stefan Fuest, and Angela Schwering. “The effects of different verbal route instructions on spatial orientation”. In: (2014).

[LHM99] Kristin L Lovelace, Mary Hegarty, and Daniel R Montello. “Elements of good route directions in familiar and unfamiliar environments”. In: *Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science: International Conference COSIT’99 Stade, Germany, August 25–29, 1999 Proceedings 4.* Springer. 1999, pp. 65–82.

[Lin+17] Allen Yilun Lin, Kate Kuehl, Johannes Schöning, and Brent Hecht. “Understanding” Death by GPS” A Systematic Study of Catastrophic Incidents Associated with Personal Navigation Technologies”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems.* 2017, pp. 1154–1166.

[LKS19] Heinrich Löwen, Jakub Krukar, and Angela Schwering. “Spatial learning with orientation maps: The influence of different environmental features on spatial knowledge acquisition”. In: *ISPRS International Journal of Geo-Information* 8.3 (2019), p. 149.

[LL99] Longin Jan Latecki and Rolf Lakämper. "Convexity rule for shape decomposition based on discrete contour evolution". In: *Computer Vision and Image Understanding* 73.3 (1999), pp. 441–454.

[Lyn64] Kevin Lynch. *The image of the city.* MIT press, 1964.

[Mar86] David M Mark. "Automated route selection for navigation". In: *IEEE Aerospace and Electronic Systems Magazine* 1.9 (1986), pp. 2–5.

[May+03] Andrew J May, Tracy Ross, Steven H Bayer, and Mikko J Tarkiainen. "Pedestrian navigation aids: information requirements and design implications". In: *Personal and Ubiquitous Computing* 7 (2003), pp. 331–338.

[MD01] Pierre-Emmanuel Michon and Michel Denis. "When and why are visual landmarks used in giving directions?" In: *Spatial Information Theory: Foundations of Geographic Information Science International Conference, COSIT 2001 Morro Bay, CA, USA, September 19–23, 2001 Proceedings 5.* Springer. 2001, pp. 292–305.

[Mil16] Greg Milner. *Pinpoint: how GPS is changing technology, culture, and our minds.* WW Norton & Company, 2016.

[Mon05] Daniel R Montello. *Navigation.* Cambridge University Press, 2005.

[Mon91] Daniel R Montello. "Spatial orientation and the angularity of urban routes: A field study". In: *Environment and Behavior* 23.1 (1991), pp. 47–69.

[Mon98] Daniel R Montello. "A new framework for understanding the acquisition of spatial knowledge in large-scale environments". In: *Spatial and temporal reasoning in geographic information systems* (1998), pp. 143–154.

[Mün+06] Stefan Münzer, Hubert D Zimmer, Maximilian Schwalm, Jörg Baus, and Ilhan Aslan. "Computer-assisted navigation and the acquisition of route and survey knowledge". In: *Journal of environmental psychology* 26.4 (2006), pp. 300–308.

[MZB12] Stefan Münzer, Hubert D Zimmer, and Jörg Baus. "Navigation assistance: a trade-off between wayfinding support and configural learning support." In: *Journal of experimental psychology: applied* 18.1 (2012), p. 18.

[OB08] Keith J Oliver and Gary E Burnett. "Learning-oriented vehicle navigation systems: a preliminary investigation in a driving simulator". In: *Proceedings of the 10th international conference on human computer interaction with mobile devices and services.* 2008, pp. 119–126.

[ONe91] Michael J O'Neill. "Evaluation of a conceptual model of architectural legibility". In: *Environment and Behavior* 23.3 (1991), pp. 259–284.

[PAE07] Avi Parush, Shir Ahuvia, and Ido Erev. “Degradation in spatial knowledge acquisition when using automatic navigation systems”. In: *Spatial Information Theory: 8th International Conference, COSIT 2007, Melbourne, Australiia, September 19-23, 2007. Proceedings 8*. Springer. 2007, pp. 238–254.

[Pas79] RE Passingham. *The hippocampus as a cognitive map— J. O’Keefe & L. Nadel, Oxford University Press, Oxford (1978). 570 pp.,£ 25.00.* 1979.

[Pin10] Thomas J Pingel. “Modeling slope as a contributor to route selection in mountainous areas”. In: *Cartography and Geographic Information Science* 37.2 (2010), pp. 137–148.

[PM88] Clark C Presson and Daniel R Montello. “Points of reference in spatial cognition: Stalking the elusive landmark.” In: *British Journal of Developmental Psychology* (1988).

[RD08] Kai-Florian Richter and Matt Duckham. “Simplest instructions: Finding easy-to-describe routes for navigation”. In: *GIScience*. 2008, pp. 274–289.

[Ric09] Kai-Florian Richter. “Adaptable path planning in regionalized environments”. In: *Spatial Information Theory: 9th International Conference, COSIT 2009 Aber Wrac’h, France, September 21-25, 2009 Proceedings 9*. Springer. 2009, pp. 453–470.

[Ric13] Kai-Florian Richter. “How using location-based services affects our understanding of our environtment”. In: *Advanced location-based technologies and services* (2013), pp. 265–282.

[RK04] Kai-Florian Richter and Alexander Klippel. “A model for context-specific route directions”. In: *International Conference on Spatial Cognition*. Springer. 2004, pp. 58–78.

[RMT04] Tracy Ross, Andrew May, and Simon Thompson. “The use of landmarks in pedestrian navigation instructions and the effects of context”. In: *Mobile Human-Computer Interaction-MobileHCI 2004: 6th International Symposium, MobileHCI, Glasgow, UK, September 13-16, 2004. Proceedings 6*. Springer. 2004, pp. 300–304.

[Rug+19] Ian T Ruginski, Sarah H Creem-Regehr, Jeanine K Stefanucci, and Elizabeth Cashdan. “GPS use negatively affects environmental learning through spatial transformation abilities”. In: *Journal of Environmental Psychology* 64 (2019), pp. 12–20.

[RW02] Martin Raubal and Stephan Winter. “Enriching wayfinding instructions with local landmarks”. In: *Geographic Information Science: Second International Conference, GIScience 2002 Boulder, CO, USA, September 25–28, 2002 Proceedings 2*. Springer. 2002, pp. 243–259.

[RW14] Kai-Florian Richter and Stephan Winter. “Landmarks”. In: *Springer Cham Heidelberg New York Dordrecht London. doi* 10 (2014), pp. 978–3.

[Sch+17] Angela Schwering, Jakub Krukar, Rui Li, Vanessa Joy Anacta, and Stefan Fuest. “Wayfinding through orientation”. In: *Spatial Cognition & Computation* 17.4 (2017), pp. 273–303.

[SH99] Molly E Sorrows and Stephen C Hirtle. “The nature of landmarks for real and electronic spaces”. In: *Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science: International Conference COSIT’99 Stade, Germany, August 25–29, 1999 Proceedings 4*. Springer. 1999, pp. 37–50.

[Sha+14] Jie Shao, Lars Kulik, Egemen Tanin, and Long Guo. “Travel distance versus navigation complexity: A study on different spatial queries on road networks”. In: *Proceedings of the 23rd ACM International Conference on Conference on Information and Knowledge Management.* 2014, pp. 1791–1794.

[Sho+00] M Jeanne Sholl, Joyce C Acacio, Rania O Makar, and Christlan Leon. “The relation of sex and sense of direction to spatial orientation in an unfamiliar environment”. In: *Journal of Environmental Psychology* 20.1 (2000), pp. 17–28.

[SW75] Alexander W Siegel and Sheldon H White. “The development of spatial representations of large-scale environments”. In: *Advances in child development and behavior* 10 (1975), pp. 9–55.

[TW06] Martin Tomko and Stephan Winter. “Recursive construction of granular route directions”. In: *Journal of Spatial Science* 51.1 (2006), pp. 101–115.

[TWC08] Martin Tomko, Stephan Winter, and Christophe Claramunt. “Experiential hierarchies of streets”. In: *Computers, Environment and Urban Systems* 32.1 (2008), pp. 41–52.

[Van16] Ann E Vandenberg. “Human wayfinding: integration of mind and body”. In: *Community Wayfinding: Pathways to Understanding.* Springer, 2016, pp. 17–32.

[Wen+14] James Wen, Agnes Deneka, William Helton, and Mark Billinghurst. “Really, it’s for your own good... making augmented reality navigation tools harder to use”. In: *CHI’14 Extended Abstracts on Human Factors in Computing Systems.* 2014, pp. 1297–1302.

[Wie+08] Jan M Wiener, Thora Tenbrik, Jakob Henschel, and Chistoph Holscher. “Situated and prospective path planning: Route choice in an urban environment”. In: *Proceedings of the Annual Meeting of the Cognitive Science Society.* Vol. 30. 30. 2008.

[Wil+09] Katharine S Willis, Christoph Hölscher, Gregor Wilbertz, and Chao Li. “A comparison of spatial knowledge acquisition with maps and mobile maps”. In: *Computers, Environment and Urban Systems* 33.2 (2009), pp. 100–110.

[Win03] Stephan Winter. “Route adaptive selection of salient features”. In: *Spatial Information Theory. Foundations of Geographic Information Science: International Conference, COSIT 2003, Kartause Ittingen, Switzerland, September 24-28, 2003. Proceedings 6*. Springer. 2003, pp. 349–361.

[WM03] Jan M Wiener and Hanspeter A Mallot. “’Fine-to-coarse’route planning and navigation in regionalized environments”. In: *Spatial cognition and computation* 3.4 (2003), pp. 331–358.

[WRN05] Stephan Winter, Martin Raubal, and Clemens Nothegger. “Focalizing measures of salience for wayfinding”. In: *Map-based mobile services: theories, methods and implementations* (2005), pp. 125–139.

[Zho+14] Yan Zhou, Weisheng Wang, Di He, and Zhe Wang. “A fewest-turn-and-shortest path algorithm based on breadth-first search”. In: *Geo-spatial information science* 17.4 (2014), pp. 201–207.

Paper I

You are not alone: Path search models, traffic, and social costs

F. Teimouri, K. F. Richter.

GIScience 2021; 11th International Conference on Geographic Information Science, Schloss Dagstuhl–Leibniz-Zentrum für Informatik, 177, pp. 1-14, 2020.

Paper II

Analysis of route choice based on path characteristics using GeoLife GPS trajectories

F. Teimouri, H. H. Hochmair, and K. F. Richter.

Submitted, 2023.

Paper III

Abstracting routes to their route-defining locations

F. Teimouri, K. F. Richter.

Computers, Environment and Urban Systems, Elsevier, 91, 101732, 2022.

Paper IV

Supporting spatial knowledge acquisition by automated augmentation of route directions with route-defining locations

F. Teimouri, K. F. Richter.

Submitted, 2023.

Paper V

‘Straight? What straight?’ Investigating navigation instructions’ applicability

F. Teimouri, K. F. Richter.

Journal of Location Based Services, Taylor & Francis, 1–25, 2021.