Exploring the Effects of Decoupling the Design Space for Mobile Navigation Technologies

D I S S E R T A T I O N
of the University of St.Gallen,
School of Management,
Economics, Law, Social Sciences,
International Affairs and Computer Science,
to obtain the title of
Doctor of Philosophy in Computer Science

submitted by

Gian-Luca Savino

from

Germany and Italy

Approved on the application of

Prof. Dr. Johannes Schöning

and

Prof. Dr. Sara Irina Fabrikant

Dissertation no. 5264

Difo-Druck GbmH, Untersiemau 2023

The University of St.Gallen, School of Management, Economics, Law, Social Sciences, International Affairs and Computer Science, hereby consents to the printing of the present dissertation, without hereby expressing any opinion on the views herein expressed.

St.Gallen, September 23, 2022

The President:

Prof. Dr. Bernhard Ehrenzeller

Für meinen Opa Adriaan

Acknowledgements

This thesis is the result of four years of PhD work. Much of this work would not have been the same without a great number of brilliant people I was lucky to meet during this journey. I want to take a moment to thank them. First and foremost, I want to thank you, Johannes, for being the best supervisor. I really couldn't have wished for anyone else. You have always inspired and pushed me to accomplish things I didn't know I was capable of. You opened so many doors for me but, more importantly, taught me how to find more doors to open for myself and others. I hope that one day I can be the person to someone else that you have been to me.

Furthermore, I want to thank you, Sara, for being the co-supervisor of my thesis. Since our paths crossed only recently, I am looking forward to many inspiring collaborations with you. I want to thank many more great minds who became co-authors of the papers presented in this thesis: Miriam, Christine, Brent, Catia, Nuno, and Thora. Furthermore I want to thank my students whose Bachelor and Master thesis work contributed to this thesis and who I had great pleasure supervising: Laura, Eve, Jessé, and Matthis. I also want to thank the program committee for considering this very first PhD thesis in Computer Science at the University of St.Gallen. I am thankful to have been part of the best and most unique HCI team in the world: the HCI Bre-Gallen team. Thank you, Jasmin, Ankit, Daniel, Benny, Dasha, Caro, Nadine, Evropi, Philipp, and Petra, for always having supported me and each other during these four years. You are amazing people. A special thank you goes to Barbara Stuckey for her editorial assistance and for the English lessons along the way.

Finally, I want to thank you, Thomas, for being my best friend and the best roommate in the world. Our personal and professional conversations have helped me grow as a person and researcher. To Marie, thank you for your endless support and being there, especially in those moments when my work got the better of me. I couldn't have done it without you. At last, I thank my family for always being there for me with more support than one can ask for. I am incredibly thankful to my parents, who enabled me to live a life without prejudice and filled with possibilities.

St.Gallen, September, 2022 Gian-Luca Savino

Table of Contents

List of Figures xi

List of Tables xiii

Abstract xv

Zusammenfassung xvi

Publications xix

1 Introduction 1

1.1 Motivation & Research Question 3
1.2 Contributions 6
1.3 Thesis Outline 11

2 Usage Patterns of Navigational User Interfaces 13

2.1 Introduction & Motivation 14
2.2 Related Work 15
2.2.1 Collecting Usage Behaviour 16
2.2.2 Map Usage 17
2.3 Experimental Studies 19
2.3.1 Survey & Participant Recruitment 19
2.3.2 MapRecorder Application 20
2.3.3 Logged Data & Interaction 21
2.3.4 Interviews 22
2.4 Results 23
2.4.1 Study 1 23
2.4.2 Study 2 31
2.5 Discussion 34
2.5.1 Implications 36
2.5.2 Limitations 36
2.6 Conclusion & Future Work 37

3 Designing Novel Mobile Navigation Systems for Cyclists 39
3.1 Introduction & Motivation . . . 40
3.2 Related Work . . . 42
3.2.1 Least-Angle Strategy . . . 42
3.2.2 Direction Conveyed through Sound . . . 43
3.2.3 Direction Conveyed through Vibration . . . 44
3.2.4 Contribution . . . 45
3.3 Study 1 - TBT vs ATCF . . . 45
3.3.1 Task & Procedure . . . 46
3.3.2 Participants & Apparatus . . . 47
3.3.3 Measures . . . 48
3.3.4 Results . . . 49
3.3.5 Summary . . . 51
3.4 Study 2 - ATCF vs ATCF+ . . . 52
3.4.1 Task & Procedure . . . 54
3.4.2 Participants & Apparatus . . . 54
3.4.3 Technical Implementation . . . 55
3.4.4 Measures . . . 55
3.4.5 Results . . . 55
3.4.6 Summary . . . 58
3.5 Discussion . . . 59
3.5.1 Cycling In the Opposite Direction to the Arrow . . . 60
3.5.2 Route Progression . . . 61
3.5.3 Cyclists Go Everywhere . . . 61
3.6 Limitations . . . 62
3.7 Future Work . . . 62
3.8 Conclusion . . . 63

4 The Effects of Street Networks on As-The-Crow-Flies Navigation 65
4.1 Introduction & Motivation . . . 66
4.2 Related Work . . . 68
4.2.1 Least-Angle Strategy . . . 68
4.2.2 As-The-Crow-Flies Navigation . . . 69
4.2.3 Street Network Analysis . . . 73

4.3 Study . . . 75
4.3.1 Agent . . . 76
4.3.2 Cities . . . 77
4.3.3 The Simulation . . . 77
4.3.4 Street Network Indicators . . . 77
4.3.5 City Types . . . 78
4.4 Results . . . 78
4.4.1 Street Network Indicator Importance . . . 78
4.4.2 City Types . . . 80
4.5 Discussion . . . 82
4.5.1 Human Error? No, Bad Street Network Design . . . 82
4.5.2 Geographic Differences . . . 86
4.6 Ways Forward . . . 88
4.6.1 Modeling Human Behavior . . . 88
4.6.2 Data Quality . . . 89
4.6.3 Street Network Radius . . . 89
4.6.4 Bike-Friendly Cities . . . 90
4.6.5 As-The-Crow-Flies Navigation Beyond the Bicycle . . . 91
4.7 Conclusion . . . 91

5 Simulating Human Behavior for As-The-Crow-Flies Navigation 93
5.1 Introduction & Motivation . . . 94
5.2 Related Work . . . 95
5.2.1 Perception of Angles by Humans . . . 95
5.2.2 Modeling Human Wayfinding with ATCF Navigation . . . 96
5.3 Pre-Study . . . 98
5.3.1 Study Design . . . 98
5.3.2 Results . . . 98
5.4 Simulation & Agents . . . 99
5.4.1 Simulation Environment . . . 100
5.4.2 Least-Angle Agent & Uncertainty Agent . . . 100
5.5 Results . . . 101
5.6 Discussion & Conclusion . . . 103

6 Safely Interacting With Technology While Cycling 105
6.1 Introduction & Motivation . . . 106
6.2 Related Work . . . 107
6.2.1 HCI & Cycling . . . 107
6.2.2 Interaction in Motion . . . 108
6.3 Pre-Study . . . 109
6.3.1 Participants . . . 110
6.3.2 Procedure . . . 110
6.3.3 Results . . . 110
6.4 VeloCity Application . . . 111
6.4.1 Input Methods . . . 112
6.5 Study . . . 114
6.5.1 Study Design . . . 114
6.5.2 Participants . . . 114
6.5.3 Procedure . . . 115
6.5.4 Measures . . . 116
6.5.5 Results . . . 116
6.6 Guidelines for Using Voice Interaction for Cyclists . . . 119
6.6.1 Use Hands and Eyes-Free Interaction . . . 119
6.6.2 Give Informative Feedback . . . 120
6.6.3 Keep Commands Short . . . 120
6.6.4 Use Robust Error Handling . . . 121
6.6.5 Make It Safe . . . 121
6.7 Limitations & Future Work . . . 122
6.8 Conclusion . . . 123

7 Discussion 125
7.1 Decoupling the Design Space for Mobile Navigation Technologies . . . 125
7.1.1 Multi-Module Innovation: An ATCF-Based Example . . . 125
7.1.2 Systematic Assessment of Novel Mobile Navigation Systems . . . 127
7.2 The Predominance of Turn-By-Turn Navigation . . . 129
7.2.1 Negative Impact of Mobile Navigation Technologies . . . 130
7.3 Ecological Validity of Mobile Navigation Research . . . 132
7.3.1 Safety . . . 133

7.3.2 Geography 134

8 Conclusion **137**

References **139**

Appendix A **159**

Appendix B **162**

List of Figures

1.1 Turn-by-turn-based mobile navigation system architecture 2
1.2 Current mobile navigation applications 3
2.1 MapRecorder application screenshots showing the interaction states . . 22
2.2 Distribution of map usage states averaged over all users (study 1). . . . 23
2.3 Examples of different MSPD sessions 25
2.4 Usage-session annotated with zoom levels 25
2.5 Analysis of MapRecorder search results (study 1) 27
2.6 Relation of distance and mode of transportation (study 1) 29
2.7 Distribution of map usage states averaged over all users (study 2). . . . 31
2.8 Analysis of MapRecorder search results (study 2) 33
2.9 Relation of distance and mode of transportation (study 2) 33
2.10 Example of design changes inspired by the MSPD and MD pattern . . . 35
3.1 Beeline user interface 41
3.2 Experiment routes with annotations 46
3.3 Heat maps of the location data of all participants (study 1) 48
3.4 ATCF+ user interface 53
3.5 Heat maps of the location data of all participants (study 2) 56
3.6 Distance and confidence analysis 58
4.1 Problematic navigation situations with ATCF navigation 72
4.2 Description of the simulation framework 75
4.3 Permutation feature importance results 79
4.4 Success rate and performance factor based on different city types 81
4.5 Success rate and performance factor for 1,633 cities 83
4.6 A selection of ten cities from our dataset 85
5.1 A comparison of as-the-crow-flies and turn-by-turn navigation 95
5.2 Two intersections which participants saw in the online survey 97
5.3 The correctness of participants judging the angles on the pictures 99
5.4 Example of an angle-decision situation for the virtual agents 101
5.5 The overlap between participant data and virtual agent data 102
6.1 User Story of the VeloCity application 112
6.2 Screenshot of a video participants saw during the experiment 115
7.1 As-the-crow-flies-based mobile navigation system architecture 126

B.1 Street network indicators across city types (1-9). 162
B.2 Street network indicators across city types (10-13). 163

List of Tables

4.1 Street network indicators and their meaning 73
4.2 City types and their descriptions 74
4.3 Design implications for ATCF navigation 86
5.1 Overlap of the agent routes with the participant routes. 102
6.1 Results of the VeloCity survey 117

Abstract

In the last two decades, digital mobile navigation technologies have been replacing physical tools (i.e. physical maps), revolutionizing how people navigate familiar and unfamiliar spaces. Initially designed for in-car use, mobile navigation systems are being continuously adapted for other modes of transportation and novel user groups. However, the underlying system architecture is not being adapted to its new users. We have seen rapid technological evolution in each of the individual modules of the system architecture of turn-by-turn (TBT) based mobile navigation systems. Still, the overall architecture has remained the same. From a Human-Computer Interaction (HCI) perspective, this rigidity is rather unusual. However, in recent years we have seen the design space for mobile navigation technologies decouple from the prototypical architecture of TBT-based mobile navigation systems. People are combining existing and new modules to design and develop completely different and novel mobile navigation systems. This thesis systematically explores this decoupling.

To assess the mobile navigation systems that result from this decoupling, Chapter 2 of this thesis presents a novel method which gives us a better understanding of usage patterns and people's intentions when they are using mobile navigation applications. Chapter 3 shows that cyclists benefit from orientation-based navigation systems. In Chapter 4 we show that the environment (i.e. the street network) influences how successfully certain mobile navigation systems can be used. Chapter 5 explores how we can improve the user experience of orientation-based navigation methods by simulating human navigation behavior. Finally, Chapter 6 presents a study on avoiding the risks of decoupling the design space for mobile navigation technologies by the designing and introduction voice assistant-based input modalities for cyclists.

In summary, mobile navigation technologies are undergoing a transformation. Decoupling the design space from its former system architecture results in novel mobile navigation systems and use-cases. Presenting a systematic approach for assessing these novel mobile navigation systems and still ensuring that interactions are safely designed, this thesis, based on an HCI perspective, contributes to the understanding, evaluation, and improvement of mobile navigation systems for specific user groups.

Zusammenfassung

In den letzten zwei Jahrzehnten haben digitale mobile Navigationstechnologien physische Hilfsmittel (z. B. physische Karten) ersetzt und revolutioniert, wie Menschen in vertrauten und unbekannten Umgebungen navigieren. Ursprünglich für die Nutzung im Auto konzipiert, werden mobile Navigationssysteme kontinuierlich für andere Verkehrsmittel und neue Nutzungsgruppen angepasst. Wir beobachten zwar eine schnelle Entwicklung der einzelnen Module der auf Turn-by-Turn (TBT) basierenden Systemarchitektur von mobilen Navigationssystemen, dennoch bleibt die Gesamtarchitektur gleich. Aus Sicht der Mensch-Computer-Interaktion ist diese Starrheit eher ungewöhnlich. In den letzten Jahren haben wir jedoch beobachtet, dass sich der Gestaltungsraum für mobile Navigationstechnologien von der prototypischen Architektur TBT-basierter Systeme entkoppelt hat. Module werden neu kombiniert, um neuartige mobile Navigationssysteme zu entwickeln. In dieser Arbeit wird diese Entkopplung systematisch untersucht.

Um die aus dieser Entkopplung resultierenden mobilen Navigationssysteme zu bewerten, wird in Kapitel 2 eine Methode vorgestellt, die uns ein besseres Verständnis der Nutzungsmuster und Intentionen von Menschen bei der Verwendung mobiler Navigationsanwendungen ermöglicht. Kapitel 3 zeigt, dass Radfahrende von orientierungsbasierten Navigationssystemen profitieren. In Kapitel 4 zeigen wir, dass die Umgebung (d. h. das Straßennetz) beeinflusst, wie erfolgreich bestimmte Navigationssysteme genutzt werden können. Kapitel 5 untersucht, wie wir die Benutzungserfahrung von orientierungsbasierten Navigationsmethoden verbessern können, indem wir menschliches Navigationsverhalten simulieren. Schließlich wird in Kapitel 6 eine Studie vorgestellt, in der wir sprachassistentenbasierte Eingabemodalitäten für Radfahrende entwickelt und uns mit der Vermeidung von Risiken einer Entkopplung des Gestaltungsraums für mobile Navigationstechnologien beschäftigt haben.

Zusammenfassend lässt sich sagen, dass sich Mobile Navigationstechnologien im Wandel befinden. Die Entkopplung des Gestaltungsraums von der bisherigen Systemarchitektur führt zu neuartigen mobilen Navigationssystemen und Anwendungsfällen. Diese Arbeit stellt einen systematischen Ansatz vor, um diese Navigationssysteme zu evaluieren und dennoch sicherzustellen, dass Interaktionen sicher gestaltet sind. Basierend auf einer Mensch-Computer-Interaktion-Perspektive, trägt diese Arbeit zum Verständnis, zur Bewertung und zur Verbesserung mobiler Navigationssysteme für bestimmte Nutzungsgruppen bei.

Publications

The core of this dissertation is based on research reported in peer-reviewed publications which I have (co)-authored during the time of my PhD studies. In the following paragraphs, I list the five publications that form the core of my thesis and outline my individual contribution to each of them. My contributions are specified according to the ICMJE guidelines for authorship criteria [147]. For all the publications listed below I approved the final version to be published. I agree to be accountable for all aspects of the work and vow that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Publications Included in This Thesis

I. Savino, Gian-Luca, Sturdee, Miriam, Rundé, Simon, Lohmeier, Christine, Hecht, Brent, Prandi, Catia, Nunes, Nuno Jardim, and Schöning, Johannes. "MapRecorder: analysing real-world usage of mobile map applications". In: *Behaviour & Information Technology* 40.7 (2020), pp. 646–662. ISSN: 0144-929X, 1362-3001. DOI: 10.1080/0144929X.2020.1714733

   I contributed to the data analysis and interpretation in the first study and led the data acquisition, analysis, and interpretation in the second study. I drafted the manuscript and revised it for the final publication [199].

II. Savino, Gian-Luca, Meyer, Laura, Schade, Eve Emily Sophie, Tenbrink, Thora, and Schöning, Johannes. "Point Me In the Right Direction: Understanding User Behaviour with As-The-Crow-Flies Navigation". In: *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2020, pp. 1–11. ISBN: 978-1-4503-7516-0. DOI: 10.1145/3379503.3403539

   I contributed to the concept and design of the work, which was composed of two separate studies, and I contributed to the data acquisition, analysis, and interpretation of both studies. Since the two studies initially were reported on in two individual manuscripts, I combined the two individual manuscripts into one full paper [196].

III. Savino, Gian-Luca, Kariryaa, Ankit, and Schöning, Johannes. "Free as a Bird, but at What Cost? The Impact of Street Networks on the User Experience of As-The-Crow-Flies Navigation for Cyclists". In: *Proceedings of the ACM on Human-Computer Interaction* 6.MHCI (2022), 209:1–209:24. DOI: 10.1145/3546744

I conceived and designed the work. I acquired the data and contributed to its analysis and interpretation. I drafted the manuscript and contributed to its revision for the final publication [195].

IV. Savino, Gian-Luca. "Improving Agent-Based Route Predictions for As-The-Crow-Flies Navigation". In: *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 2022, pp. 1–6. ISBN: 978-1-4503-9156-6. DOI: 10.1145/3491101.3519709

This work and the published manuscript is a single author contribution [193].

V. Savino, Gian-Luca, Moraes Braga, Jessé, and Schöning, Johannes. "VeloCity: Using Voice Assistants for Cyclists to Provide Traffic Reports". In: *Proceedings of the 29th ACM International Conference on Multimedia*. 2021, pp. 3482–3491. ISBN: 978-1-4503-8651-7. DOI: 10.1145/3474085.3475509

I contributed to the design of the work and to the data analysis and interpretation. I revised the manuscript for its final publication [197].

Publications Not Included in This Thesis

I. Savino, Gian-Luca, Sawitzky, Tamara von, Matviienko, Andrii, Sturdee, Miriam, Woźniak, Paweł W., Löchtefeld, Markus, Kun, Andrew L., Riener, Andreas, and Häkkilä, Jonna. "Cycling@CHI: Towards a Research Agenda for HCI in the Bike Lane". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–5. ISBN: 978-1-4503-8095-9. DOI: 10.1145/3411763.3441316

   I contributed to the concept and design of this work and led the drafting and revising of the manuscript for the final publication [198].

II. Savino, Gian-Luca, Emanuel, Niklas, Kowalzik, Steven, Kroll, Felix, Lange, Marvin C., Laudan, Matthis, Leder, Rieke, Liang, Zhanhua, Markhabayeva, Dayana, Schmeißer, Martin, Schütz, Nicolai, Stellmacher, Carolin, Xu, Zihe, Bub, Kerstin, Kluss, Thorsten, Maldonado, Jaime, Kruijff, Ernst, and Schöning, Johannes. "Comparing Pedestrian Navigation Methods in Virtual Reality and Real Life". In: *2019 International Conference on Multimodal Interaction*. 2019, pp. 16–25. ISBN: 978-1-4503-6860-5. DOI: 10.1145/3340555.3353741

   I contributed the the design of the work and performed parts of the data acquisition, analysis, and interpretation. I contributed to drafting the manuscript and took the lead in revising it for the final publication [194].

1 Introduction

During the last two decades, mobile navigation technologies have revolutionized the way people navigate within familiar and unfamiliar spaces [102]. Digital tools have replaced and are continuously replacing physical tools (i.e. physical maps) which people have been using for millennia [102, 123]. Starting with in-car satellite navigation (satnav) systems, which shaped many people's first experience with mobile navigation technologies [56, 209], mobile navigation applications have become ubiquitous [7, 212, 213]. One innovative trigger was the discontinuation of Selective Availability (SA) for the Global Positioning System (GPS) in 2000 [2]. Without SA, the accuracy of GPS increased and thereby accelerated innovation in the domain of mobile navigation. Figure 1.1 shows a typical system architecture of a turn-by-turn (TBT) based mobile navigation system. The design space of this architecture contains eight modules: GPS, sensors, positioning, a digital map, map matching, route planning, route guidance, and a user interface. During the last two decades, even though there has been innovation within each of these modules, the overall architecture remained the same. A prototypical example of this overall architecture was designed and developed by Park et al. [159]. Park et al. [159] used GPS and additional sensors (i.e. a gyroscope and a wheel sensor) for positioning; they utilized shortest path algorithms for route planning. Route guidance was provided through TBT instructions and the user interface featured a route map screen with visual and audio-based output modalities [56, 59, 159].

Taking a closer look at the individual modules of the design space, positioning saw several innovations. While GPS is still most commonly used for mobile navigation systems [119], especially for outdoor applications, the positioning output was enhanced by improved digital maps [9, 20, 161] and better map matching algorithms [173]. Additionally, there are other technologies, such as radio frequency signals (e.g. Bluetooth, WiFi), light (e.g. visible and infrared), sound (e.g. audible and ultrasonic), and magnetic fields [35], which can be used to locate mobile navigation systems. Particularly, the field of indoor navigation has seen improvements over the years by employing sensors for WiFi [234], Bluetooth Low Energy (BLE) [72], and Radio Frequency Identification (RFID) [120] to locate devices inside buildings.

For route planning, the shortest path remains a widely used approach [77, 160]. Still, novel user groups (e.g. pedestrians, cyclists) are also interested in alternatives featuring properties like accessibility, safety, comfort, and/or convenience [160]. This has led

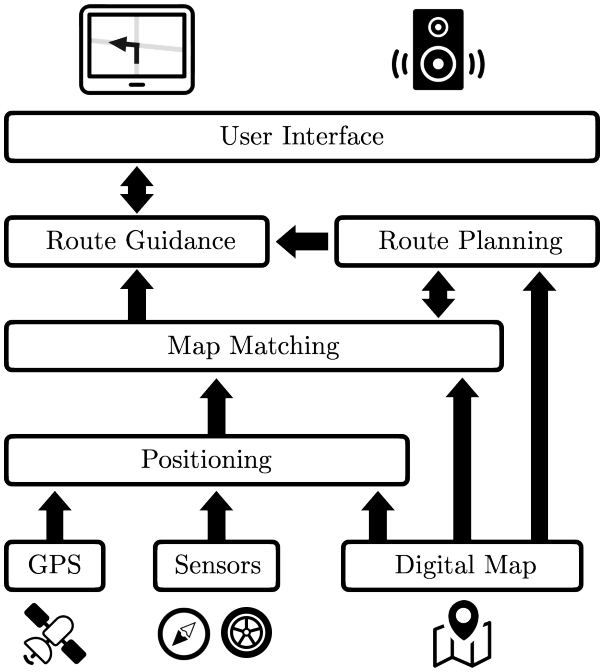
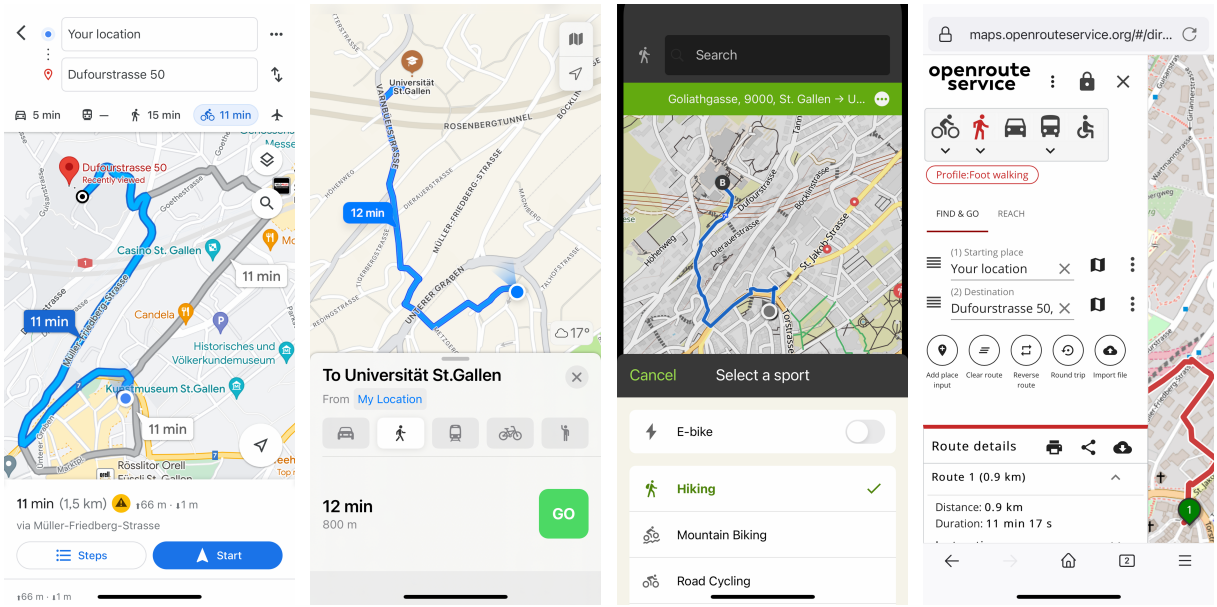


Fig. 1.1 Prototypical turn-by-turn-based mobile navigation system architecture, based on Park et al. [159], which has been serving as the design space for mobile navigation technologies.

researchers to explore other routing techniques [106] that compute the simplest [62], safest [74], most-scenic [189], and/or most eco-friendly [34, 57] paths. These specialized routing techniques have varying effects: they can be more environmentally friendly, as in the case of Google's eco-friendly routing [57], or they can improve accessibility for user groups with specific needs, like wheelchair users [217, 218].

When it comes to route guidance, TBT is still the default method for most mobile navigation systems [6, 82, 184, 204]. Still, researchers are exploring alternatives. Reference-based route guidance, for example, makes use of users' existing location knowledge to formulate written or spoken instructions, such as "the destination is 190 meters southwest of the Ferris wheel" [121]. Orientation-based route guidance indicates only the general direction and straight-line distance to the destination [121]; such guidance can be provided through various modalities [4, 167, 168] and is specifically targeted to user groups, like cyclists [4, 167].

Finally, user interfaces for mobile navigation systems have seen a variety of innovations in interaction modalities. Novel output modalities – music [4, 90, 97], vibration [138, 166, 167, 184, 214], light [138], and projection [53] – give novel user groups access to navigation and location information while on the move, without diverting the users' focus



(a) **(b)** **(c)** **(d)**

Fig. 1.2 Current mobile navigation applications supporting different modes of transportation. (a) Google Maps [82], map data ©2022 Google; (b) Apple Maps [6], map data ©2022 Apple; (c) Komoot [113], map data ©OpenStreetMap contributors; (d) Openrouteservice [89], map data ©OpenStreetMap contributors.

from the locomotion activity itself [134]. Additionally, novel input modalities, such as gestures [53], voice [23], and controllers [233], allow user groups to safely interact with mobile navigation systems while moving. These innovations are especially useful for novel user groups, like cyclists who benefit from less visual interaction modalities [4].

1.1 Motivation & Research Question

The number of user groups and modes of transportation for which mobile navigation systems are being designed has increased over the years. Today, there are mobile navigation applications, like Google Maps [82] and Apple Maps [6], which offer mobile navigation services for pedestrians [61] and cyclists [57, 170]. The outdoor navigation application Komoot [113] provides mobile navigation services for hikers [203] and mountain bikers [16]. Websites like Openrouteservice [89] offer mobile navigation services for a large set of users (see Figure 1.2). However, while mobile navigation systems have become more diverse, their system architecture has stayed rigid.

To understand this development, we inspected it from a Human-Computer Interaction (HCI) perspective. HCI is concerned with the design, evaluation, and implementation of

interactive computing systems for human use and with the study of major surrounding phenomena [91]. Throughout the last two decades, HCI research has been intensively investigating mobile navigation technologies within the different modules of the design space. These investigations range from improvements in route guidance [121], over investigating alternative route planning approaches [62, 74, 106, 189], to testing novel input and output modalities [53, 90, 97, 138, 164, 184, 233]. Yet, innovation has mostly been linked to changes within individual modules of the design space. For example, novel interfaces were compared to existing interfaces [90, 164, 233]; most-scenic path algorithms were compared to shortest path algorithms [189]. Currently, we are seeing first attempts at designing entirely new mobile navigation systems. In these novel systems that are being designed to support particular user groups, we are seeing innovation not only within multiple modules but also in the underlying system architecture. To understand the challenges of these attempts at designing new systems and reaping their potential benefits, this thesis reports on our research into and studies of the effects of decoupling the design space for mobile navigation technologies from its rigid prototypical system architecture. This decoupling puts the design space in a free floating state, where multiple modules can be combined in novel ways without sticking to a predetermined prototypical structure. We address the following overarching research question:

RQ What are the effects from a user perspective of decoupling the design space for mobile navigation technologies?

In this thesis, we argue that compared to the single-module innovations we have seen in the past, innovation within multiple modules of the design space, taking place all at once, increases the complexity of studying the newly created mobile navigation systems. This thesis describes our work toward achieving a systematic approach for understanding, evaluating, and improving such novel mobile navigation systems. In addition, we have emphasized the need to ensure that interactions with these systems are safely designed. Using human-centered design [153], we (1) examined people's usage behavior with mobile navigation applications, (2) evaluated the user experience of novel mobile navigation systems, (3) measured the environment's effect on the user experience, and (4) improved the design of novel mobile navigation systems beyond optimizing for navigation efficiency. Lastly, (5) we ensured that mobile navigation systems are designed in a safe way for users' interaction.

Beyond the technical innovation that results from decoupling the design space, we see further effects which these novel mobile navigation systems can have on the user. Especially important is the effect on people's spatial cognitive abilities [187, 204]. Spatial cognition is a discipline within cognitive science and is concerned with how humans and animals perceive and interact with their spatial environment [228]. Such research helps us understand how humans navigate, how they understand spatial relationships, how they build up spatial knowledge, and consequently how we can assist the carrying out of these tasks. This assistance is frequently realized through mobile navigation systems [186]. Thus, it is crucial for a system's successful development to understand how it affects people's spatial knowledge [8, 220, 232]. Central to an understanding of spatial knowledge are the concepts of survey-knowledge, route-knowledge and landmark-knowledge [208]. According to Siegel et al. [208], humans acquire spatial knowledge in three stages. First, landmark knowledge is acquired by perceiving and remembering the appearance of objects along a path. Once a clear representation of those objects exists, route knowledge is acquired. This means that people, over time, learn the sequence of necessary turns at decision points. This sequence is cognitively encoded either with direct instructions, e.g. "turn left, then right" [221], or with the help of landmark-directions, e.g. "turn right at the museum" [118]. Once the route knowledge is fully acquired, survey knowledge follows. With survey knowledge people form an internal representation, i.e. a cognitive map of their environment [111, 133, 156, 208]. Recent research suggests that the idea that the different kinds of spatial knowledge are acquired in stages, might be wrong. Rather, much of this knowledge may be acquired in parallel [111]. Regardless, HCI researchers have started measuring landmark, route, and survey-knowledge in their experiments [8, 40, 101, 117] to support spatial knowledge acquisition through technology. However, current mobile navigation technologies seem to be doing the opposite. Initial studies have found that the dependence on TBT-based mobile navigation systems harms spatial cognitive abilities [40, 105, 187, 204]. However, novel mobile navigation systems can counter this development by designing technology that supports our spatial cognitive abilities [100] instead of technology that diminishes them [204].

Despite their potential negative side effects on our spatial cognitive abilities, using mobile navigation systems has become a widespread activity [142]. Almost every second person in Germany [213] and the USA [212] owns or uses a mobile navigation system. With increasing numbers of people using these systems, routing algorithms of large mobile navigation applications determine on which routes hundreds or thousands of people move

through a particular area. This has been shown to affect community-level externalities, for example, increasing the risk of collisions and/or shaping people's perception of a city when avoiding certain areas [106]. Johnson et al. [106] investigated the externalities that arise when novel routing criteria are introduced, e.g. simplicity, safety, and beauty. The study's results show that safety routing removed and/or increased traffic from specific communities, leading to economic and social impacts. Traffic was not just redistributed to nearby areas but was redirected to highways and large thoroughfares circumventing a much larger area [106]. With novel non-TBT-based navigation, we are moving away from predefined route planning and towards more autonomy as part of the navigation experience [167, 196]. Thus, for specific user groups, our research demonstrates that new approaches to mobile navigation can mitigate some of the societal effects caused by the large-scale route guidance currently being used by car drivers [106].

Finally, researchers must safely evaluate novel mobile navigation technologies resulting from decoupling the design space. Like car drivers [50, 202], novel user groups, such as pedestrians and cyclists, must be attentive and aware of their environment when using mobile navigation systems [76, 188, 214]. Thus, decoupling the design space for mobile navigation technologies requires the development of safe interaction modalities. At the same time we need a more thorough evaluation of such interaction modalities.

In summary, mobile navigation technologies are evolving. The design space for mobile navigation technologies is decoupling, allowing researchers and practitioners to create novel systems and use-cases. Given a more thorough knowledge of mobile navigation technologies, spatial cognition, and the societal consequences of mobile navigation gained in our work, this thesis offers guidelines from an HCI perspective for the understanding, evaluation, and improvement of mobile navigation systems for specific user groups.

1.2 Contributions

To structure this thesis, we subdivided our overarching research question into five sub-questions (*RQ1-5*). One of these five sub-questions is addressed in each of the five designated publications in its own dedicated thesis chapter. The questions were derived from the need for a systematic approach to understanding, evaluating, and improving novel mobile navigation systems while ensuring that possible interactions with these systems are safely designed. After gaining an understanding of how people use mobile navigation technologies, we researched how different navigation methods empower

specific user groups, investigated whether street network structures affect the use of novel mobile navigation systems, explored how to improve the user experience of those novel mobile navigation systems, and evaluated the risks of decoupling the design space for mobile navigation technologies.

RQ1: How do people use mobile navigation technologies?

In order to understand the effects on the user of decoupling the design space for mobile navigation technologies, we first investigated the usage behavior of people with mobile map applications [199]. By monitoring everyday usage through a wrapper application, we gained insights into people's usage patterns and intentions. We discovered both a few common usage patterns and that people mainly use mobile map applications for exploring information available on the map. Mobile map applications were primarily designed to search, to investigate places on a map, and to get directions to destinations. To our surprise, exploring the map was by far the most used interaction. From these results we learned that users interacted with the application in unexpected ways, strengthening the need for more HCI research in this domain. Our study led to a method that allows collecting in-app usage behavior, which can then be used for evaluating novel mobile navigation applications resulting from decoupling the design space for mobile navigation technologies. With mobile map applications being just one category of mobile navigation technologies, our results motivated us to look for further misconceptions about the relationship between the design of mobile navigation technologies and actual usage behavior.

RQ2: Do different user groups benefit from different types of route guidance?

Decoupling the design space for mobile navigation technologies introduces the possibility for novel mobile navigation systems for specific users groups. Each user group has its own needs for mobile navigation technologies. In our studies we focused on cyclists, one of the most at-risk road users [207]. The cognitive capacities cyclists can allocate to secondary tasks, like receiving navigation instructions, differ from other user groups [54]. Thus, we investigated a novel mobile navigation system that was specifically designed for "bikers on the move" [196]. While TBT route guidance has been optimized for car drivers, who are bound to follow the course of existing street networks, cyclists have much more freedom to choose their route. Here, mobile navigation systems based on as-the-crow-flies (ATCF) route guidance offer an alternative. With such ATCF route

guidance users receive the general direction to their destination, e.g. in the form of a compass needle. Using this information, the users must decide themselves where to turn at each decision point. We explored graphical user interface options which communicate the direction to the destination, while avoiding common user errors, like participants going into dead ends, taking long detours, or not knowing whether they are still going in the right direction. We found that while TBT route guidance was still the more efficient approach for cyclists in terms of travel time, participants articulated a preference for ATCF route guidance whenever they were not in a rush. When compared to using TBT route guidance, participants showed signs of improved orientation after using the ATCF route guidance.

RQ3: Do existing street network structures affect the use of novel mobile navigation systems?

Even though our previous study showed that cyclists were able to successfully use ATCF-based mobile navigation systems, they faced some common problems: (1) going into dead ends, (2) taking long detours, (3) not knowing whether they were going in the right direction. Some of these problems can be accounted for by human error and a novelty factor with participants not fully understanding the type of route guidance [167, 196]. However, in a subsequent study, we investigated if the street network itself also affects how well people are able to use ATCF-based mobile navigation systems [195]. Running into dead ends was one of the potential problems. Thus, an environment with lots of dead ends potentially bears a higher risk of error when using ATCF route guidance. To explore this idea, we built a virtual agent that proxied human use of an ATCF-based mobile navigation system. The agent was used to simulate navigation tasks for 10,000 origin-destination pairs in 1,633 cities worldwide. Using feature importance analysis, we identified critical street network indicators which affected the agent's success and efficiency when finding routes in a particular area. We saw significant differences among geographical areas of the world and thus concluded that the environment in which a novel mobile navigation system will be used must be part of its design and evaluation process.

RQ4: How can we improve the user experience of novel mobile navigation systems?

While the previous study provided insights into the effect of the street network on the user experience of ATCF-based mobile navigation systems, there were shortcomings in terms of the design of the virtual navigation agent. The virtual agent was based on the state-of-the-art implementation of the least-angle strategy (LAS) developed by

Hochmair [95]. The agent followed a strict angle-based decision-making process, always choosing the street with the least angle deviation to the final destination at each decision point. Results of our previous navigation study with participants using the ATCF-based mobile navigation system showed that participants had problems deciding which streets to take at decision points. We observed that the participants did not always choose the street with the least angle deviation when two streets had a similar deviation. This led to two insights: (1) the virtual agent was behaving differently from participants in specific navigation situations and (2) a better simulation of actual human navigation behavior can be used to predict routes and improve the user interface feedback of the ATCF navigation application presented in one of our previous studies [196]. In this study we investigated how we could make the virtual agent's behavior more human-like by analyzing people's ability to interpret small angle deviations in an ATCF navigation setting [193]. Using an online study, we presented pictures of ATCF-based navigation situations to participants. These pictures showed two street options and an ATCF user interface with a compass needle pointing to the destination. Participants, then, had to chose one of the two street options, based on the ATCF user interface. The angle deviation to the destination between the two options was minimal, ranging from 2.5° to 15°. Based on the answers of sixty-four participants, we derived an error function which described the error rate of humans making these choices. Given this error function, we introduced uncertainty behavior into the agent from the previous study, making the agents decisions more human-like. This change improved results when compared to actual human navigation behavior [196].

In sum, we found that novel ATCF-based mobile navigation systems not surprisingly induced less predictable navigation behavior than TBT-based systems. With novel navigation technologies which do not use TBT instructions, we will need to be able to predict people's navigation decisions using new techniques, like simulation, to anticipate and counteract potential navigation errors and thus improve the user experience.

RQ5: What are the risks of decoupling the design space for mobile navigation technologies?

With the decoupling of the design space for mobile navigation technologies, researchers and practitioners have been busy designing and developing mobile navigation systems for specific user groups and use cases. However well-intended in their construction, novel interaction modalities can be dangerous to use in real-world environments [134]. In urban environments, navigating often involves being part of road traffic and taking unfamiliar

routes or paths. When interacting with technology while moving, either by bike, on foot, or when operating a vehicle [134], the situation demands cognitive effort and can lead to increased safety risks. Therefore, we must ensure that current and future research investigates how people can safely interact with technology while in motion. One of our contributions is an application for cyclists to report traffic incidents. Such a feature has been available to car drivers for a long time through the popular mobile navigation application Waze [229]. In our study, we investigated how cyclists can safely interact with such a reporting application, while keeping their attention on the traffic and their surroundings [197]. Due to the restrictions/inhibitions that cycling puts on users' hands and feet [134], we found that voice interaction through a voice assistant worked best to keep people's visual attention on the traffic while still being able to interact with the mobile application.

The design space of mobile navigation technology has been decoupling and novel ideas are being developed at an increasing pace. As HCI researchers, we must investigate these technologies to inform and guide design today and in the future. A major challenge during this development is to balance responsibly the ecological validity of our results and the safety of our participants during navigation experiments.

Summary: RQ1-5

This thesis explores the effects from a user perspective of decoupling the design space for mobile navigation technologies. We see innovation across multiple modules of the design space, enabling the design of novel mobile navigation systems for specific user groups. Evaluation of these innovations requires methods that help us understand people's usage behavior with and within these systems and applications. *RQ1* focuses on the development of a method to collect in-app usage data for understanding common usage patterns and people's intentions as they use mobile navigation applications. Our results provide guidelines for designing current and novel mobile navigation systems. However, not every new system is suited for every user group. ATCF-based mobile navigation systems, for example, offer alternatives to current TBT-based approaches. Hence, *RQ2* addresses the need to investigate which user groups can benefit from particular novel mobile navigation systems. Moreover, much like the user groups, the environments in which these novel systems are used must be investigated. Many studies on mobile navigation technologies are conducted in arbitrarily chosen environments [143]. Thus, *RQ3* asks whether the environment, i.e. the street network, influences how successfully certain

mobile navigation systems can be used. Furthermore, when shifting the requirements for successful navigation away from the fastest or shortest path, we need to think about novel ways – besides optimizing for efficiency – to improve these technologies. Therefore, *RQ4* addresses how we can improve the user experience of novel navigation methods. Finally, novel mobile navigation systems and applications need to be tested to ensure they can be safely used in real-world environments. We have to design interaction modalities and experiments that increase the safety of users while they are using and testing these novel technologies. Hence, *RQ5* is focused on the risks of decoupling the design space for mobile navigation technologies. Based on our findings, (1) we now better understand people's usage behavior with mobile navigation applications, (2) we can better evaluate user experiences with novel mobile navigation systems, (3) we can accurately measure the environment's effect on user experience, and (4) we have improved application design. Lastly, (5) we can ensure that mobile navigation systems are designed in a safe way.

1.3 Thesis Outline

This thesis is structured into eight chapters. In this first chapter, we introduce the design space for mobile navigation technologies, motivate and pose our research questions, and summarize the core contributions of the thesis. Each of the following five chapters presents one research paper and addresses one sub-research question. Chapter 2 gives our answers to *RQ1* by establishing an understanding of common usage patterns of mobile map applications. Chapters 3-5 are concerned with using ATCF-based mobile navigation systems for cyclists. Chapter 3 pursues *RQ2* by testing an ATCF-based mobile navigation system with cyclists in a field study designed to identify and investigate common usage errors and to improve on existing interface designs. Chapter 4 proposes answers to *RQ3* which we discovered by investigating to what extent usage errors of ATCF-based mobile navigation systems are induced by the environment rather than being caused by human error. Chapter 5 answers *RQ4* with the results of our exploring how we can simulate human navigation behavior with ATCF route guidance to improve the user experience of ATCF-based mobile navigation systems. Chapter 6 answers *RQ5* by our looking at how cyclists in the real world can safely interact with a traffic reporting application while cycling. Finally, in Chapter 7 we discuss our systematic assessment of novel mobile navigation systems. Furthermore, we discuss the predominance of TBT route guidance and the importance of ecological validity. Lastly, in Chapter 8 we conclude the thesis with our proposition for future directions in mobile navigation research.

2 Usage Patterns of Navigational User Interfaces

Decoupling the design space for mobile navigation technologies resulted in the development of novel mobile navigation applications. Methods to understand people's usage behavior while using these novel applications is necessary in order to identify user needs and to design for more meaningful interactions. Thus, in this chapter, we report on our investigation of the usage behavior of people interacting with mobile map applications. By developing a wrapper application, we were able to monitor users' everyday usage of the mobile map application. We found a surprising predominance of exploratory behavior (i.e. exploring the map). Furthermore, we identified common usage patterns and were able to formulate detailed design recommendations for future mobile map applications. As part of our work we developed a **method** for collecting in-app usage data for a popular mobile map app by using a wrapper application. We have presented **empirical** results of the usage behavior of 34 participants in our experiments.

The contents of this chapter originally appeared in Savino, Gian-Luca, Sturdee, Miriam, Rundé, Simon, Lohmeier, Christine, Hecht, Brent, Prandi, Catia, Nunes, Nuno Jardim, and Schöning, Johannes. "MapRecorder: analysing real-world usage of mobile map applications". In: *Behaviour & Information Technology* 40.7 (2020), pp. 646–662. ISSN: 0144-929X, 1362-3001. DOI: 10.1080/0144929X.2020.1714733

2.1 Introduction & Motivation

Mobile map applications like *Google Maps* are extremely popular. For instance, the annual *ComScore* report on application usage in the United States indicates that *Google Maps* is the fifth-most-used mobile application [70]. Other studies have found *Google Maps* to be the fourth-most-used application in terms of total usage time [33]. And while *Google Maps* is the most widely used, other mobile map applications like *Apple Maps*, *Waze* or *OpenStreetMap* are popular alternatives featuring similar user interfaces and functionality. However, while we know that mobile map applications are used quite often, we know very little about *how* they are used. For instance, what is the most prominent action users take within these applications? Are there reoccurring interaction patterns? How are they making use of the search functionality? Do different user groups show different kinds of behavior?

Usage data from commercial providers is not publicly available, and this situation is likely to persist owing to the extensive competitive and privacy concerns associated with releasing this type of information. Outside of the mobile map space, HCI studies that examine foundational application usage behavior have received extensive attention thanks to the research and design guidance they afford. These studies help not only to understand general smartphone and application usage [33, 92] but shed light on specific domains like information search [41, 45, 107] and notifications [165]. This paper seeks to extend the benefits of this literature to the important and prominent domain of mobile map applications. To do so, we take inspiration from Carrascal and Church [41] who used an in-situ approach to investigate mobile search application behavior from 18 participants by creating an application which acted as a "wrapper" for a popular search engine on Android. We developed such a "wrapper" application for *Google Maps* called *MapRecorder* which "wraps" the *Google Maps* mobile website. This allows researchers to capture rich behavioral logs while affording a very similar experience to the standard application. We performed two separate studies. The first study took place in Bremen, Germany and was conducted with 28 local participants who used *MapRecorder* for four weeks. We captured 483 minutes of interaction with *MapRecorder* across 443 sessions. The second study took place in Madeira, Portugal, and was conducted with 6 cruise-ship tourists (non-locals) who used *MapRecorder* for one day. We captured 97 minutes of interaction with *MapRecorder* across 112 sessions. We analyzed usage across the four main interaction states of *Google Maps*: *Search*, *Place*, *Direction* and *Map-View Manipulation*.

Our main finding is the prevalence of exploratory behavior in the form of panning and zooming, supporting the notion of "user-as-explorer" [18, 88] in mobile map applications. Indeed, this exploratory behavior made up more than 60% of users usage time with *MapRecorder* in both studies. As we discuss below, this may have important implications for the development of mobile maps which currently focus mostly on text search to enable way finding rather than geographic exploration. As our results show, mobile maps are no longer just a means to get directions from A to B but enable users to find information about their surroundings in an exploratory fashion.

Besides our results associated with exploration, we also noticed a number of other behavior patterns with significant potential design implications. For instance, we observed that search behaviors demonstrated a clear preference for named places (e.g. a specific restaurant) rather than entity classes such as "restaurants" or other *near me* options. Our findings also suggest that users exhibit similar patterns of use in order to get directions to a specific location with a high percentage of sessions displaying specific transitions across usage states within the map application.

We are releasing our complete anonymized data set so that other researches may conduct additional analyses using our data.

2.2 Related Work

Descriptive studies of smartphone and smartphone-app usage behavior have been of interest to the HCI community since the inception of smartphones. While some studies focus more on the evaluation of general mobile phone usage throughout users daily life (e.g. time of day of use, location of use, length of usage session) [22, 33, 45, 47, 145], others are more concerned with more technical analyses about the time and overuse [122] as well as the impact of network and energy usage [65, 231] of mobile phones. Further work in this area covers the categorization of different types of interactions [13, 92], analysis and prediction of interaction patterns [206, 211], privacy and security [68], notifications [165, 192] or other types of usage contexts (sometimes including qualitative user data) [150]. However, few studies have engaged in descriptive analyses of within-application usage [41]. The lack of information about how people interact with applications is due, at least in part, to the understandable hesitancy of developers to release this information. This hesitancy is compounded by the challenges inherent in outside parties attempting to collect organic, unbiased within-application usage information [47].

In the sections below, we review in more detail the literature that helped motivate our methodological choices while being an external party attempting to collect high-quality within-application usage data. More importantly we provide our motivation for collecting information about mobile map usage behavior in the first place, as we show that studying map usage behavior has already been done in the era of paper maps and still holds its justification in the mobile age, even though or rather because publicly available data in this domain is very scarce.

2.2.1 Collecting Usage Behaviour

User testing of novel application designs provides useful information when developing new products, but these test cases are usually conducted in a controlled environment to discover glitches before a product is released. In comparison, unsupervised usage data collection occurs naturally, with organic situations and outcomes, but can be difficult to organize and collect [46, 47]. To give a widespread example of unsupervised usage data collection, commercially provided data such as *Google Analytics* can provide detailed information about items such as site visits or page views, and thus can be used to infer some details on unsupervised use – such as examining the usability of E-Commerce sites [87].

An application-specific study which was successful in collecting unsupervised usage data was developed by Lettner et al. [124] to examine screen-to-screen navigation within applications and identify navigation errors. This method was able to provide the developers with a large amount of naturalistic data and some usability insights, but only works for those applications where between-screen navigation is used, and does not collect associated data, so has limited use in other contexts.

A larger data set was analyzed by Böhmer et al. [33] (4,125 users over 163 days) with over 22,000 sessions of application usage recorded. As with Do et al. [60], a logging application was developed and deployed so as not to interfere with the general user experience. Data such as local time and location was collected, in addition to the time an app was open and previous app interaction. Within this data set, *Google Maps* usage was collected and was shown to be the fourth-most-used application in terms of time spent in-app, and although a peak in early evening usage suggested peaks in user engagement, no in-app behavior data could be collected.

In contrast to the large-scale application studies, single application usage behavior has also generated a lot of interest (e.g. McMillan et al. [146]). Here, the redesign and

deployment of a Windows PDA game onto a new mobile platform was investigated using in-app communication with users, as well as evaluations taken from social media sites. As the developers, the in-app access was unbarred, and this freedom was used to gather complex data about the game *Hungry Yoshi* and its users, although most researchers do not have this luxury.

An alternative to gather application usage data requires an additional program to "contain" the application in question and run in the background while normal use occurs. The data collected by such studies is also of high quality (in comparison to the above), and allows us to get a glimpse of what happens whilst the user is interacting with the application. The in-situ approach used by Carrascal and Church investigated mobile search application behavior by creating an application which acted as a "wrapper" for a popular search engine on Android. The resulting logged data of the application from 18 users, together with qualitative interviews and a daily on-line diary over the course of two weeks revealed how this data can be used to enrich the mobile search experience and help users complete their information search [41].

2.2.2 Map Usage

Although there is limited information about interaction with mobile map applications, the study of user engagement with maps has already been a subject of research back in the era of paper maps. In 1987, Blades and Spencer [25] wrote a review about some of the current research on maps designed for navigation. Despite of the importance of these maps themselves, they acknowledged the little research that had been done on how people actually use them. Blades and Spencer were mainly concerned with the cognitive abilities that go into using a map for way finding and the usability of the map itself but highlight the lack of empirical studies that produce sufficient data on everyday map use to make these analyses.

The current situation does not look different. There are only a few studies that have sought to understand how people interact with mobile maps and these have been limited to in-situ recording, self-reporting, corpus analysis of offline data sets, or do not produce in-app usage data. Methods such as self-reporting and taking screenshots during normal use produced a valuable overview of issues with navigation (in particular when driving) for *Google Maps* [150], but this data was limited to analysis of user behavior and comments as a result of application usage, and did not record the issue in real time.

Corpus analysis has proven valuable in identifying feature gaps in map applications from analysis of themes common in catastrophic accidents [126], and can identify omissions in particular map areas. These themes also enable application developers to generate new routing software which takes into account features such as inclement weather and improving instruction quality, however – although there is no real-time usage data of the application to provide detailed analysis of user behavior, this work shows the value of studying user behavior to identify patterns.

Of the literature reviewed, the most in depth analysis of *Google Maps* (or any other map application) was conducted by *Google*, but as a result, only limited data was shared with the research community [182]. As developers, they had unparalleled access to user data, and used their findings to improve the *Google Maps* experience. To collect the data, 24 participants (from four countries) were recruited from a pool of volunteers, and paid to use a version of the main application for a period of two weeks. The data collection also included a qualitative component (as with Carrascal et al. [41]) of telephone interviews and a debriefing session in order to understand particular usage behaviors during the study period. With this being the first field study that investigated *Google Maps* usage they were able to understand "real" goals of users which they could address in the interviews and "real" intervening factors that could be addressed by future design changes. This highlights the benefits of collecting "real", organic data to identify "real" problems and characteristics of mobile map usage behavior.

Although the previous work is the most comprehensive view of *Google Maps* to date, it was not a completely unsupervised data collection, and focused on a now outdated version of the application (2007). The above paragraphs highlight a need for current, detailed, usage data for mobile map applications from real-world usage which can only be obtained by tracking in-app behaviors from unsupervised users. We use *Google Maps* in the mobile environment to gather unsupervised usage data as it is not only the fourth-most-popular application [70], but it is the most used mobile map application within our two samples. We follow the naturalistic application use in order to provide an in-depth analysis of mobile map application behavior with which we can enhance our understanding of this type of app and suggest implications for the ongoing design and development of the navigation and exploration experience.

2.3 Experimental Studies

In order to answer the questions posed in the introduction this paper presents two studies. Study 1 was conducted in Bremen, Germany with 28 local participants over the course of four weeks using our *MapRecorder* application. Study 2 was conducted in Madeira, Portugal with 6 tourists (non-locals) during a period of one week using the *MapRecorder* application. The following section will describe both study designs and their differences. Study 1 employed a three-stage process in order to collect mobile map application data involving a large-scale pre-survey, the use of our "wrapper" application *MapRecorder* and a qualitative interview at the end. Study 2 did not include any interviews and had a post-survey after the use of the *MapRecorder* application.

The details of participant recruitment, the design of *MapRecorder* and its functions as well as the design of the interview are described in the following sections.

2.3.1 Survey & Participant Recruitment

Study 1

Online survey participants (n=159) were recruited via the university's social media sites (*Facebook* and *Twitter*), by word of mouth, and from internal advertising. Our survey comprised of five sections and covered basic demographic data, type of smartphone, map application preference, how often the map application was used, and what it was used for (e.g. getting directions, searching for the location of a place). At the end of the survey, participants were invited to sign up for the user-study by downloading the *MapRecorder* application. As *iOS* was the preferred operating system among survey participants they then received a link to download *MapRecorder* from the *Apple App Store* and were asked to use the app for all of their mobile map-needs for the next four weeks. Participants who signed up and completed the *MapRecorder* study were given a 20 Euro voucher.

159 participants completed the survey and 49 downloaded and installed the *MapRecorder* application and used it at least once. To ensure a valid comparison between the two different user groups (locals and tourists) and to only count "active" users, we filtered out non-local participants and participants with less than five sessions in the study period. In total, 28 participants (15 male and 13 female) from the local area (within 100km from the university) between the ages of 20 and 47 completed the survey and used the *MapRecorder* application regularly until the end of the study period (which they were reminded of one week in advance). The data of these 28 participants was later on used in the analysis. The consent to take part in the study and data collection was given on the

splash screen of the *MapRecorder* application at its first launch. After the experiment eight participants agreed to a follow up interview.

Study 2

Six cruise ship tourists (4 male and 2 female) between the ages of 38 and 58 were recruited on three different days (arrival days of the cruise-ships) within the week the experiment was conducted. Since they spent only up to a day on the island and had the cruise ship as a fixed start and end point of their visit, they made for the ideal tourist group to approach. After they agreed to take part in the study and data collection, by signing a consent form, they could choose a device with their preferred operating system (*iOS* or *Android*, as we were not able to determine their preferred operating system beforehand) with the *MapRecorder* application already installed. They were then free to explore the island on their own terms. The average day trip during which they used the application lasted 4 hours and 15 minutes (sd: 86 minutes) and was mainly taking place in the capital Funchal. Upon return they handed back the smartphone. At the end of the experiment they were asked to fill out a survey which comprised of three sections and covered basic demographic data, map application preference, how often the map application was used, what it was used for (e.g. getting directions, searching for the location of a place) and whether they use their map application differently on vacation.

Our sample, usage period, and methodology are in line with other influential studies which explore similar user behaviors and are documented at prominent HCI conferences. We ensure that we have sufficient participant numbers to be able to make sound inferences about the data as with [12, 41, 175], and that the study period covers at least several weeks to gain an accurate overview of what constitutes regular use [33, 60].

2.3.2 MapRecorder Application

In order to collect detailed, organic user behavior data we designed and developed a mobile application called *MapRecorder*. As noted above, *MapRecorder* is a "wrapper" application that allows users to interact with the *Google Maps* website as normal and unobtrusively records usage data. We make use of the `WebView` class provided by the *Android* and *iOS* SDK respectively to display the *Google Maps* website within our *MapRecorder* application. This allows us to deliver the same user experience as the original website and at the same time record device and website data as described in the next sections. *MapRecorder* was built to run on *iOS* and *Android* devices and allows the

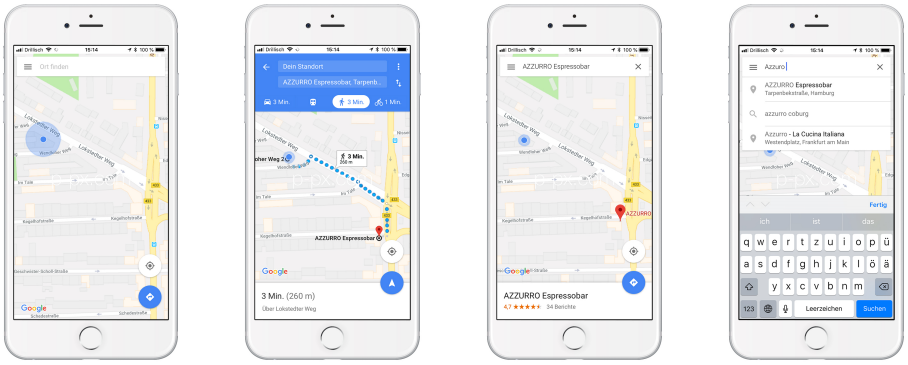
Google Maps web-interface to be shown in full screen. A session with a unique ID is generated from the time the application is opened until it is sent to the background, and the resulting session data is sent to a remotely hosted server.

2.3.3 Logged Data & Interaction

The *MapRecorder* application is able to record the following information for each session (a session is defined from the time the user opens the application until the time it is sent to the background):

- Unique session ID,
- User ID
- Device information: Phone type (e.g. iPhone 6S), resolution (e.g. 667 x 375), network connection type (e.g. GSM or Wi-Fi)
- Start of a session (as a timestamp)
- Duration of a session
- URL
- Timestamped interaction with the device: Compass orientation, device orientation (portrait/landscape), coordinates of touch-points on the screen, type of the touch interaction (e.g. pinch, tap), keyboard input
- Timestamped interactions with the map (e.g. change in zoom level, current center point of the map, current position of the user)

With this information we can subdivide the interaction with the mobile map application into four main states (see Figure 2.1) that also correspond to the main roles and functions of maps in general as described in [114, 115, 162]. Therefore we subdivided the interaction with the mobile map application into *Search, Place, Directions* and *Map-View Manipulation* corresponding to traditional GIS functionality such as answering questions like “where is...”, “what is...”, “what is the shortest route between...” and “exploration” [114, 115]. In our framework the *Search* state starts from the time the user starts typing a search query, until the time that they are redirected to a result, either by choosing one of *Google’s* auto-complete results or by immediate redirection. The *Place* state covers the time after a user has clicked on a place icon on the map or has



(a) (b) (c) (d)

Fig. 2.1 Screenshots of the *MapRecorder* application for each of the states: *Map-View Manipulation* (a), *Directions* (b), *Place* (c) and *Search* (d). Map data and image ©2019 Google.

been redirected to a place (e.g. a restaurant or a neighborhood) after a search. The user leaves the *Place* state when they either click on the map directly (discarding the place information) or they begin the directions to a place, which triggers the *Directions* state. During the *Directions* state the user is able to look up routes between a start and goal location. Users enter this state by either clicking on the directions button in the lower right corner of the application, or requesting directions whilst in the *Place* state. Users remain in this state as long as they interact or view the route or a route description, or as long as a start and destination is chosen. It is important to note that it is not possible to use the in-app navigation within *MapRecorder* since the mobile web version of *Google Maps* does not allow for it. On requesting navigation users get redirected to their natively installed version of *Google Maps* thus navigation could not be tracked. The state of *Map-View Manipulation* includes all interactions that are needed to manipulate the map view, e.g. *panning*, *zooming* and *viewing* the map.

2.3.4 Interviews

Study 1 included a semi-structured interview after the experiment with participants who have agreed to take part in a follow-up interview. With the help of a semi-structured interview guide the participants were asked questions about their behaviors and habits regarding their use of online maps and the patterns that became apparent through the map recording. This semi-structured guide allowed an open approach to the participants and their statements but also offered a focus to keep in mind while conducting the interviews. The interview guide, therefore, covered six aspects: (1) Personal background, (2) map



Fig. 2.2 Distribution of map usage states averaged over all users (study 1).

use, (3) perception of space, (4) linking to other services, (5) data privacy and (6) views and opinions. The participants gave permission for the interviews to be recorded and transcribed. In total, eight participants agreed and were interviewed for 15 minutes each via phone or Skype. The interviews were then transcribed and evaluated by two coders. Significant statements were paraphrased, coded and analyzed. Study 2 did not include any interviews.

2.4 Results

This section presents the results of both study 1 and study 2 separately. Study 1 presents a study with 28 participants and focuses on how local users use mobile map applications over a period of four weeks. We exhibit that locals in our study show a high percentage of map exploration, a tendency to search for specific places instead of entity classes and that they utilize specific usage patterns within the application as well as other user behaviors. Study 2 on the other hand presents a study with 6 participants that tries to understand the mobile map usage behavior of tourists. We find a lot of overlap in the results of both groups but cannot find indicators for usage patterns in tourist's usage behavior.

2.4.1 Study 1

The results for the preliminary survey and the *MapRecorder* analysis are outlined below providing a statistical overview of the study, as well as describing the user-states identified within the *Google Maps* application (e.g. *Map-View Manipulation*, *Directions*, *Place* and *Search*). This is followed by an analysis of patterns of interaction between those states and a detailed breakdown and analysis of specific findings for each state.

Online Survey

The survey recruited 159 participants between 19 and 65 years of age (average: 28). Ninety of the participants were students and other occupation types ranged from journalists, to nurses and engineers. Over 61% of respondents were from Germany (98 people) and device type was split between three types of operating systems with the most popular

being *iPhone* (49%) and *Android* (48%). The results indicate that *Google Maps* was the preferred map application with nearly 80% of users flavoring it over its competitors such as *Apple Maps* (14.5%) or *Waze* (around 2%) amongst others. Within the subset of *iPhone* users, exactly two thirds chose *Google Maps* as their preferred map app, despite the availability of the iOS native *Apple Maps*. We see the same trends in our smaller *MapRecorder* user group which utilized the application throughout the study period.

For general map application usage, 11.3% of participants reported that they use a mobile map application every day, 39% use it multiple times in a week, 27% use it only a few times a week, 19.5% use it only a few times a month, and 3.2% use it very infrequently. This high usage pattern is consistent with recently measured map application popularity [70]. The reasons given for using the applications were (in order of popularity): to search for a location or place (86.1%), for walking directions (83.6%), for driving directions (71.7%), to explore the map (50.9%), or to get public transportation directions (49.7%). Of these 159, 28 (15 male and 13 female) were local users (within 100km from the university) between the ages of 20 and 47 (avg: 30) who used the application more than five times during the study period. These 28 participants were used for the following data analysis. 22 of them were university students from different subjects, the remaining participants came from a variety of disciplines.

Overview of MapRecorder Data

In total 443 sessions were recorded for 28 participants, resulting in 483 minutes of total application usage time. This corresponds to an average of 15 (median: 11) sessions and 17 (median: 8.6) minutes per participant over the study period. The average application session lasted 65 (median: 44) seconds (similar to the 71.56 second average found in Böhmer et al. [33]), with a range of 3–751 seconds. In the following sections we first analyze the high-level user-data, looking at how the previously defined usage-states are distributed across users and user-sessions. We then provide insights into the usage-patterns that can be observed between users. We also present analyses of the four usage states individually as well as examining other user preferences and interests.

Overview of Interaction States

When analyzing the average session states (*Map-View Manipulation*, *Directions*, *Place* and, *Search*), we found that users spent around 67.5% of the length of a session in the *Map-View Manipulation* (M) state, 21.1% in the *Directions* (D) state, 8.2% in the *Place*

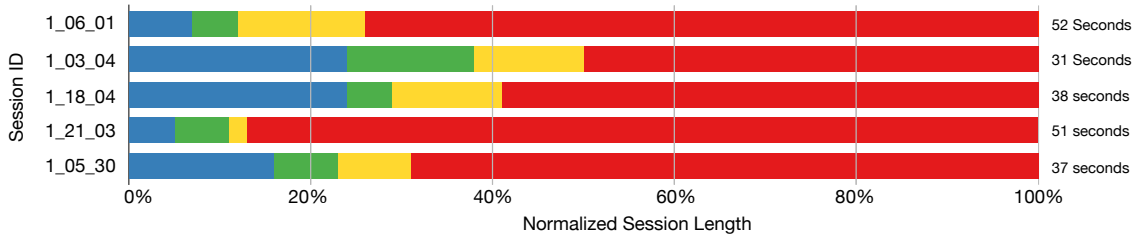


Fig. 2.3 Example MSPD sessions. From left to right: Map-View Manipulation (Blue), Search (Green), Place (Yellow), Directions (Red). The session ID is composed of: *Study_ParticipantID_SessionID*.

(P) state, and the remaining 3.2% in the *Search* (S) state. The average session states for all users can be seen in Figure 2.2. Further analysis revealed a repeating usage pattern across sessions by different users across the data set. When looking at the user transition between states, we discovered that MSPD (*Map-View Manipulation–Search–Place–Directions*) is a typical session pattern. An example of MSPD session data is shown in Figure 2.3. The two most common sequences were MSPD (12.1% of all sessions – 54/443) and MD (13% of all sessions – 58/443), indicating that at least 25.1% of all sessions resulted in getting directions.

In the case of the MSPD pattern, users typically started by examining the map for a short amount of time (M). This ranged from a few seconds (for example thinking about their search term) to 20+ seconds of proper map interaction including touch input. They then began to enter a query into the search bar (S). After issuing the search request

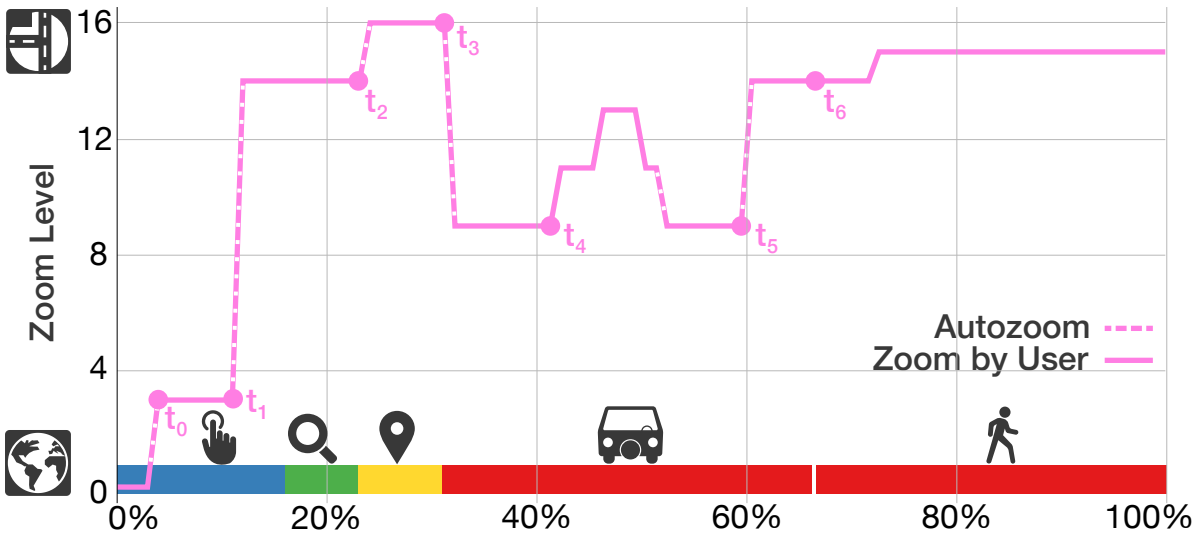


Fig. 2.4 Usage-session annotated with zoom levels; user 5 session 30.

they then got directed to the place that they were searching for (P). Finally, they use the directions button to bring up directions menu for the currently active place (D), usually with their current location set as the origin.

To explore additional user interactions, we also plotted a typical MSPD session (session 30 from user #5) with annotations including the zoom levels (automatic/user) and URL data (e.g. mode of transport) in Figure 2.4. This is indicative of a typical user session with *Google Maps* from our data. The graph shows how the automatic changes (dotted lines) in zoom levels are co-located with the state transitions. Transitioning from *Search* to *Place* automatically redirects the center point of the map to the searched location, and then adjusts the zoom level as necessary to fit the content of the screen. *Google* tries to estimate zoom levels according to the area around a certain place, or according to the distance between two locations (e.g. automatically zooming out for places that are further apart). Users also sometimes manually adjust these zoom levels which is indicated by the solid lines.

Figure 2.4 shows the following interactions: 1) After loading the map (t_0), the default location of *Google Maps* is displayed – t_1 indicates the time at which the application locates the users' position and automatically redirects the center point of the map towards them; 2) The user issuing a search query results in a place (t_2) and the app again auto-zooms and pans toward that location; 3) Timestamp t_3 indicates the point at which the user touches the "directions" button, and thus requests directions to the chosen place (resulting again in an automatic zoom and map adjustment to match the route); 4) t_4 demonstrates a short time frame within which the user manually adjusted the zoom level; 5) The user then changes the start and endpoint of the route, and the map automatically adjusts again (t_5); 6) At t_6 the user changed the mode of transportation from car to foot, and finished the session by zooming in, probably to get a better look at the exact route.

Map-View Manipulation Analysis

Map-View Manipulation yields the highest average usage time of any state during the study (67.5%). The data collected for this includes panning, zooming, "glancing" and map loading times (the latter accounting for 7.6% of all sessions). This shows that users are generally interested in exploring the map in an organic manner [18, 88]. *MapRecorder* is able to log the zoom level of a session as well as the various center points throughout the session from which we are able to infer panning behavior. For these behaviors, it is difficult to distinguish between (1) zooming/panning behavior by the system, and (2)

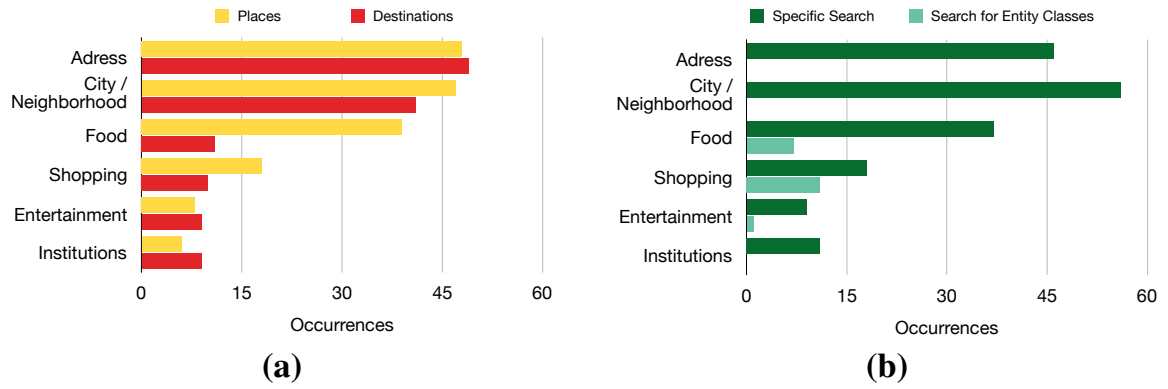


Fig. 2.5 Total occurrences of places and destinations (a), Total occurrence of specific- and entity class searches (b).

zooming/panning behavior of the user, but we are able to infer individual incidences of this behavior (as in Figure 2.3).

We discovered that 221 sessions out of 443 only contained the *Map-View Manipulation* state. In 167 of these cases, participants simply used panning and zooming to explore the surroundings, but we were able to record an average of 290 touch events (user making contact with the screen) per session. Further, 54/221 sessions did not contain any touch events and 20 of those we classify as *glances*, meaning that users reopened a session shortly after sending it to the background and glanced at the map without additional interaction.

Directions Analysis

Although users were not able to use the in-app navigation in our wrapped version of *Google Maps*, *Directions* was the second most frequently used state (21.1%) apart from *Map-View Manipulation* (requesting navigation redirected users to their own installed version of *Google Maps*). This shows that our participants were using it to inquire about distances and modes of transportation between two locations. We analyzed and categorized the destinations for which users requested directions to get an overview of the types of destination that users were interested in (Figure 2.5 (a)). We used *Google's Places API* to generate low level categories for each of the destinations and summarized these into six top level categories: *street addresses*, *city/neighborhood*, *food*, *shopping*, *entertainment* and *institutions*. Almost 70% of all destinations were categorized as *street addresses* or *city/neighborhood* as can be seen in Figure 2.5. Additionally, we were able to observe the preferred mode of transportation from the URL between two locations.

Figure 2.6 shows that the *Car* routing seems to be used for most distances (median: 6.86 km), with motorized transportation of all types being increasingly chosen for trips over longer distances.

Place Analysis

In our data set, 8.2% of the average interaction time was related to places (Figure 2.2). After categorizing the individual places (in the same manner as presented above) we found that most places referred to specific *street addresses* and *city/neighborhood* names, followed by *food* related places like restaurants and cafes. The categories *shopping*, *entertainment* and *institutions* (in this order) were also popular places users explored (see Figure 2.5 (a)). We also explored the distance of places that users were interested in. The median distance from the place users were examining compared to their current location was 8.02 kilometers. This rules out immediate walking distance as an option (walking 8km takes an average of 100 minutes), but as a large number of the locations studied lie within 100 kilometers we consider this being in the local area.

Search Analysis

MapRecorder is able to log the character-by-character input for search queries. This allows us to analyze not only what participants search for, but also their general search behavior patterns. As *Search* in most cases acts simply as a means to reach the users' goal or point of interest on the map, it accounts only for a small part of the session time – but this is still an integral part of the *Google Maps* experience – as *Search* was used in every second session. In our data the search behavior accounts for 3.2% of the total recorded time (Figure 2.2).

To examine the semantics of search behavior, we evaluated all 254 search queries contained within our data set (see Figure 2.5 (b)) and categorized them into specific search types (address, *Antonio's Pizzeria*, etc.), and entity classes (restaurant, hotel near me, etc.). We discovered our users made 220 specific searches, and 29 entity class searches, which suggests that users typically knew the name of the place they were looking for in advance, but since our sample was local to the area, we would expect the number of entity class searches to be low (locals have existing knowledge of particular locations). Additional investigation also revealed that 162 of all searches made use of the *auto-complete* function, meaning that *Google Maps* is successfully pre-empting the users' input in more than 50% of all searches.

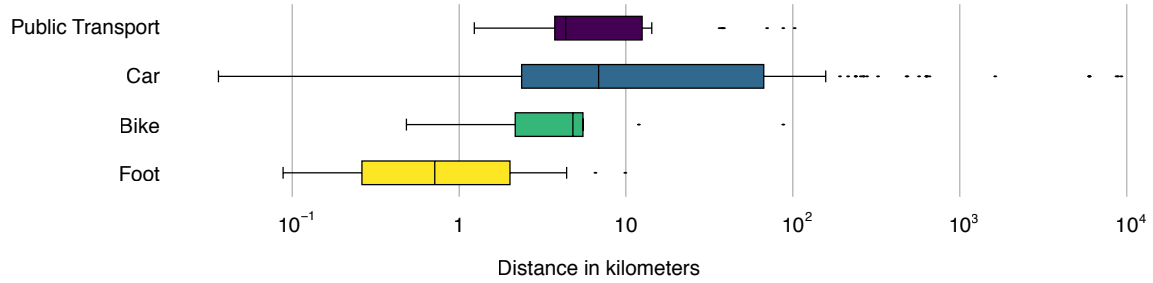


Fig. 2.6 Relation of distance and mode of transportation.

Finally, we take a look at the differences and connections between the *Search*, *Place* and *Directions* categories from Figure 2.5. Since we have found a very prominent usage pattern we wanted to see what conclusions we can draw with the MSPD usage pattern in mind. Generally, all the occurrences in the categories between the states overlap rather well, which is what we assume because of the MSPD pattern. A search term results in a place, which then gets chosen as the destination for directions. But for some of the categories we see differences. Most interestingly, in the *food* category a place does not usually result in a destination. This could be explained by the nature of how *Google Maps* displays information about restaurants. Things like opening hours, the menu and reviews can be enough of a reason to look at a place without the immediate need to look at directions for it.

Interviews

The qualitative content analysis of the eight interviews showed three topics to be significant in using mobile maps: (1) Additional benefits in using *Google Maps*, (2) triangulation of navigation options and (3) data security. Interviewees described several features of *Google Maps* as particularly useful in addition to the actual navigation services. These were real-time information on traffic and traffic jams, reviews for restaurants, bars and the option to, for example, look at their websites and menus directly, information on public transport and exploring places as in mobile sightseeing tours, e.g.“[I also use Google] if I’m just looking for the nearest ATM or a good restaurant. [...] And then you can immediately have a look at reviews and stuff” (ID 1_03).

While Interviewees appreciated the benefits of using Google Maps, they simultaneously expressed a mistrust of traditional navigation systems (such as in-built car navigation software). As a consequence, they perform a triangular navigation when

planning a trip: They use traditional maps, navigation apps on mobile devices and plan the route beforehand using a navigation web-service on a computer in order to check that the options given are optimal, e.g."So, in the car I have a TomTom. [...] I then use Google in between because sometimes the routes are a little different or you want to see if actually the map is the way the navigation system sends you and if it makes any sense" (ID 1_19). If participants have local knowledge, they will also juxtapose their own past navigation experiences with information currently received through the devices mentioned. A third theme which transpired through the interview material is that of data security. Especially tracking services were considered with a degree of ambivalence. On the one hand, they simplify navigation and support participants in their everyday life. On the other hand, the participants are not certain that their data is handled in an ethical and responsible way, e.g. "I'm really bickering about the insane support I have through such [navigation apps] and the loss of self-control and that feeling of being remotely controlled" (ID 1_26). Interestingly, we found two re-occurring story lines in the interview data: People had either "given up" and tried not to think about their digital traces any longer. Or alternatively, they were engaging in some form of a resistance or "minimal data"-strategy by activating the geolocation service as little as possible. Thinking about current and future development within the realm of mobility brought similar results regarding a sense of ambivalence and ultimately, for some of our interview partners, raised questions around freedom, decision making and possible mismatch of information they needed to make informed choices and information withheld by a variety of agents.

Summary

Our analysis outlines a combination of high and low-level findings, highlighting usage patterns that occur repeatedly throughout the data set. We have shown a coherent model of an example session that demonstrates the range of data that the *MapRecorder* application is able to collect (Figure 2.3). We also show how the different characteristics of each state within *Google Maps* are linked through the usage patterns that we identified during the study period. It is apparent that the most used – and maybe therefore most interesting – interaction is the *Map-View Manipulation*. This challenges our notions of prescriptive user behavior in navigating with online maps. From the interviews we learn that users intentions and behavior are not only driven by in-app factors but are also influenced by



Fig. 2.7 Distribution of map usage states averaged over all users (study 2).

secondary factors like trust and security. How we can utilize these results, and what the implications of the findings are, is explored in the discussion.

2.4.2 Study 2

The results of study 2 are presented in the same order as the results of study 1. We describe the survey results and the analysis of the *MapRecorder* data, provide a statistical overview over the study and as before the usage data is classified according to the usage states (M, D, P, S). Even though we compare some of the results from study 1 with the results of study 2, it is important to keep in mind that study 1 focused on local users using the application over a four week period whereas study 2 investigated non-locals' behavior over one day of application usage.

Survey

The survey was taken by all 6 participants whose age ranged between 38 and 58 years (average: 52) with the occupations of electrical engineer, druggist, clerk and plumber. Five respondents were from Germany and one from Switzerland (all German speaking). Three of them have never been to Madeira before, two answered that they have been on the island once and one participant was there multiple times before. The results indicate that *Google Maps* was the most preferred map application with 83.3% of users favoring it over its competitors. The only alternative map application that was mentioned by one participant was *Ulmon* (which is popular with tourists for its elaborate offline functionality). For general map application usage, 33.3% of participants reported that they use a mobile map application multiple times a day, the rest uses it only occasionally. The reasons given for using the applications were (in order of popularity): To search for a location or place (83.3%), for walking and driving directions (66.7%), to explore the map (33.3%), or to get public transportation directions (16.7%). Half of the participants reported that they are using their map application differently when being on vacation. They use it more often, more detailed or they do not look up traffic information, whereas at home they do (which is in line with our results from study 1).

Overview of MapRecorder Data

In total, we recorded 112 sessions for 6 participants, resulting in 97 minutes of total application usage time. Every participant produced an average of 19 (median: 19) sessions and used the application for 16 (median: 13.1) minutes over the study period. The average application session lasted 52.29 (median: 35.32) seconds, ranging from 1.4 - 303 seconds. In contrast to study 1 we found that users had shorter and overall more sessions. In the following sections we analyze the high-level user-data, looking at the distribution of usage-states across users and user-sessions. We examine the data for some of the usage-patterns that we found in study 1 (e.g. MSPD, MD) and present analyses of the four usage states (*Map-View Manipulation*, *Directions*, *Place* and *Search*).

Overview of Interaction States

When looking at the usage states of the tourist users we found that they spent around 64.6% of their overall usage time in the *Map-View Manipulation* state, 20.6% in the *Directions* state, 11.8% in the *Place* state, and the remaining 3.0% in the *Search* state. Figure 2.7 shows the overall average of this distribution. In contrast to study 1 we did not find any particular usage patterns (e.g. MSPD, MD) across the data set. The most common sequences were exclusively *Map-View Manipulation* (56/112) and exclusively *Directions* (15/112). This shows that in half of all sessions participants just used *Map-View Manipulation*, similar as in study 1.

Map-View Manipulation Analysis

With 64.6% *Map-View Manipulation* also yields the highest average usage time of any state during this study. We discovered that 56 sessions out of 112 only contained the *Map-View Manipulation* state. In 45 we found touch gestures suggesting that participants used panning and zooming to explore the the surroundings. This observation leaves 11/56 sessions without any interaction, which we were not able to classify.

Directions Analysis

Directions was the second most frequently used state (20.6%) in our data set. We again analyzed and categorized the types of places for which users requested directions to get an overview of the top six categories of destination within the area, which were very different from the ones we found in study 1: *culture*, *area*, *park*, *food*, *shopping*, *church*. The destinations were more evenly distributed across those categories than in study 1 as Figure 2.8 (a) shows. In total 39 destinations were searched for of which 21 used

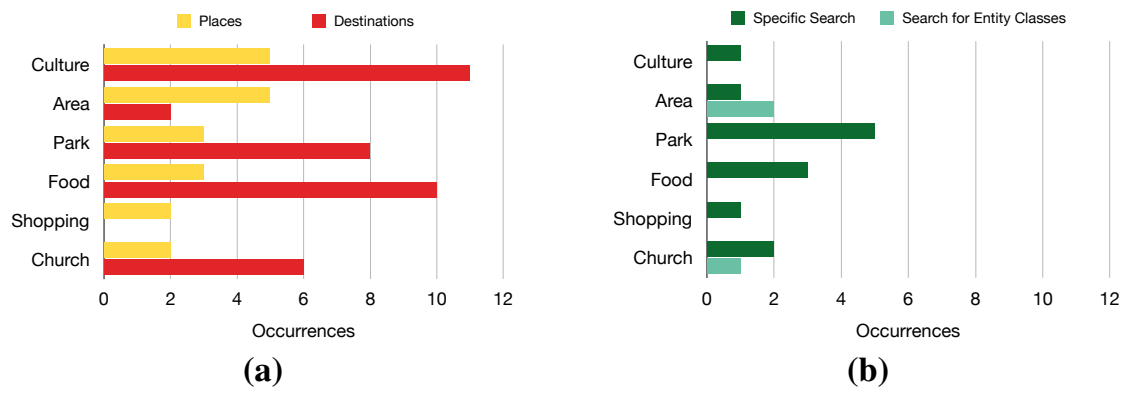


Fig. 2.8 Total occurrences of places and destinations (a), Total occurrence of specific- and entity class searches (b).

information for navigation by foot, 17 by car and 1 by public transport. Figure 2.9 shows that participants inquired mainly about very close distances (median: 0.378 km) to be reached by foot. For transportation by car the median distance was 1.74 km. This can be explained by both the size of the island (76,15 km^2) and the short time they spent there (less than a full day).

Place Analysis

11.8% of the average interaction time was related to places (Figure 2.7).The places participants were interested in all relate to sightseeing, food or shopping and were located quite close to the participants location. As Funchal, the capital of Madeira is quite small and cruise ship tourists usually spend the day close to the ship we expected tourists to not travel too far from there. This was confirmed by our data as we found a median distance of 490 meters between the users current location and the place on the map they were interested in.

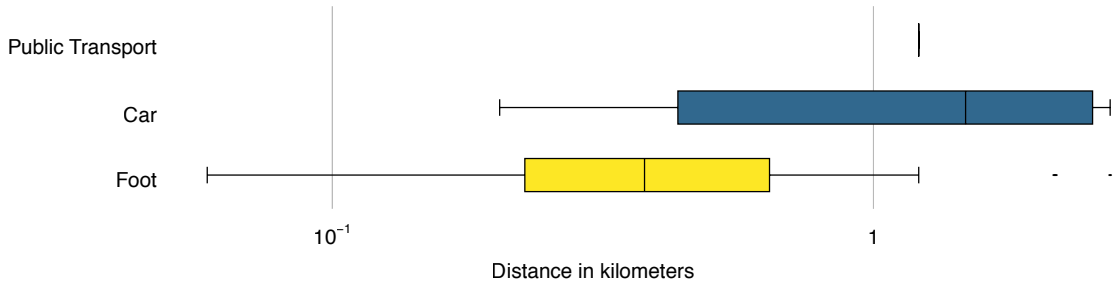


Fig. 2.9 Relation of distance and mode of transportation.

Search Analysis

The search behavior accounts for 3.0% of the total recorded usage time (Figure 2.7) which is made up of 19 searches in total (a relatively low number compared to study 1). We discovered that of these 19 search queries our users made 16 specific-, and 3 entity class searches (see Figure 2.8 (b)). So tourists do not seem to search for entity classes more than locals do. By looking at the difference between Figure 2.8 (a) and 2.8 (b), we can make assumptions about what kind of places are being most often explored with or without search. Two of the most prominent examples where we can observe this are the *Culture* and the *Food* category. Here searches are very limited even though those are the most frequent categories when it comes to places and destinations. Also the destinations have a lot more occurrences than the places. This suggests that participants more often got directions to a place directly without going through the *Place* state first which is supported by *Directions* being the second most frequently used usage pattern.

Summary

The analysis of the data collected from tourists give first insights into how this user group uses mobile map applications. We have shown a general overview over the state distribution that indicates a high portion of it being *Map-View Manipulation*. We found that users are mostly interested in places that are within walking distance and that they do not search a lot for entity classes and places related to *Culture* and *Food* are usually explored without search. Being a small study the results presented above should not be generalized (even though some results look promising due to their similarity) but guide future studies that want to investigate tourists as mobile map users.

2.5 Discussion

Mobile map application usage is a complex set of behaviors and interactions that tells us a lot about how people explore the world around them in the digital age. We have shown that our approach makes it possible to collect valuable data to give insight into the regularities and exceptions of mobile map usage behavior. Looking at two different user groups we can give first insights into how mobile map usage behavior may vary between different users and think about consequences this can have for future designs of mobile maps. In the following we discuss the findings, compare some of the results and talk about limitations of our approach.

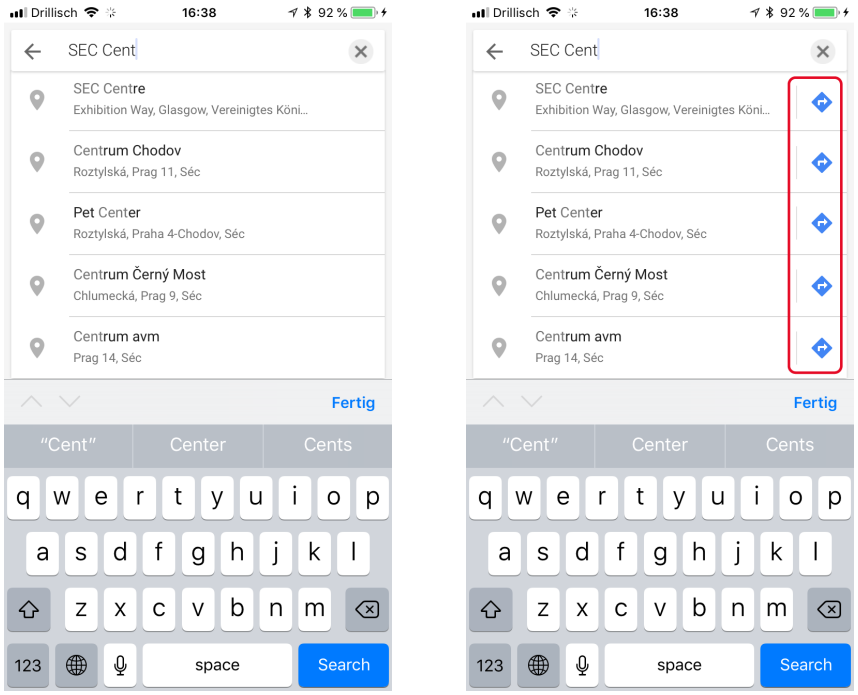


Fig. 2.10 Example of design changes inspired by the MSPD and MD pattern. Original interface (a) versus design changes (b). Map data and image ©2019 Google.

People like to explore maps, either through necessity or curiosity, and this is reflected through the high usage times in the *Map-View Manipulation* state in both studies. When taken in context of the other states of map use, this might be indicative of a preference for agency during search. This predisposition of users to engage largely in the *Map-View Manipulation* state is a suggestion that this interaction should be made as rich and meaningful as possible. This fits evidence stating that exploratory search is a widely adopted behavior to look for information on the web [88], and that users enjoy panning and zooming to explore their area [18]. In the interviews users mentioned exploration and information retrieval, like looking up restaurants' menus or homepages, as crucial parts of the mobile map experience. Some of our users even reported using *Google Maps* without location services turned on completely neglecting the navigation aspect of it (referring to the native application). These behaviors support our intuition that mobile map applications are no longer just used to get from A to B but also serve as an important source of information beyond that.

We see indications that this is already picked up on by industry with *Google's* ever increasing number of *Place Icons* within its maps [155] as well as the recent introduction

of the "explore menu" [127] to *Google Maps*. This menu exactly taps into the *Map-View Manipulation* state and introduces new ways of exploring your surroundings and finding the information you need more quickly. Only future investigations can show whether this is an adequate substitute for exploring the map yourself.

2.5.1 Implications

In study 1 we were able to identify complex usage patterns whilst examining the whole corpus of data collected over the month the study was active. Patterns like MSPD or MD showed us that users find different ways of accomplishing their goal of information retrieval in an mobile map application. This information could potentially influence the design of future mobile map services as with the knowledge about usage patterns effective shortcuts can be developed (see Figure 2.10). Study 2 however did not reveal those patterns. This could hint towards a unique quality of tourist users but could also be explained by the lack of a sufficiently big enough data set.

The low usage incidence of searching for entity classes was observed in both studies showing that most of all users locals and tourists alike rather search for the actual name instead of the entity class. We think this points toward the conclusion that text search is not the preferred way to look for entity class information. Again here we find support in the current developments in industry. Instead of searching for restaurants or hotels "around you" *Google* now offers this information within their "explore menu" [127], which our data suggests will be helpful for local and tourist users alike.

2.5.2 Limitations

Our results and findings are based on a thorough data collection and analysis. We incentivized users to comply with this data collection and found no indications in our data, that they did not. By excluding participants with less than five sessions, we also tried to filter out participants who would only do minimum work to receive the reward (they were not informed about the five session threshold). Still, unsupervised data collection bears the risk of collecting artificial usage data or missing out on a certain amount of usage data that is produced outside the tracking possibilities of the study. As we report earlier *MapRecorder* is not able to track in-app navigation. Thus whenever participants wanted to use this feature they were redirected to their native *Google Maps* application. This is a common challenge researchers face in unsupervised data collection and is discussed in related literature as well [41]. We saw consistent usage over the whole study

period, and session lengths that are line with other large scale mobile app usage study and thus cannot raise any concerns.

Even though we are confident to have recorded genuine and organic usage behavior, with study 1 featuring 28 and study 2 featuring six participants we want to highlight generalizability as another important limitation. We agree with Church et al. [47] that our results can only be interpreted in connection to the participants of our study. We present quantitative findings and comparisons about usage behavior that is unlikely to hold to another population. We also agree that these studies still have great value, as the research community is able to combine and contrast different studies on usage behavior in different situations with different populations. This way we can build a better overall understanding of mobile users as we tie more of these behaviors together.

The large engagement in the *Map-View Manipulation* state is one of our most intricate findings. Due to the coarse categorization of the *Map-View Manipulation* we find it challenging to formulate well defined implications. Our study was supposed to explore this unexplored territory of mobile map usage behavior. In our findings on *Map-View Manipulation* and *Google*'s recent design changes to *Google Maps* we see great potential for future research that will be able to analyze this exploratory behavior in more detail.

2.6 Conclusion & Future Work

Our analysis considered the behavior of two user groups, namely local users and tourists. Study 1 looking at local users found a variety of behaviors, of which the most prominent are: A prevalence of exploratory behavior indicated by the *Map-View Manipulation* state, a search preference for named places instead of entity classes, and the use of specific usage patterns. Study 2 found similar results for the amount of *Map-View Manipulation* and the search behavior but is lacking any indication of usage patterns. The results of study 2 can give first insights into how different user groups use mobile map applications differently (or like in our case, similarly).

With the technical constraints on recording in-app navigation this paper puts its focus on the actual map interaction and exploration. Nevertheless we acknowledge that there is already a big research corpus dealing with mobile navigation (e.g. [39, 93, 126, 141, 230]) and that contributing to this corpus with unsupervised usage data of navigation applications is a worthwhile goal to pursue. Adding a navigation component to *MapRecorder* could also give us valuable data to complement our findings presented in this study. Looking into other mobile map applications than *Google Maps* could help

us making steps into this direction in the future and could then tell us not only a lot about how we explore but also navigate the world around us. Till then this paper begins the process of shining a light on the high-profile black-box that is among the most used applications in the world.

We present an organic map application usage study using our *MapRecorder* wrapper application and *Google Maps* to understand and explore user behavior within mobile maps. In addition to two surveys of device and map application usage, we provide analysis for four main states of map interaction. We give one example of how this data can be used to compare ways in which different users (locals and non-locals) typically engage with these applications. We hope that these findings can help to provide context for mobile map research and practice, as well as to encourage the investigation of real-world, unsupervised application usage for other programs and in other domains.

3 Designing Novel Mobile Navigation Systems for Cyclists

Decoupling the design space for mobile navigation technologies resulted in mobile navigation systems designed for specific user groups. In this chapter we look at as-the-crow-flies (ATCF) based mobile navigation systems as an example of a novel system designed specifically for cyclists. ATCF route guidance, compared to turn-by-turn (TBT) route guidance, provides users with information about the general direction to the final destination (e.g. in the form of a compass needle). To investigate if cyclists can benefit from this route guidance, we experimentally compared ATCF to TBT. We identified common usage errors arising through the use of ATCF-based mobile navigation systems and then derived, implemented, and tested design implications. We found that cyclists showed a personal preference for ATCF route guidance for leisure biking. As part of our work we built an **artifact** in the form of an ATCF-based mobile navigation application. The building of the artifact utilized design implications from our studies. We carried out a field study with twenty-six participants who were testing both route guidance approaches. We then analyzed the **empirical** results of this testing.

The contents of this chapter originally appeared in Savino, Gian-Luca, Meyer, Laura, Schade, Eve Emily Sophie, Tenbrink, Thora, and Schöning, Johannes. “Point Me In the Right Direction: Understanding User Behaviour with As-The-Crow-Flies Navigation”. In: *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2020, pp. 1–11. ISBN: 978-1-4503-7516-0. DOI: 10.1145/3379503.3403539

3.1 Introduction & Motivation

Turn-by-turn (TBT) guidance is the default navigation method for most kinds of transportation modes, including bicycles. Its ability to guide people from A to B along a shortest or fastest path, using clear instructions about where to turn at each decision point, has been proven to be the preferred routing choice for most people already back in 1995 [78]. And in spite of many research studies that investigate alternative routing options like safest, simplest or most scenic [62, 106, 181, 237], the fastest route remains the default option in many car navigation systems more than twenty years later. In contrast to that, we now see novel navigation methods called "compass mode" or "as-the-crow-flies" being introduced into the commercial domain of bicycle navigation.

The as-the-crow-flies (ATCF) navigation method, while novel for most users, is not unknown to the research community. Instead of giving TBT instructions to guide the user, it indicates the general direction to the destination. It is a sub domain of mobile navigation research, and has its origins in the development of navigation methods for the blind [130]. When looking at bicycle navigation research many studies revolve around making navigation less intrusive, allowing cyclists to focus more on their surroundings as cycling in heavy traffic is not only demanding but also potentially dangerous [83, 126, 205]. This is often achieved by using auditory [4, 90, 97, 137, 238] or tactile [137, 167, 171, 214] cues to convey the navigation instructions. Other modalities include instructions conveyed through light signals inside the helmet [137, 222], on an external navigation device [227] or projections in front of the bicycle [52, 53]. Most of these navigation systems use TBT navigation, giving information on where to turn at each decision point. Some of them do use ATCF navigation, but only in combination with auditory or tactile cues. However, commercially available products [17, 27, 210] exclusively use visual user interfaces. The Beeline application shown in Figure 3.1 is one example and was used in our studies. The interface features an arrow that indicates the direction of the destination or the next waypoint and information about the remaining distance.

Based on related literature by Hochmair [95] and Albrecht et al. [4], we identified two main challenges that confront users of ATCF navigation: (1) knowing whether they are currently on a route leading to their destination; (2) knowing whether a potential turn might result in a dead end or detour. We studied these challenges of everyday use of visual ATCF navigation methods and by doing so contribute to the understanding of ATCF navigation. We conducted two studies:



Fig. 3.1 Beeline is a mobile navigation application with a simplistic interface. It consists of a single arrow pointing into the straight line direction of the next waypoint or destination and additionally displays the straight line distance to them. © Beeline.

- Study 1 compares a commercial implementation of ATCF with a commercial implementation of TBT navigation.
- Study 2 takes the insights of study 1 to build an improved version of the implementation and compares two ATCF navigation interfaces.

Both studies use an A/B testing design allowing us to observe user behavior related to the above mentioned challenges. We present quantitative data recorded from participants' performances (route length, number of errors, task load and orientation) and give insights about wayfinding and users' navigation behavior with ATCF navigation based on observations and interviews.

Our results show that whenever the destination lies in the opposite direction to the one in which the user is currently riding, users respond by either turning around or trying to find a different route, even if that means carrying their bike up a staircase. In order to travel strictly in the direction provided by the navigation system some participants even rode through private property. We derive and evaluate design implications to counter these reactions and improve users' confidence while using ATCF navigation.

In line with previous literature [4] we find that a basic implementation of ATCF navigation, as it is used in most commercial products, can have major disadvantages compared to TBT navigation when looking at navigation efficiency (reaching a destination as fast as possible without errors), at least with a route design like the one we used in our study. To explain these disadvantages we report on several situations that proved a challenge for ATCF navigation and test how much, if at all, these same situations affect TBT navigation. We present indicators that ATCF navigation can lead to improved orientation abilities, as participants had better knowledge of the direction of their initial starting position compared to TBT users. Furthermore, we confirm findings from Pielot et al. [167] that participants liked the ATCF navigation method for leisure biking.

Additionally, we identify that communicating *progress to the destination* during the navigation task is a very crucial aspect of building confidence. In our implementation this was communicated through the remaining straight line distance to the destination on the top half of the screen (see Figure 3.4a). However, this distance increased whenever participants were getting further away from the destination, which (apart from errors) naturally happened when they had to find a way around some obstacle (see Figure 3.6a and 3.6b). Being used to TBT navigation, where the distance to the destination continuously decreases, many participants associated the rising distance with negative feedback. This clearly impacted users' confidence about whether they were still on the right track.

3.2 Related Work

This section summarizes previous research relevant to ATCF navigation. We present the underlying wayfinding heuristic "Least-Angle Strategy" (LAS), followed by related research on ATCF in combination with auditory and tactile cues [4, 97, 166, 167, 168, 184, 238].

3.2.1 Least-Angle Strategy

The heuristic underneath the ATCF navigation method was first formulated by Hochmair in 2000 [94] and is called the Least-Angle Strategy: "At the beginning of the navigation, the agent perceives his navigation target [...]. He moves in a street network and navigates towards the target without using a paper map. At an intersection, he takes the road which has the least deviation α from the direct target direction. In a city, physical objects often block the direct view to the target. Then [...] estimations of directions and distances, especially of a reference direction, need to be made. The estimations can be disturbed by

estimation errors" [94]. ATCF navigation aids are designed to eliminate these estimation errors. Instead of keeping track of the direction towards the destination, which can be challenging after a few turns with no landmark to orient towards [96], one can make use of the constant direction indication for each navigation decision. This way the LAS can always be used to its maximum potential. Based on this description of the LAS and the way visual ATCF navigation like Beeline works, the following scenarios may occur in which people are likely to run into problems using LAS with ATCF navigation:

1. The user is generally uncertain whether the current route is progressing towards the destination.

2. There is a street that points in the direction of the destination, but the user is unable to see its end, so it might be a dead end or turn away from the destination.

3. Maybe as a result of previous situations, the arrow is facing in the opposite direction to the direction of travel (i.e., the destination is currently behind the user), and there is no immediate way to turn other than making a U-turn.

To better understand how users might deal with such scenarios, we look at related work addressing ATCF navigation methods with auditory or tactile cues.

3.2.2 Direction Conveyed through Sound

The idea of using spatial audio for navigation revolves around humans' ability to localize the source of sound [26]. In navigation this was initially explored by Loomis et al. (1998) [130] to build assistive navigation technology for the blind. They used spatial audio successfully to guide blind people along a predefined path in an open field environment. A few years later, Holland et al. (2002) built a first mobile version using spatial audio for pedestrians and car drivers. While they found that it was usable for locating targets on foot, it was insufficiently responsive to be used in a car [97]. The first time this approach was successfully used on a bicycle was in a study on spatial audio for beacon (ATCF) or route (TBT) guidance by Albrecht et al. [4]. They were able to route pedestrians and cyclists through a suburban environment using spatial audio in an ATCF manner. They used spatial audio to indicate the direction towards the destination and volume to present the distance between the user and the destination. In general they found that beacon guidance (ATCF) was preferred for more familiar surroundings and touristic exploration. Route guidance (TBT) was considered the better alternative for people in a hurry [4]. In

one condition they found that participants experienced uncertainty walking on a straight path with nowhere to turn toward the direction of the destination, as there was no way of knowing whether that street would eventually lead to the destination. This supports our intuition (cf. situations 1 and 2 above) that such scenarios are problematic for ATCF navigation users.

3.2.3 Direction Conveyed through Vibration

Auditory cues rely on a sense that is also used to identify possible threats in traffic. In contrast, the sense of touch is not otherwise required and thus available for input during cycling. This makes vibration an attractive choice for conveying navigation information.

Prasad et al. [171] created HaptiMotor, a vest for motor cyclists with multiple vibration motors that were able to indicate left, right, straight and U-turn at an approaching decision point. They show that HaptiMotor increases riders' situational awareness and that users found the mapping to be intuitive. A similar approach for cyclists is illustrated by Steltenpohl and Bouwer with Vibrobelt [214]. The tactile belt is worn around the waist and "gives waypoint, distance and endpoint information using directional tactile cues" [214]. They compared it to a visual route guidance system and found that participants using Vibrobelt had improved spatial knowledge acquisition. These two setups require the user to wear a dedicated piece of technology to receive the directional information.

A TBT-system built directly into the bicycle was used by Matviienko et al., who compared auditory, tactile and visual TBT instructions for child cyclists [137]. Auditory navigation was the most preferred, but light- and tactile navigation cues were also positively perceived and found to be valid supplementary navigation aids for younger children. In their setup, the vibration was built into the handlebar of the bicycles. This made for a very straight forward mapping for TBT instructions. However, the same approach was also used to convey directional information for ATCF navigation in a study by Pielot et al. (2012) [167]. Instead of just having the left or right handle vibrate, the relative intensity of the vibration was used to cue the direction in relation to the bicycle's heading. They found that the cues were understandable and effective and that none of the participants lost orientation as long as haptic feedback was provided. One issue they identified was that people who were very familiar with TBT navigation still expected the system to give instructions at every turn despite very detailed instructions about the functionality of ATCF navigation. The study took place on a small, touristy, island. There were many alternative paths and the whole area was geographically constrained.

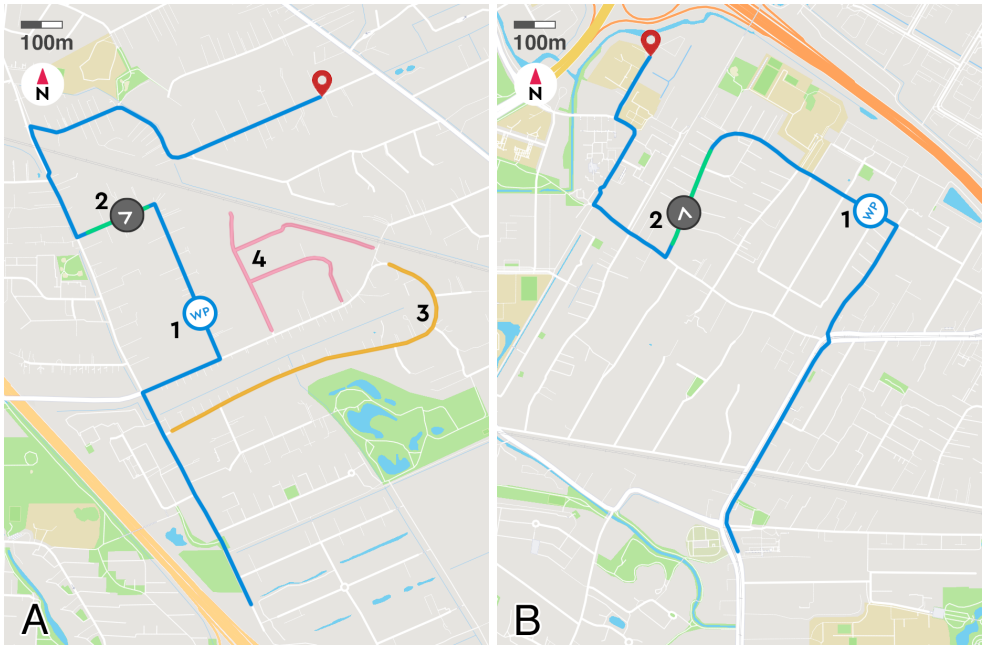
"Thus, [...] participants would usually find a way to their destination as long as they kept going roughly into the right direction, and they did not have to be afraid of getting lost by going into the wrong direction for too long" [167]. The results might, therefore, not be completely transferable to sub-urban city environments, where a wrong turn can sometimes lead to large detours and traffic is a more prominent factor while navigating. The authors concluded that ATCF navigation conveyed through vibration patterns works well for longer tours in unfamiliar environments [167].

3.2.4 Contribution

In this paper we extend the related research in two main directions: First, to our knowledge there is no previous research on the usability and performance of *visual* ATCF navigation methods. As ATCF navigation methods steadily increase in popularity, a better understanding of their performance is paramount for guiding their development from an HCI perspective. Secondly, little is known about user behavior while using ATCF navigation methods in contrast to TBT navigation. Most existing studies show that ATCF navigation can be used to successfully guide people from A to B. However, they deliver only limited results concerning everyday problems people might face in urban environments, like running into dead ends and knowing whether or not one is still on the right track. In order to create an experimental setup that allows to address both these issues we embedded the navigational task of riding in the opposite direction to the arrow into two user studies. The first one compared ATCF to TBT on two consecutive routes. The second one improves the ATCF navigation interface to include information about dead ends, detours and correct route choices.

3.3 Study 1 - TBT vs ATCF

The goal of study 1 was to evaluate the differences between visual TBT and visual ATCF navigation to highlight their effect on navigation performance, orientation and how both these systems deal with the aforementioned problem scenarios, focusing particularly on the arguably most disturbing situation (3) in which users find themselves riding in the opposite direction to the arrow. Participants used Google Maps as a representative TBT navigation system and Beeline as a representative ATCF navigation system respectively on two consecutive routes. Besides observing their navigation behavior, we tested the following hypotheses:



(a) **(b)**

Fig. 3.2 (left) Route A used in study 1 + 2, (right) Route B used only in study 1. Map annotations: (1) Waypoint; (2) Situations where the arrow points in the opposite direction; (3) Detour participants took in study 2 with ATCF+; (4) Dead end/detour area which caused problems for participants using ATCF. Basemap © Mapbox © OpenStreetMap.

H1: Given our route design, participants using TBT navigation will make fewer errors and produce a shorter route than participants using ATCF navigation.

H2: Participants using TBT navigation will have poorer orientation with respect to the direction of the initial starting position than participants using ATCF navigation.

3.3.1 Task & Procedure

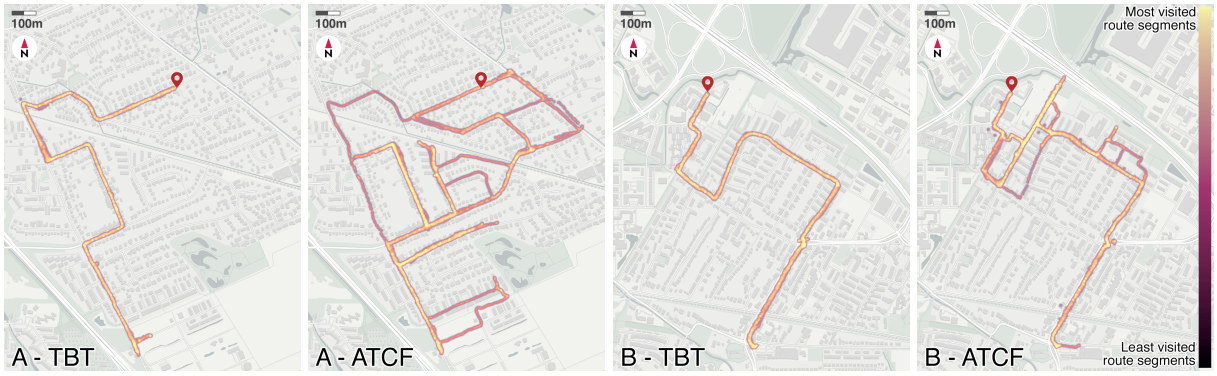
Each participant cycled two different routes (see Figure 3.2). Each started on route A and was randomly assigned a navigation method to start with, followed by the other method on route B. Thus, half of the participants used TBT navigation on route A and ATCF navigation on route B (condition 1), and the other half used ATCF navigation on route A and TBT navigation on route B (condition 2). Both routes were 2.45km long, had roughly 20 decision points (not counting private driveways) and low to medium traffic. Both were designed to include a part where participants would need to cycle in the opposite direction to the arrow (see Figure 3.2, number 2). To ensure that all participants would be routed into this situation, a waypoint was added to each of the routes (see Figure 3.2,

number 1). Participants were not shown a map in advance. For safety reasons and to reduce stress during the study, we explicitly told every participant that they were free to do the task at their own pace.

Before each condition, participants were introduced to the navigation method and application they were about to use (ATCF or TBT). They were explicitly shown how the arrow behaves and functions and could ask questions. After filling in a demographic questionnaire, participants cycled the routes on their own and met the experimenters again at the destinations. After each route, an in-between questionnaire about the route and experience with the navigation device, a NASA TLX questionnaire and an orientation test (pointing into the direction of the starting location) were conducted. The participants were questioned in a semi-structured interview about the navigation method they had just used, and were asked to express their opinion and describe their experience. At the end of the study, participants were asked to describe the difference between the navigation methods, and state which one they preferred and give further comments. The semi-structured interviews were loosely transcribed to capture their content, and evaluated.

3.3.2 Participants & Apparatus

We used a within-subjects design with 12 participants (9 male and 3 female, all university students) between the age of 23 and 29 (mean=25.15, median=25, sd=1.83). Most of them ride bikes on a regular basis and all participants had used Google Maps before but never the Beeline application (or any other kind of ATCF navigation service). Participants were asked to rate whether they were familiar with the study location on a scale from 1 (very familiar) to 6 (not familiar at all) and gave a mean rating of 4.79 (median=5, sd=1.37). Google Maps and Beeline were installed on an iPhone 6s, which was mounted to the handlebar of the bicycle (see Figure 3.1). The questionnaires were completed by the participants on an iPhone 7. Participants additionally received a Google Pixel 2 which logged the GPS position throughout the study. All of them had overcast weather conditions.



(a) **(b)** **(c)** **(d)**

Fig. 3.3 Heat maps of the uncorrected location data of all participants from the respective combinations of routes and navigation methods in study 1. Basemap © OpenStreetMap.

3.3.3 Measures

Completion time was recorded but not further considered as there are too many influential factors (e.g. traffic) unrelated to the conditions. Also, participants had been told to take as much time as they liked. For purposes of analysis we used the following definitions:

Dead end: A street with only one inlet or outlet.

Detour: A street segment that causes a longer route compared to the shortest path from the participants' position to the current destination.

The following five factors were measured.

Route length

The actual route participants took and its length was calculated from the GPS trace of their position (see Figure 3.3). Even with our best efforts to filter and clean the data, the GPS trace included variations unrelated to participants' decision making. Therefore we retraced the routes using openrouteservice [157].

Errors

An error was defined as an event where participants turned around after noticing or thinking that they had gone the wrong way, and returned using the exact same route that was used to enter the street (e.g. running into a dead end).

Task Load

The task load was measured using NASA TLX through the NASA TLX application provided by NASA [151].

Orientation

After each condition, participants were asked to point in the direction of the starting position using the native compass app of a freshly calibrated iPhone 6s. We calculated the deviation to the correct angle.

Wayfinding Behavior

In addition to the quantitative measures above we used our observations, questionnaires and interviews to understand and analyze participants' behavior, including the situation where they had to ride in the opposite direction to the arrow.

3.3.4 Results

All participants were able to complete both routes successfully. The following results are presented for each of the two routes separately. We used Welch Two Sample t-tests for normally distributed data (indicated by reported t-value) and Wilcoxon rank sum tests for not normally distributed data (indicated by reported W-value). To ensure that familiarity with the environment did not influence the results, we tested for correlations between our measures and familiarity. No correlation was found for any of them ($p > 0.05$).

Route Length

As expected, participants produced significantly shorter routes using TBT navigation in comparison with ATCF navigation. Because our TBT application was set to calculate the shortest path, even a small mistake or detour using ATCF immediately means a longer route. On route A, TBT based routes (mean = 2467m, median = 2450m, sd = 41m) were significantly shorter (W = 0, p = 0.0037 | effect size = 0.86, ci = 0.64-0.94) than ATCF based routes (mean = 4228m, median = 4282m, sd = 583m). Likewise, on route B, TBT based routes (mean = 2450m, median = 2450m, sd = 0m) were significantly shorter (W = 0, p = 0.0028 | effect size = 0.89, ci = 0.73-0.95) than ATCF based routes (mean = 3076m, median = 2882m, sd = 532m).

Errors & Riding In the Opposite Direction to the Arrow

On route A participants made a total of 14 errors using ATCF navigation compared to 1 error using TBT navigation. On route B participants made a total of 9 errors using ATCF navigation compared to 0 errors using TBT navigation. Most of the errors on route A included driving into a dead end whereas on route B the most frequent error was riding in the wrong direction with no way to correct but to turn around.

8 out of the 24 total errors were caused by participants having to ride in the opposite direction to the arrow. This happened to 4 participants on route A who turned around afterwards and to 4 participants on route B who found another route that led toward the target direction. This route required them to carry their bike up the stairs which they did despite of the instruction to not get off their bike during the ride. None of this behavior was shown by any of the participants using TBT navigation on either route.

Task Load

The task load was significantly lower for participants using TBT navigation on both routes. On route A the participants' task load using TBT navigation had a mean value of 36.7 (median = 34.5, sd = 14.5) compared to 55.8 (median = 54.3, sd = 12.5) with ATCF navigation ($t = -2.46$, $df = 9.8$, $p = 0.0344$ | effect size = 1.42, ci = 0.1-2.68). On route B their task load using TBT navigation had a mean value of 16.3 (median = 13.5, sd = 10.3) compared to 47.7 (median = 49.5, sd = 21.5) with ATCF navigation ($t = -3.23$, $df = 7.16$, $p = 0.0141$ | effect size = 1.86, ci = 0.44-3.22).

Orientation

Numerically, participants using ATCF navigation appeared to perform better in estimating the direction of the starting location on both routes. On route A results showed a higher mean deviation angle ($W = 21$, $p = 0.6991$ | effect size = -0.14, ci = -0.74-0.47) for TBT (mean = 48°, median = 42°, sd = 28°) than for ATCF (mean = 35°, median = 32.5°, sd = 13°). Likewise, on route B results showed a higher mean deviation angle ($t = 1.1$, $df = 6.16$, $p = 0.3109$ | effect size = 0.64, ci = -0.54-1.79) for TBT (mean = 53°, median = 28°, sd = 59°) than for ATCF (mean = 25°, median = 22°, sd = 20°). Although these results were not statistically significant, the lower standard deviation for ATCF could hint towards improved orientation in the environment as compared to TBT navigation.

3.3.5 Summary

Our results show that TBT navigation leads to better performance in terms of route length, errors and task load. This confirms H1. Routes with TBT navigation are shorter than with ATCF and lead to fewer errors. The difference in route length shows a large effect with medium confidence intervals. The observed effect is therefore very likely to exist. However, for task load the effect is large with a large confidence interval and the orientation results show small to medium effect sizes with large confidence intervals, which means for both more data would be needed in future work to clearly state whether we can be sure that these observed effects exist (according to thresholds presented in [183]). A post-hoc power analysis using G*Power for study 1 revealed a mean power of 0.23 [66]. It is important to note that the route design most likely had an impact on this outcome as the situation where the arrow points in the opposite direction was expected to negatively influence the performance of ATCF navigation users. The comparison gives a first impression of how strong this influence was.

When asked whether they could have found their way back to the starting location if the navigation device had failed during their ride, 7 out of 12 participants answered yes for ATCF and 8 out of 12 answered yes for TBT. So in both conditions participants felt just as sure that they could find their way back. When asked to rate their orientation (1 – very well oriented; 6 – no orientation at all), participants using TBT gave a mean rating of 1.75 while participants using ATCF gave a mean rating of 3.08 – contrary to the results of the orientation test. A possible explanation for this could be that participants were generally less confident with the ATCF navigation method. Only one participant using ATCF was always sure to be on the right route to their destination compared to 9 participants who felt the same way using TBT. Participant 6 commented on this (translated from the German original): “When I was not going into the direction the arrow pointed in, I felt frustrated. Because I wasn’t sure, in an unknown environment, whether a street would turn up that pointed in the direction of my destination, or if I should turn back and try a different street”. Based on our results we are not able to statistically confirm H2 but see indications that ATCF might have advantages over TBT navigation when it comes to orientation.

A situation that clearly added to the insecurity of participants using ATCF navigation was having to ride in the opposite direction to the arrow. 4 out of 6 participants on both routes A and B turned around or away when faced with this situation. On route B, we observed just how much people tried to move in the direction of the arrow. Figure 3.3d

shows that instead of following the road and riding against the arrow for a short while, participants turned around or immediately took a small pathway that led in the target direction, even if that meant carrying their bike up a staircase (while scouting the routes, we were actually not aware of this "shortcut"). On route A there were no further options than to either carry on against the arrow's direction, or to turn around (see Figure 3.3b) - which is what 4 out of 6 participants did. This demonstrates indicatively how users deal with difficult navigation situations using ATCF.

ATCF users also reported difficulties developing survey knowledge of the area. For many, this resulted in running into (sometimes even multiple) dead ends (see Figure 3.3b). Beeline didn't seem to be "[...] very helpful when it came to getting an overview" (participant 6), whereas with Google Maps they "always knew the optimal streets" (participant 7).

Implications for Study 2

From the results of this study, we deduced the main shortcomings of a basic visual implementation of ATCF navigation. (1) There is no information about whether one is still on the right route to the destination (leading some users to turn around even when they don't have to) and (2) there is no way to get information about one's surroundings (like adjacent streets, detours or dead ends). Based on these shortcomings we built our own prototype of a more advanced visual ATCF navigation application, which we evaluate in study 2 to gain further insights into users' behavior when using ATCF navigation. Before describing the design of our own prototype it is important to mention that the Beeline tool itself includes a "Route Assistant" feature (not used in our study), which creates waypoints at every decision point along the route. This effectively makes it a turn-by-turn approach in which ATCF navigation is only used to get to the next intersection. In contrast, our redesign aims to keep most of the ATCF functionality while enabling users to make more informed navigation decisions.

3.4 Study 2 - ATCF vs ATCF+

From the results of study 1 we were able to identify design implications whose effects we could test in an improved ATCF+ version. In particular, we added three kinds of visual cues to inform the user whether they are still on the right route to their destination or heading into a dead end or detour, plus further information about their surroundings. In detail these design changes include:

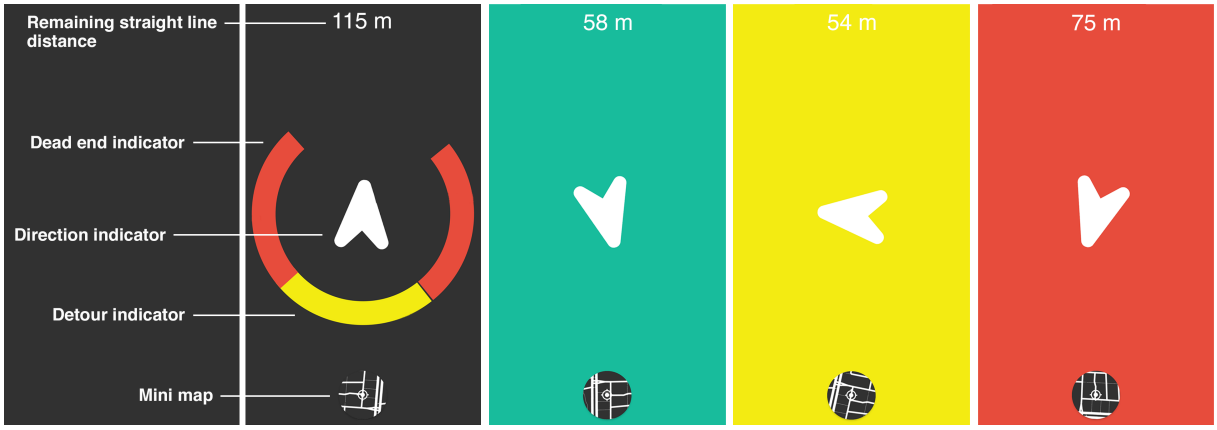


Fig. 3.4 ATCF+ interface: (a) A detour behind the user and a dead end to the left and right; (b) The user is on the right route to their destination, even though it lies in the opposite direction; (c) The user is on a detour; (d) The user is in a dead end

- Background color indicating whether users are on the right route to their destination (green, see Figure 3.4b), taking a detour (yellow, see Figure 3.4c) or heading towards a dead end (red, see Figure 3.4d).
- Visual cues that indicate upcoming dead ends or detours (see Figure 3.4a).
- A mini map with live updates about the users position (see Figure 3.4).

These changes were designed to alleviate the main shortcomings of the application used in study 1. To implement the changes we developed our own visual ATCF navigation application for Android following the example set by Beeline. This approach allowed us to have two versions of our app: one which is identical in functionality and very similar in design to the Beeline application used in study 1, and another with the above mentioned features.

For consistency, this study has a similar setup to study 1 except for a few changes which will be described in the following subsections. The main difference is that we used only route A with a between-subjects approach, with participants in one condition using the ATCF version and participants in the other condition using the extended ATCF+ version. To identify more detailed implications we wanted to focus only on one aspect of error handling: the behaviour of turning around after having to ride in the opposite direction to the arrow. Therefore we replicated study 1 for the ATCF condition on route A, and added another condition (ATCF+) for direct comparison. We did not include route

B because of the unexpected staircase-based shortcut that some participants used. Our hypotheses were as follows.

H1: Participants using ATCF+ will be less likely to turn around when they have to ride in the opposite direction to the arrow than participants using ATCF navigation.

H2: Participants using ATCF+ will make fewer errors than participants using ATCF.

H3: Routes with ATCF+ will be shorter than routes with ATCF.

3.4.1 Task & Procedure

Each participant cycled one route (route A from study 1, see Figure 3.2a) and was randomly assigned the condition ATCF or ATCF+ (7 participants per condition). Before starting their ride they were shown the application and an info graphic explaining its functionality. For the ATCF+ condition this included the various interface changes and their meaning. As in study 1 they were not shown a map and were instructed to go at their own pace. They filled in a demographic questionnaire, cycled the route on their own and met the experimenters at the destination. As in study 1, after reaching the destination they were asked to complete another questionnaire about the route and experience with the navigation device, a NASA TLX questionnaire and an orientation test (pointing into the direction of the starting location). Finally, participants were able to give comments in a semi-structured interview.

3.4.2 Participants & Apparatus

We used a between-subjects design with 14 participants (7 male and 7 female; 7 students and 7 with varying job roles) between the age of 22 and 60 (mean=30.86, median=25, sd=13.17). 10 out of 14 said they cycled frequently (three or more times a week). None had heard of or used any ATCF navigation before the study. Participants' familiarity rating with the environment (5 = very familiar, 1 = not familiar at all) resulted in a mean rating of 2.5 (median=3, sd=1.02). Both the ATCF and the ATCF+ applications were installed on a Samsung Galaxy Note 8 which was mounted to the handlebar of the bicycle as in study 1. The same smartphone was used for completing the questionnaires and tracking the GPS position using our own navigation applications. All participants had sunny to overcast weather conditions.

3.4.3 Technical Implementation

The ATCF+ application uses a graph representing the street network of the local area around route A. The graph consists of several nodes per street. Each node holds information on whether it is part of a dead end or detour. We use the GPS sensor and magnetometer of the smartphone to implement the ATCF (compass) navigation. Whenever the user gets into the vicinity ($25m$) of a node, said node triggers an event, for example if its neighboring node is a dead end. Using the graph and the user's location the system knows how far the user is into a dead end or detour and can react accordingly. To make sure participants would not go too far off track we added "dead end nodes" all the way around the study area.

3.4.4 Measures

The measures are identical to study 1: route length, errors, task load, orientation and wayfinding behaviour. Additionally, we evaluated the straight line distance to the destination over time.

3.4.5 Results

All participants were able to complete the route successfully with either navigation method. The following results compare both conditions, ATCF and ATCF+, to each other. To ensure a valid comparison between the sample of each study, a Wilcoxon rank sum test did not find any significant differences between both age groups (W=84.5, p=1). As before, no correlation was found between participants' familiarity with the environment and the following test results ($p > 0.05$) in study 2.

Route Length

Route length was not significantly different between the two conditions ($t = -1.25$, df = 9.41, p = 0.2428 | effect size = 0.67, ci = -0.43-1.73). Contrary to our expectations, it even seemed that participants using the ATCF navigation method used shorter routes (mean = $4163m$, median = $4140m$, sd = $1389m$) on average than those using ATCF+ (mean = $5504m$, median = $6100m$, sd = $2486m$).

Errors & Riding In the Opposite Direction to the Arrow

Participants made almost the same number of errors with a total of 20 errors using ATCF navigation compared to 21 with ATCF+. But as Figure 3.5 shows, participants struggled



(a) **(b)**

Fig. 3.5 Heat maps of the uncorrected location data of all participants from the two conditions in study 2. (a) ATCF, (b) ATCF+. A 25m trigger radius causes the gap around the destination. Basemap © OpenStreetMap.

less with the dead end/detour area using ATCF+ (compare Figure 3.5a and 3.5b and see Figure 3.2a, number 4).

In general ATCF+ did address some of the errors caused by ATCF but it also introduced new ones: with ATCF 5 out of 7 participants turned around when they had to ride in the opposite direction to the arrow (similar to the 4/6 when using ATCF in study 1). None showed this behavior with ATCF+. One participant using ATCF+ did not face this situation, as they went a completely wrong way and then entered the street from the other side (see Figure 3.2a, number 2). The remaining 6 (ATCF+) participants all got to the end of the road successfully after the first waypoint. The following T-intersection unveiled another problem caused by the functionality of ATCF navigation: Whenever the arrow faces either straight ahead or straight back at an intersection, users have no basis for deciding whether to turn left or right. Three participants struggled with this situation turning left towards the start (two participants) or back to where they came from (one participant).

Task Load

Participants scored a numerically slightly lower task load using ATCF (mean = 47.1, median = 48.3, sd = 5.8) than with ATCF+ (mean = 51.7, median = 56.7, sd = 16.7), but the difference was not significant (t = −0.68, df = 7.40, p = 0.5185 | effect size = 0.36 , ci = −0.70-1.41).

Orientation

The mean deviation angle when pointing back to the start location was lower with ATCF (mean = 19°, median = 12° sd = 16°) than with ATCF+ (mean = 38°, median = 16°, sd = 42°). Although this difference was not significant (t = −1.12, df = 7.74, p = 0.295 | effect size = 0.6, ci = −0.49-1.66), it is interesting to note that the difference in the means is caused by two participants in the ATCF+ condition who had a deviation of 88° and 107°. All other participants in both groups had a deviation lower than 40°.

Distance

An important feature of visual ATCF navigation is to present the current straight line distance to the destination to the user (see Figures 3.1 and 3.4). This feature was mistaken by many participants, who are used to TBT navigation, as an indication of progress. TBT navigation usually uses the remaining travel time, remaining distance or both to report progress during the ride. In the case of TBT navigation the remaining travel distance should always decrease as long as one follows the predefined route of the navigation system. With ATCF navigation, however, the straight line distance is not representative of the actual remaining travel distance, as the street network in most cases does not allow for a straight path towards the destination. So whenever one is deviating more than 90 degrees from the target direction, one is actually increasing the straight line distance between the current location and the destination. This is in most cases unavoidable, but can have a severe impact on user confidence. To test this impact, we calculated how much the distance to the current goal (waypoint or destination) actually increased during the ride of each participant (for instance in the case of a necessary detour into the opposite direction of the goal). We summed up all those incidents for each participants which were either caused by the layout of the street network or by errors in decision making by the participants. Figure 3.6 shows two examples: One of a run without any mistakes (Figure 3.6b) with a total increase of $241m$, and a run where the participant struggled to find the correct way (Figure 3.6a), where all incidents accumulated to a total increase of

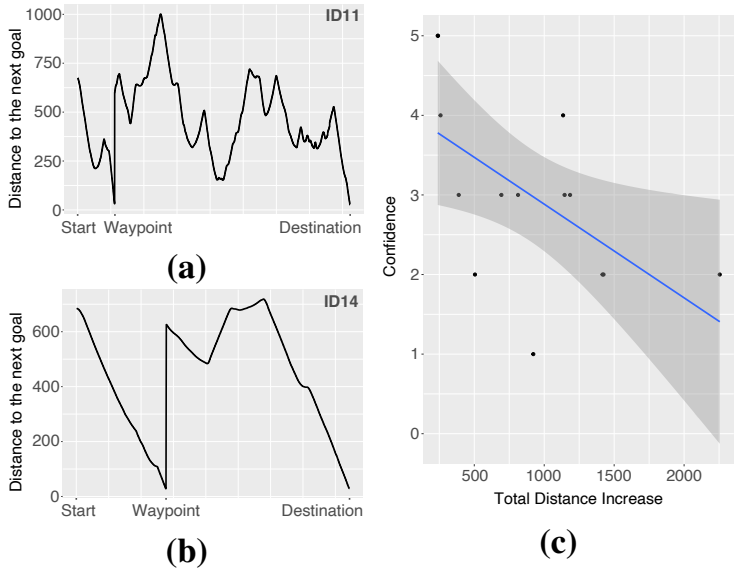


Fig. 3.6 Distance tracking for ID11, who had a confidence score of 2 (a) and ID14, who had a confidence score of 5 (b). The graph shows the distance to next goal (waypoint or destination) which was indicated on the screen as can be seen in Figure 3.4 a. After reaching the waypoint the distance jumped to indicate the distance to the final destination; (c) The correlation between user confidence (from the questionnaire) and the total increase of the distance to the destination or waypoint on their trip.

2255*m*. Through a Pearson's correlation we found that these numbers negatively correlate with the confidence rating (1 = not sure – 5 = sure) that participants gave when asked about how sure they felt during their ride that they would actually reach their destination ($t = -2.44$, $df = 12$, p-value = 0.03, $ci = -0.85\text{--}-0.067$). Figure 3.6c shows that their confidence was lower when they experienced a higher total distance increase.

We should think carefully about how to present progress with ATCF navigation. Especially when most people are already familiar with TBT navigation. Some participants told us, that at some point they were actively using the distance indication rather than the arrow to find the correct way, as in their thinking reducing that distance was a valid strategy.

3.4.6 Summary

Our results confirm that indicating that users were still on the right route helped to keep participants from turning around when the arrow was facing in the opposite direction. This confirms H1. Nevertheless, both groups still made a similar number of errors. Participants were able to avoid the most difficult dead ends, but uncovered new ambiguous situations

where they would turn into the wrong direction due to the lack of information about the surroundings. Also, ATCF+ navigation did not succeed in shortening the routes. Therefore, neither H2 nor H3 can be confirmed. One main reason for the lack of improvement in route length is that several participants using ATCF+ took a large detour (see Figure 3.2a, number 3). Some participants using ATCF also started on this route but turned around quite quickly (see Figure 3.5a). This highlights an effect of the green background functionality (see Figure 3.4b) as people were reassured after running into the detour that they were still on the right track. This result made us realize that longer routes are not necessarily a bad thing, as long as the participant takes informed decisions, which was one of the main goals of the ATCF+ method.

The most interesting insight concerned the way in which participants relied on the on-screen distance indication (see Figure 3.4a). Some participants told us in the interviews that they did not fully understand the ATCF navigation method until halfway through their ride. So, not only did they sometimes mistake the arrow for a turn-by-turn instruction (supporting similar findings by Pielot et al. [167]), but they also tried to use the distance indication as a basis for navigation - which did not always work out. Thus, participants often traveled further away from the destination which then decreased their confidence of reaching the destination at all. Still, 12 out of 14 participants would choose ATCF over TBT navigation if time constraints were not an issue on their route. This supports findings of Albrecht et al. [4] who found that TBT navigation was preferred when in a hurry, whereas ATCF guidance was preferred for exploration.

All of the results show small to medium effect sizes with large confidence intervals, which means in future work more data is needed to show if we can be sure that the observed effects in this study really exist (according to thresholds presented in [183]). This is also reflected in a post-hoc power analysis using G*Power for study 2, which revealed a mean power of 0.21 [66].

3.5 Discussion

Our two studies compared two basic navigation methods (TBT as a highly established one, and ATCF as a novel one whose popularity is currently increasing) with each other (study 1), and further addressed some possible design improvements for the novel ATCF method (study 2).

For purposes of fast and error free navigation, there is little doubt that visual TBT navigation is superior to visual ATCF navigation, at least for users already familiar with

TBT. TBT reliably removes uncertainty especially in the case of unforeseeable obstacles and dead ends. In contrast, ATCF provides much more freedom to choose a route while still remaining oriented towards the destination, leading to a potential preference for ATCF for leisure biking. This result extends the findings of Pielot et al. and Albrecht et al. on auditory [4] and tactile [167] ATCF interfaces to visual ATCF interfaces. It shows that visual ATCF navigation has a lot of intuitive appeal for users previously unfamiliar with it, in spite of the associated increased route length and effort.

Our studies were specifically designed in such a way as to create difficult situations for the ATCF navigation method. While related literature suggests that TBT navigation is more efficient than ATCF navigation [4], we present first insights about situations and behavior that cause these differences in efficiency. We also found indications that visual ATCF interfaces may improve the user's orientation as compared to classical TBT interfaces; this possible effect will need to be confirmed in subsequent studies. Study 2 introduced practical improvements to the design and functionality of visual ATCF interfaces. The improved interface version appeared to help participants avoid the error of turning round when the arrow was pointing in the opposite direction of travel. Also, study 2 highlighted additional challenges. In the following three sections we address our main insights in detail.

3.5.1 Cycling In the Opposite Direction to the Arrow

Ideally the shortest path towards a destination is a straight line between the user and where they want to go. If that was always the case, one would always find the shortest path using ATCF navigation, for instance on an open field with no restraining streets or obstacles. In a street network, the straight line to the goal is typically constrained by the roads and blocked by buildings, parks, bodies of water and the like. Users of ATCF navigation will therefore often have to deviate from the ideal direction of travel, sometimes so much so that they're actually heading towards the opposite direction for a while. As a consequence, we saw participants turning around (Route A) or finding alternative but very bike-unfriendly paths (Route B) to escape this kind of situation. This is related to the lack of knowledge participants had about the route and surrounding street network, as aptly expressed by one participant in study 2 (ATCF condition): "Is there still a path back there, or am I going in the wrong direction for 5 kilometres hoping that there will be a path?". These results support findings by Albrecht et al. where long stretches without anywhere to turn caused uncertainty among participants [4]. Similar to Albrecht

et al. [4], we did not show participants a map of the area or the position of the waypoint or destination. The mini-map we introduced with the ATCF+ version did not seem to make much of a difference. One participant told us that they tried to click the map to enlarge it which didn't work. They suggested a full screen map with a small compass needle for ATCF navigation, which could be a worthwhile concept to test in future studies.

3.5.2 Route Progression

Cycling in the opposite direction to the arrow particularly affected participants' sense of making progress towards the destination. During the interviews of study 2 participants told us that they often kept track of the distance indicated at the top of the screen (see Figure 3.4a). Many of them used it as a way to check their progress and evaluate their navigation decisions. One participant even solely relied on the distance indication because they had problems understanding the functionality of the compass. The problem with this is that relying on the distance can be very counter-intuitive when using ATCF navigation systems, as the straight line distance displayed on the screen might rise even though one is on the fastest path (e.g., at number 2 in Figure 3.2).

Turn-by-turn navigation systems, in contrast, clearly indicate progress relative to the destination. Their main feature is to convert the task of minimizing the distance between the user and the destination into following a set of instructions. The route length that is presented to the user directly corresponds to the length of the route when following the instructions. This representation is more accurate and reliable when it comes to representing progress. The fact that this behavior was not observed or reported in study 1 could mean that the design of the remaining distance indicator was mainly responsible for the confusion (compare Figure 3.1 and Figure 3.4) - i.e., it may be important that the distance is provided directly within the arrow rather than separately. In any case, improving user confidence concerning progress towards the goal while using ATCF navigation is an important point to consider for improving ATCF user interfaces. As the total length of the journey is not known in advance, this is difficult to assess. One way could be to estimate the average route length based on possible paths that are likely to be taken by the user.

3.5.3 Cyclists Go Everywhere

An observation that could make such an estimation difficult is that cyclists will find many different paths. Our participants were not only willing to go to great lengths to follow

the direction indicated by the ATCF navigation system, but also found creative pathways through inaccessible terrain or private property. This is potentially very important when thinking about how navigation systems for cyclists should differ from navigation systems for cars. A navigation system for cyclists should not limit its knowledge base to the official street network but allow for and react accordingly to off-road riding behavior.

3.6 Limitations

Many participants reported that they had problems understanding the underlying ATCF navigation principles at first glance. While all of them were used to TBT navigation systems, a steep learning curve was required for the ATCF interface. In future studies, it would be useful to provide a practical training phase before the study for ATCF and especially ATCF+ (with its extended features), so as to make sure that participants are fully comfortable with the functionalities and information provided in the interface. Since none of the participants in our studies had previous experience with ATCF navigation, the results are consistent throughout our samples in that regard, but the comparison to TBT is clearly influenced by the difference in familiarity with the navigation method.

Furthermore, the results of this study are influenced by the cycling infrastructure in Germany. In other countries with different cycle paths and infrastructure, a visual ATCF navigation system might be used in different ways than that which we observed. ATCF navigation also relies heavily on the street layout. Not only will using it in urban or rural areas make a difference, but also different cities with a more grid-like street layout (like many large US cities) or more unstructured ones (like most European cities) will probably influence the way people use ATCF navigation. Finally, the comparison favors TBT over ATCF as both studies include a “Go from A to B” type navigation task, which TBT navigation is very well suited for. A more open task like the one used in Pielot et al. [167] could paint a very different picture when comparing both navigation methods.

3.7 Future Work

Visual ATCF navigation is already used in consumer navigation systems. However, there it is usually an alternative to TBT navigation. We envision multiple approaches that combine some of the aspects of ATCF and TBT navigation. One approach could for example try to insert multiple waypoints on the route while minimizing the deviation angle for these subsections. This could eliminate situations where the arrow points in the opposite direction of travel. The effect of such a method on orientation and spatial

knowledge acquisition would need to be tested. One participant suggested to combine the map from TBT navigation with a notion of the general direction. Future work could test different visualizations of this concept and for example investigate how route suggestions could look like for ATCF navigation. In their current design, most visual ATCF navigation methods do not communicate a route's efficiency or appropriateness in different situations (e.g. informing users about potential dead ends that they are likely to run into), which leaves some potential for frustration. They might be very well suited for open tasks like exploring a new place without time restrictions as in Pielot et al. [167], but less so if you urgently need to reach a specific destination.

Future work could investigate how ATCF navigation systems can give users a clear idea of how well suited they will be for the given task and when or if they should offer assistance.

3.8 Conclusion

Our results show that the route design effectively introduced a challenging situation for participants using the standard ATCF navigation method. Participants had problems reaching their destination without errors, detours or creative wayfinding behavior (e.g. carry their bike up a staircase, riding through private property). Our ATCF+ navigation interface, using colored cues, successfully assisted participants in some of these situations, alongside highlighting further unanticipated effects such as over-reliance on the distance information. This increases our insights on ATCF navigation. In agreement with related literature [4, 167], we find that ATCF navigation is less efficient than TBT navigation (in terms of route length and navigation errors) and users prefer TBT navigation in situations where they need error free, fast, reliable navigation. Nevertheless, many users would prefer ATCF over TBT navigation for leisure biking.

While ATCF navigation is at the moment exclusive to bicycle navigation, it might only be a matter of time until it finds its way into other more mainstream navigation systems. With more research on this topic HCI researchers will be able to successfully guide decisions in this domain and increasingly understand the advantages and disadvantages of ATCF navigation.

4 The Effects of Street Networks on As-The-Crow-Flies Navigation

In Chapter 3 we introduced as-the-crow-flies (ATCF) based mobile navigation systems as an alternative to turn-by-turn (TBT) based systems for cyclists. Compared to TBT route guidance, ATCF provides information about the general direction to the final destination. In our study we discovered problems (e.g., running into dead ends) that affected user experience. In this chapter, we discuss whether these problems were caused exclusively by human error or if the street network itself was also an issue. We present our analysis of 1,633 of the worlds largest cities and how their street networks affect the success and performance of a virtual agent. The virtual agent was programmed to use the least-angle strategy, proxying human navigation behavior with an ATCF-based mobile navigation system. We found that the agent's success and performance differed significantly among geographical parts of the world. We concluded that the geographical environment must be part of evaluating novel mobile navigation technologies. Using the **empirical** results of our analysis we assess the impact of street network indicators and city types on the success and performance of the ATCF route guidance. We then created a **dataset** combining our analysis of the 1,633 cities with thirteen street network indicators.

The contents of this chapter originally appeared in Savino, Gian-Luca, Kariryaa, Ankit, and Schöning, Johannes. "Free as a Bird, but at What Cost? The Impact of Street Networks on the User Experience of As-The-Crow-Flies Navigation for Cyclists". In: *Proceedings of the ACM on Human-Computer Interaction* 6.MHCI (2022), 209:1–209:24. DOI: 10.1145/3546744

4.1 Introduction & Motivation

Cycling is an environmentally friendly and carbon-neutral mode of transportation that has increased in popularity throughout the last decades [67, 172, 177]. One reason is the looming climate crisis, as cycling is an essential contributor to the UN sustainable development goals [223]. Thus, more and more people are taking up cycling for environmental but also health benefits [235]. Similar to car drivers and pedestrians, cyclists can choose to use mobile navigation technologies to help them find their way around known and unknown locations. Navigation methods play an essential role in this wayfinding process, with turn-by-turn (TBT) navigation being the most popular method. It has become prevalent due to its ease of use inside the closed cockpit of a car [163, 178]. However, it is not the only option cyclists have to navigate their environment. Especially with the lack of dedicated cycling infrastructure, cyclists can make use of their existing knowledge and local circumstances (e.g. road surface) to make their own navigation decisions. An alternative navigation method less focused on strict turn-by-turn instructions that allows for this flexibility has been popularized in the cycling domain: as-the-crow-flies (ATCF) [196]. Instead of following instructions [184], the ATCF navigation method provides a general sense of direction to the traveler at all times. This allows cyclists to better attend to their environment and make navigation decisions as they see fit while still being oriented [196].

Also known as compass-, beeline-, or beacon navigation, ATCF navigation has found its way into commercial products like Beeline [17] and Smarthalo [210] and can be used by people all around the world. Due to its nature, ATCF navigation uses sparse navigation cues and supports exploration [166]; both traits that are believed to improve spatial knowledge acquisition [19, 73]. Furthermore, through the lack of TBT instructions, ATCF navigation could improve learning spatial configurations during active wayfinding [204]. Thus, with most mobile navigation devices for cyclists being only slight adaptations of their car and pedestrian counterparts using visual and audible TBT instructions, ATCF navigation is a promising alternative. Finally, in contrast to ATCF, TBT navigation depends on an underlying routing algorithm [106] and routing criteria interesting for cyclists (e.g., safety [71], beauty [189], or steepness [174]) are only partly accessible in common mobile navigation devices. With ATCF navigation, on the other hand, people can make use of the information accessible in their immediate environment and choose the street with the bike lane instead of the path along the highway, even without dedicated routing.

However, while, in theory, ATCF navigation sounds like an excellent way for cyclists to get around, taking advantage of their ability to freely and quickly move across varying streets and paths, research has shown that people run into three main problems using this method in a real environment:

- Ending up in dead ends [184, 196]
- Going in the "wrong" direction [166, 167, 196]
- Not knowing when to take a turn [4, 196]

Some of these problems originate from human estimation errors (e.g., misinterpreting the angle of deviation [4]) or the lack of feedback in existing implementations [196]. However, maybe these difficulties are also inherent to the environment (i.e., the street network) that cyclists are trying to navigate. In navigation, street networks are represented by an underlying graph consisting of nodes (intersections) and edges (streets). They can be described by a plethora of indicators like count of nodes/edges, mean street segment length, count of physical street intersections, and many more [29, 30]. In this paper, we will use these indicators to get a better understanding of how street networks affect the ATCF navigation by answering the following research question:

RQ How does a city's street network affect the success, performance, and user experience of ATCF navigation?

To investigate how different street networks affect the success and performance of ATCF navigation, we use agent-simulation in combination with a feature importance analysis of 1,633 cities to identify street network indicators responsible for the agent's success (whether an agent was able to find a route) and its performance (ratio of the length of the routes compared to the shortest path; the lower the better). Furthermore, we identify geographic differences by categorizing the agent's results based on nine different city types [219].

Our results show that the agent's success is mainly influenced by the average number of in and outgoing streets per intersection and the average length of streets. Straight streets with a low circuity and overall few dead ends increase the success rate. The performance also benefits from many in and outgoing streets per intersection. In addition, the performance factor decreases as the entropy lowers, meaning the more grid-like a city is, the lower the performance factor and thus the shorter the routes. Furthermore, we find

that cities suited for ATCF navigation are mostly found in East Asia and North America, while the most unsuited cities are in Western Europe. According to the nine city types defined by Thompson et al. [219] the best performing city types are *Irregular*, *Sparse* and *Motor City* cities. So, in summary, the perfect city for ATCF navigation is a grid-like city with long straight streets, many different options to turn at each decision point, and few dead ends.

Based on the related work, it appears that most of the existing studies we examined were conducted in Western Europe (geographically the most unsuited area). Therefore, we propose that it needs more diverse study locations for future navigation experiments. We recommend that, wherever the street network does not favor ATCF navigation, researchers and designers should make sure that they are aware of these impacts and design artifacts and interactions accordingly. This study contributes the necessary context to improve the design of ATCF navigation for these areas and recognizes that different environments need different design approaches.

4.2 Related Work

While ATCF is a novel navigation method for cyclists, it has been studied in academic research throughout the past 20 years. The navigation method relies on a wayfinding heuristic called the least-angle strategy (LAS), which is also at the core of our agent implementation. In this section, we describe the LAS in detail, including the shortcomings and challenges that come with it. We explain how the ATCF navigation relates to and takes advantage of the LAS. We highlight the problems studies find with ATCF navigation in the field and how these can be explained by human error or experiment circumstances. Lastly, we present how the analysis of street networks is used to learn about different indicators of cities, classify different city types, and show how this knowledge can be used to analyze the success and performance of the ATCF navigation method across cities.

4.2.1 Least-Angle Strategy

The least-angle strategy (LAS), first defined by Hochmair [95], is a heuristic for navigating unknown environments without a map or similar contextual information. The only knowledge they have is the direction to the destination (e.g., seeing a landmark like the top of a building in the distance); they do not have an external map or knowledge about the street network. At each decision point (e.g., an intersection with multiple outgoing

streets), the person has to decide which street to take based on the angle deviation between the direction a street is heading into and the direction to the destination. Following the LAS, they choose the option with the least deviation angle [95].

One caveat of the LAS is that a person might see the destination (e.g., a tall building) initially but could lose sight of it throughout the navigation task. This can lead to estimation errors as they have to estimate their position while moving to the destination. In this case, their estimation might get distorted by path-integration errors [95, 112, 129], and their overall estimation of the direction to the destination becomes less precise. This is among the primary reasons why Hochmair describes the LAS as a temporary strategy for shorter distances [95] and evaluated it only for a maximum distance of 500 meters. The longer a person goes without resetting their estimation of the direction to the destination (e.g., by getting a glimpse at the landmark), the less successful the strategy.

To evaluate the LAS, Hochmair [95] conducted a virtual simulation. In order to build an agent that was able to traverse a street network with close to human-like performance, he extended the presented strategy with the memorized least-angle strategy as the basis for his agent. In addition to the above-described behavior, the agent could memorize the last node visited but could not return to this last node in a subsequent step (except when in a dead end) [95]. This, in turn, forms the basis for the implementation of our LAS agent described in Section 4.3.1.

This section focused on the human wayfinding behavior induced by the LAS and forms the basis of our own implementation of the LAS agent (see Section 4.3.1). The following section presents the navigation method built on top of the LAS by providing a sense of direction throughout the navigation task for better orientation and fewer estimation errors.

4.2.2 As-The-Crow-Flies Navigation

As-the-crow-flies navigation is a navigation method that utilizes the LAS by constantly (or on-demand) providing the direction to the destination. This eliminates the previously mentioned estimation errors described by Hochmair [95, 112, 129] since with a dedicated device, a person knows the exact direction to the destination at each decision point. So ATCF navigation, by providing this direction information, enables people to make use of the LAS to find their way from an origin to a destination. Different consumer products and research studies implement various ways to communicate the direction through multiple modalities like touch, sound, and vision. All of these come with their

own benefits and drawbacks. In this section, we present and discuss these different approaches and highlight the overarching navigational problems that have been recorded over multiple studies.

ATCF Navigation Using Vibrotactile Feedback

Vibrotactile feedback for ATCF navigation means that the direction to the destination is encoded in a (spatial) vibration pattern. Robinson et al. [184] for example, used a mobile device to indicate the direction towards the destination for pedestrians. In their study, all participants were able to navigate to a destination within 1,500 meters successfully. The ATCF navigation motivated them to explore and take shortcuts which sometimes, however, resulted in walking into dead ends [184]. In a similar study of Pielot et al. [166], pedestrians walked shorter routes (a few hundred meters) but faced problems when there was an obstacle between them and the destination (illustrated in Figure 4.1 (b)). In these situations, they had to "go the wrong way" for some time until being able to turn towards the destination again [166]. While for pedestrians, the mobile device encoded the direction to the destination in a vibration pattern [166], for cyclists, there was a different approach. In a study, Poppinga et al. [168] used vibrating handlebars to encode the direction to the destination. Depending on the direction, the left and right handle vibrated with different intensities. This design was successful in guiding tourists on cycling trips. However, some participants had problems in understanding the ATCF navigation method, as they expected TBT instructions.

In summary, people were motivated to take shortcuts when using ATCF navigation through vibrotactile feedback since the ATCF navigation let them easily and freely explore their environment. However, this sometimes resulted in people ending up in dead ends [184]. Furthermore, when a path did not allow them to directly follow the indicated direction (caused by an obstacle like a building), people got irritated and unhappy with the lack of specific instructions [166].

ATCF Navigation Using Audio Feedback

One of the first applications of ATCF navigation came in the form of audio feedback. While early research had already picked up this technology for navigation for the blind [130], Holland et al. [97] implemented the first version meant for sighted people. While somewhat sluggish in response (due to latency) for faster travel modes like cars or bicycles, pedestrians could navigate using spatial audio in their study. Fourteen

years later, Albrecht et al. [4] saw the benefit of hands- and eyes-free navigation for cyclists and implemented ATCF navigation for pedestrians and cyclists alike. Instead of an artificial sound to indicate the direction, they used music to indicate where to go. They found that people generally considered ATCF navigation suitable for familiar surroundings, but TBT instructions were the preferred choice for unfamiliar surroundings. A problem participants mentioned with the ATCF navigation (in the paper called beacon guidance) was that if a path was not leading straight towards the destination, they were unsure when to take the next turn. The reason being that they did not know how far the next opportunity to turn in the "right" direction would be (illustrated in Figure 4.1 (c)). This was reflected in participants' confidence with the navigation method [4].

The previous examples show that ATCF navigation can also be conveyed through audio. However, the study by Albrecht et al. [4] introduced an interesting problem. Participants were sometimes unsure when to take a turn, as they did not have a map. Thus, they were unsure whether a turn into the "right" direction would be available if they skipped a current one. This reduced their confidence while riding.

ATCF Navigation Using Visual Feedback

In contrast to the previously presented modalities, the visual communication of ATCF navigation is the most common one used for consumer products [17, 210] despite there being only limited research on it. The reason for this is likely the prevalence of visual interfacing for mobile navigation and, through it, a familiarity that lowers the entry barrier for using these products. Among the existing products which utilize ATCF navigation are the two devices Beeline [17] and SmartHalo [210]. Both function as small devices attached to a bicycle's handlebar and feature ATCF navigation (called compass mode) as an alternative to the also available TBT navigation. Besides the success of the visual ATCF navigation in consumer products, there is limited academic research on it. Among them, a recent study by Savino et al. [196] investigates the advantages and consequences of this modality and the navigation method as a whole for cyclists. Their study compares ATCF navigation (based on the Beeline device) with TBT navigation (Google Maps). The results showcase the superiority of TBT navigation in following the shortest path and highlight the shortcomings of ATCF navigation, confirming results from previous studies. They find that people had problems going into a direction that deviated from the indicated direction to the destination, similar to what Pielot et al. [166] found for pedestrians. Furthermore, participants were unsure when to take a turn due to the lack of

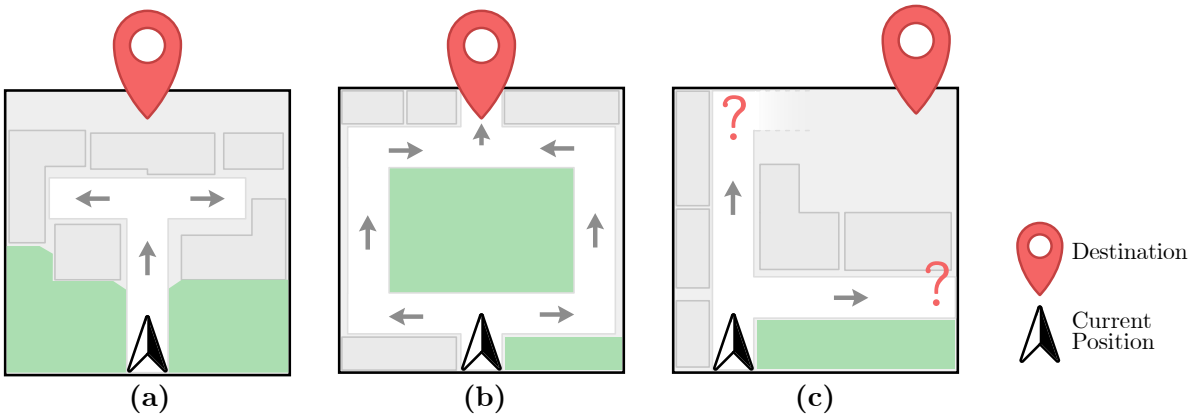


Fig. 4.1 Situations identified by related work that cause problems with the ATCF navigation: a) Ending up in dead ends; b) Having to go in the "wrong" direction; c) Not knowing when to take a turn.

a map, similar to the results of Albrecht et al.[4]. Finally, participants ran into dead ends while exploring possible routes to the destination, as also seen in the study of Robinson et al. [184].

ATCF Difficulties Across Modalities

In summary, the related work suggests three major problems, illustrated in Figure 4.1, that can be observed when people use the ATCF navigation in real-world navigation tasks:

- **Ending up in dead ends:** Exploration can lead to people ending up in dead ends [184, 196].
- **Going in the "wrong" direction:** Not being able to directly follow the indicated direction or following a direction that deviates from the indicated direction leads to confusion [166, 167, 196].
- **Not knowing when to take a turn:** Not knowing when to take a turn, due to the lack of a map and the interpretation of angle deviations [4, 196].

To investigate these problems, we implemented an agent that closely models the behavior observed in the studies above. Furthermore, during the analysis of the above-presented literature, we noticed a similarity between most studies. Through a combination of the author's affiliation, route descriptions, and images published in their works, it appears that most studies have been conducted in Western Europe. As geographic

Street Network Indicators	
Indicator	Description
node_count	The number of all the nodes in the graph.
street_segment_count	The number of all (undirected) edges in the graph.
length_mean	Mean (undirected) edge/street length in meters.
length_total	Sum of (undirected) edge lengths in meters.
intersect_count	Count of (undirected) edge/street intersections.
prop_4way	Proportion of nodes that represent 4-way street intersections.
prop_3way	Proportion of nodes that represent 3-way street intersections.
prop_deadend	Proportion of nodes that represent dead-ends.
self_loop_proportion	Proportion of edges that are self-loops.
k_avg	Average node degree (mean number of inbound and outbound edges incident to the nodes).
cc_avg_dir	Average clustering coefficient (extent to which node's neighbourhood forms a complete graph).
circuity	Average circuity (ratio of street lengths to straight-line distances).
orientation_entropy	Entropy of street bearings (i.e. how ordered/grid-like the network is).

Table 4.1 Street network indicators and their meaning based on OSMnx [29] and Boeing [30].

differences are part of our analysis, we will come back to this finding later in the discussion.

4.2.3 Street Network Analysis

In this paper, we are looking at cities and their street networks from two perspectives: (1) the graph representations of the street networks and their formal network indicators and (2) a high-level classification of nine different city types based on visual representations of their street networks. In this section, we present the related literature for both these perspectives.

Street Network Indicators

A street network is usually represented as a directed multi-graph consisting of nodes and edges. Based on this formalization, many well-established indicators from graph theory are used to describe a street network: e.g., the number of nodes/edges, the total

City Types	
City Type	Description
Informal	Sparse, low capacity informal road infrastructure, low railed transport, low formal green space.
Irregular	High green space, mixed formal and informal low and high capacity road networks, low mass transit.
Large Block	Medium density formal low and high capacity road networks, medium railed transport.
Cul de Sac	Very high density, low capacity mixed formal and informal road networks, low mass transit.
High Transit	Medium density, high capacity, formal road networks, high public transport.
Motor City	Medium to low density, high capacity, grid-based, road networks, medium railed transport.
Chequerboar	High density, medium capacity mixed formal and informal road networks, medium public transport.
Intense	Very high density, mixed formal high capacity and informal road networks, high public transport.
Sparse	Low capacity, low density formal and informal road networks, low public transport.

Table 4.2 City types and their descriptions. The descriptions are direct quotes from Table 1 in the Appendix of Thompson et al. [219].

edge length, the proportion of 4-way intersections, among others [30]. We used the street network information available through Open Street Map (OSM) [158] for our study. OSM is an open-sourced global database for graph-based street networks. It features a comprehensive database of cities and their street networks and offers an API that researchers and practitioners can use to process and interact with this data.

To extract the indicators from the respective street networks, we used the Python library OSMnx by Boeing [29]. In recent publications, Boeing extracted multiple street network indicators for cities around the globe [29, 31, 32] resulting in a dataset of "Street Network Models and Indicators for Every Urban Area in the World" [30]. Based on his research, we chose a subset of street network indicators relevant for the ATCF navigation to be used in our study, which can be seen in Table 4.1.

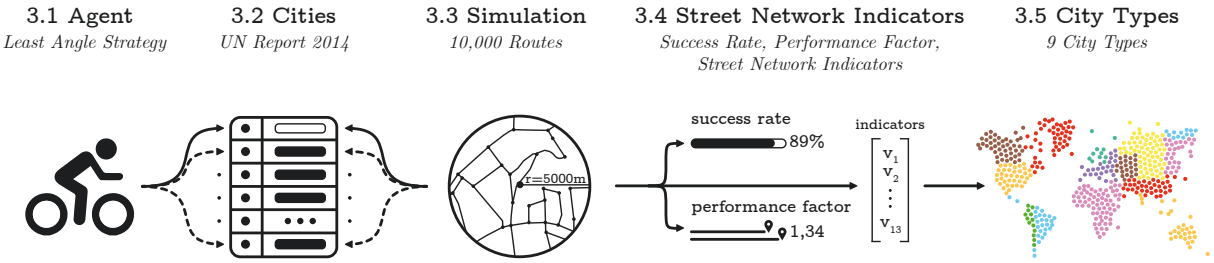


Fig. 4.2 Description of the simulation framework: For 1,692 cities in the 2014 UN world urbanization prospects [224], our agent tried to find 10,000 routes based on 10,000 random origin and destination pairs between 1-5000m distance. We then computed the success rate, performance factor, and 13 street network indicators for each city and assigned its city type.

City Types

Beyond the individual street network indicators, Thompson et al. [219] came up with a classification of nine different city types. Based on visual representations of the street network of the 1,692 largest cities by population from the 2014 UN world urbanization prospects [224], they used a convolutional neural network to cluster them into nine different city types: *Informal*, *Irregular*, *Large Block*, *Cul de Sac*, *High Transit*, *Motor City*, *Chequerboard*, *Intense*, and *Sparse* (see Table 4.2 for detailed descriptions). While for example *Motor City* cities are mostly located in North America and Australia and feature consistently organized, grid-based networks [219], *High Transit* cities are mainly found in Western Europe and show a more intense network structure compared to most other city types [219].

In this study, we will use street network indicators and the city type to look at cities worldwide in terms of their suitability for applying the LAS. Together, these two ways of looking at street networks result in a comprehensive evaluation of how the environment can affect the performance and success of ATCF navigation. We use the network indicators in a feature importance analysis to determine which ones can affect the performance factor and the success rate. Furthermore, a comparison between the city types can provide information about the geographic differences.

4.3 Study

To assess how much the city structures themselves contribute to the success or failure of the ATCF navigation method, we investigated street networks across the 1,692 largest

cities in the world by population size. Evaluating our research questions on a global scale, required an agent proxying human navigation behavior with ATCF. Therefore, we built an agent implementing the least-angle strategy [95] and a framework to collect the city network data. In this section, we will describe the implementation of the agent and the simulation framework we built using the python library OSMnx [29] (see Figure 4.2). Throughout this study and our results, we will refer to the success and the performance of the agent in terms of the success rate and performance factor as described by Hochmair [95].

4.3.1 Agent

We implemented the agent using a modified depth-first search to find a route between an origin and a destination using the least-angle strategy (LAS). Based on the implementation of Hochmair [95] it starts at the origin and always chooses the next unvisited neighbor node with the least angle deviation towards the destination. This behavior continues until the agent has either reached the destination or is caught in a loop. Being caught in a loop is defined by visiting a node V twice from the same previous node with all immediate neighbors of V already visited (this behavior covers both Hochmair's original cycle and circuit criteria [95]). If the agent, given the stopping criterion, reaches the destination, the run is considered successful. In this study, we use the agent's success rate as a metric for evaluating how well a city is fit for using the LAS. A human in a similar situation would not stop the navigation altogether but could, for example, resort to asking for directions or use a different navigation method like TBT. Still, such situations result in frustration and loss of confidence [196]. Thus, the agent's success rate is a proxy for not being confronted with such situations during the navigation, which makes the navigation more pleasant and positively affects the user experience.

Furthermore, the agent calculates the total length of the route (including the parts where it backtracked or walked in circles). These two measures are then used to calculate an overall success rate and performance factor per city as seen in Hochmair [95]. The success rate describes the percentage of successful routes given 10,000 origin-destination pairs. The performance factor describes the average by which the routes found by the agent are longer than the shortest path between the origin and destination (e.g., a performance factor of 1.4 means that the routes found by the agent were on average 40% longer than the respective shortest paths). The following section describes how we collected the city data for the agent to run on.

4.3.2 Cities

In order to have the agent use its wayfinding algorithm on existing street networks, we collected the necessary data with the OSMnx library [29]. OSMnx is a python library that allows downloading Open Street Map data in a graph format. For our simulation, we chose the 1,692 largest cities by population based on the 2014 UN world urbanization prospects [224]. This dataset includes, among other attributes, the coordinates of each city's center (based on OSM) as well as its name and country. Using OSMnx, we downloaded a fixed area comprising all nodes within a 5km radius around the center for each city. When downloading the graph of each street network, OSMnx simplifies and fixes the graph so that the result is a connected graph with a clean periphery. We used the OSM network type "bike" in combination with a custom filter to exclude motor highways, footways, and private streets like driveways to ensure the network consisted of streets where cyclists are allowed to ride.

4.3.3 The Simulation

For the simulation, we generated 10,000 origin-destination pairs for each of the 1,692 cities. The origin-destination pairs were randomly chosen and were between 1 and 5,000 meters apart. Additionally to the route the LAS agent generated, we collected the shortest path for each origin-destination pair. This resulted on average in routes that were 4790 meters long for the LAS agent and 3360 for the shortest path, in line with typical average commute lengths for cyclists [36]. With the collected routes, we calculated the success rate and the performance factor for each city. Additionally, we collected the 13 street network indicators shown in Table 4.1, which are described more closely in the next section.

4.3.4 Street Network Indicators

From the cities and their corresponding graphs, we collected the inherent street network indicators. As the reader might recall, we analyze all cities' street network indicators using a feature importance analysis to find out which indicators are responsible for the success or failure of the ATCF navigation method in terms of success rate and performance factor. To achieve the former, we identified basic and relevant street network indicators [29, 30]. Table 4.1 shows all indicators with their descriptions. For our analysis, we divide these indicators into two groups: absolute and relative. Absolute indicators are those which change in absolute numbers with the size of the graph. These

include: *node_count*, *street_segment_count*, *length_total*, and *intersect_count*. All other indicators (e.g., *k_avg* or *length_mean*) are relative and thus comparable across cities with different network densities.

4.3.5 City Types

In addition to the street network indicators, we used the city types identified by Thompson et al. [219] to compare the success and performance of LAS agent across them. In their work, Thompson et al. [219] used the same UN 2014 data set [224] to cluster city types based on their visual street network using a convolutional neural network. This analysis resulted in nine different city types, which can be seen in Table 4.2. In our analysis, we compare the results of the LAS agent across these city types. Additionally, we use the city type as the 14th feature in our feature importance analysis, adding a visual feature to our otherwise abstract feature set.

After including the city types, we had to exclude 59 cities from our initial dataset due to inconsistencies with the dataset from Thompson et al. [219] and the UN 2014 data set [224] (for a detailed explanation see Section 4.6) resulting in a total of 1,633 cities for the analysis.

4.4 Results

In this section, we present the results of the agent simulation. From the total of 16,330,000 origin destination pairs, the agent was able to successfully find 8,418,141 routes across all 1,633 cities. We describe the importance of the different street network indicators for the agent's success rate and performance factor. Furthermore, we look at the different city types by Thompson et al. [219] and how the results of the agent differ between them.

4.4.1 Street Network Indicator Importance

To find the most important features responsible for the success and the performance of the agent using the LAS, we used permutation feature importance analysis. We first fit a random forest regressor to our data for the success rate ($R^2 = 0.87$) and the performance factor ($R^2 = 0.37$) respectively. The permutation feature importance i then revealed the most important features of our model (see Figure 4.3). The overall most important indicators are the average (undirected) node degree (*k_avg*), the mean (undirected) edge length in meters (*length_mean*), and the city type. Another important feature for the success rate is the *node_count*. However, it is important to keep in mind that the *node_count* is an absolute feature and thus does not compare well across cities

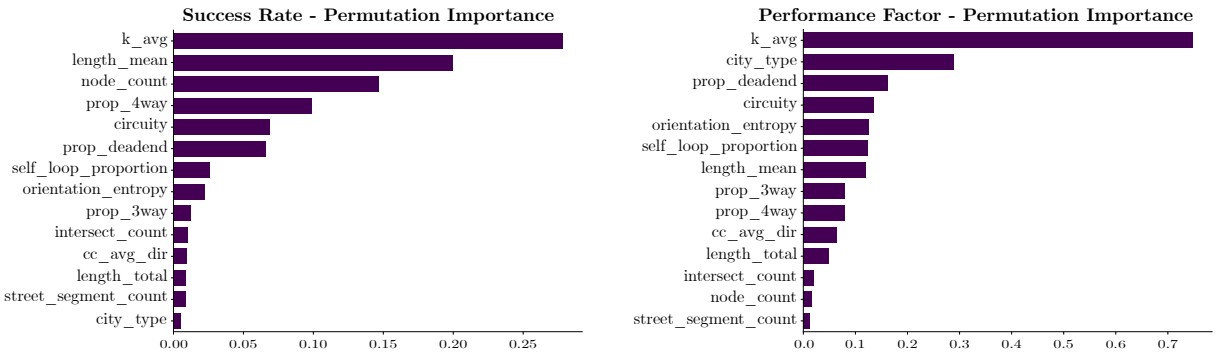


Fig. 4.3 Permutation feature importance results for the (a) success rate and the (b) performance factor. Note the different scales on the x-axis for both plots.

with different network densities. A Spearman correlation showed that it has a high multicollinearity with the remaining absolute features: *length_total*, *intersect_count*, and *street_segment_count*. To indicate the relationship between an indicator and the measured variable, we report the Spearman rank-order correlation coefficient c and its p-value p for each feature.

Success Rate

For the success rate the average (undirected) node degree (*k_avg*, $i = 0.28$, $c = +0.32$, $p < 0.01$) was the most important indicator. The higher the degree, the higher is the success rate. This is followed by the mean (undirected) edge length (*length_mean*, $i = 0.20$, $c = +0.63$, $p < 0.01$). Here, with increasing length the success rate also increases. The next feature is the *node_count* ($i = 0.15$, $c = -0.64$, $p < 0.01$). Here we see that with fewer nodes the success rate increases, meaning that smaller graphs (in absolute numbers) result in a higher success rate. The next features by importance are the proportion of 4-way intersections (*prop_4way*, $i = 0.10$, $c = +0.65$, $p < 0.01$), the circuity ($i = 0.07$, $c = -0.56$, $p < 0.01$), and the proportion of dead ends (*prop_deadend*, $i = 0.05$, $c = -0.62$, $p < 0.01$). All other indicators had a mean feature importance below 0.05. For the full list please see Figure 4.3a.

Performance Factor

The most important indicator for the performance factor was the average (undirected) node degree (*k_avg*, $i = 0.75$, $c = -0.42$, $p < 0.01$). With increasing node degree the performance factor gets smaller, meaning the LAS routes become shorter. Second

most important was the city type as a feature (0.29). The effect of the city type on the performance factor can be seen in Figure 4.4 and is discussed in the next section. The third most important feature is the proportion of dead ends ($prop\_deadend$, $i = 0.16$, $c = +0.06$, $p < 0.05$). While deemed important by the feature importance analysis, the proportion of dead ends does not seem to have a positive or negative linear relationship with the performance factor. The next important feature is the circuity ($circuity$, $i = 0.13$, $c = +0.14$, $p < 0.01$), followed by the orientation entropy ($orientation\_entropy$, $i = 0.13$, $c = +0.25$, $p < 0.01$). This shows that the less ordered a street network is and the less straight its streets are, the lower is the performance factor. For the remaining features see Figure 4.3b.

Overall, we see that the average node degree strongly influences the success rate and performance factor, meaning that a higher number of incoming and outgoing going streets per intersection improves the agent's performance. While for the success rate, the mean edge length, node count, and proportion of 4-way intersections play an essential role, the performance factor is affected by the city type, the circuity, and the orientation entropy. Furthermore, dead ends affect whether the agent reaches the stopping criterion and thus reduce the success rate. This results in successful routes including fewer dead ends, and therefore, they have little effect on the performance factor.

4.4.2 City Types

To compare our results based on the city types by Thompson et al. [219] in terms of success and performance of the ATCF navigation method, we recreated their dataset [224] and collected these metrics for each city. Figure 4.4 shows all cities and their respective type located on a world map. For a visual example of each city type see Figure 4.6. In the following subsections, we will compare these city types based on our agent's success rate and performance factor. For all comparisons, we conducted a one-way ANOVA with posthoc t-tests.

Success Rate

We found that overall all city types have a lower success rate than 70%. A one-way ANOVA found significant differences between the city types ($F = 99.71$, $p < 0.001$). *Irregular* (69%) and *Sparse* (63%) cities had the highest success rates with the former being significantly higher than the latter ($p < 0.05$). The next city types by success rate are *Informal* (50%), *Intense* (48%), *Motor City* (46%), and *Chequerboard* (45%)

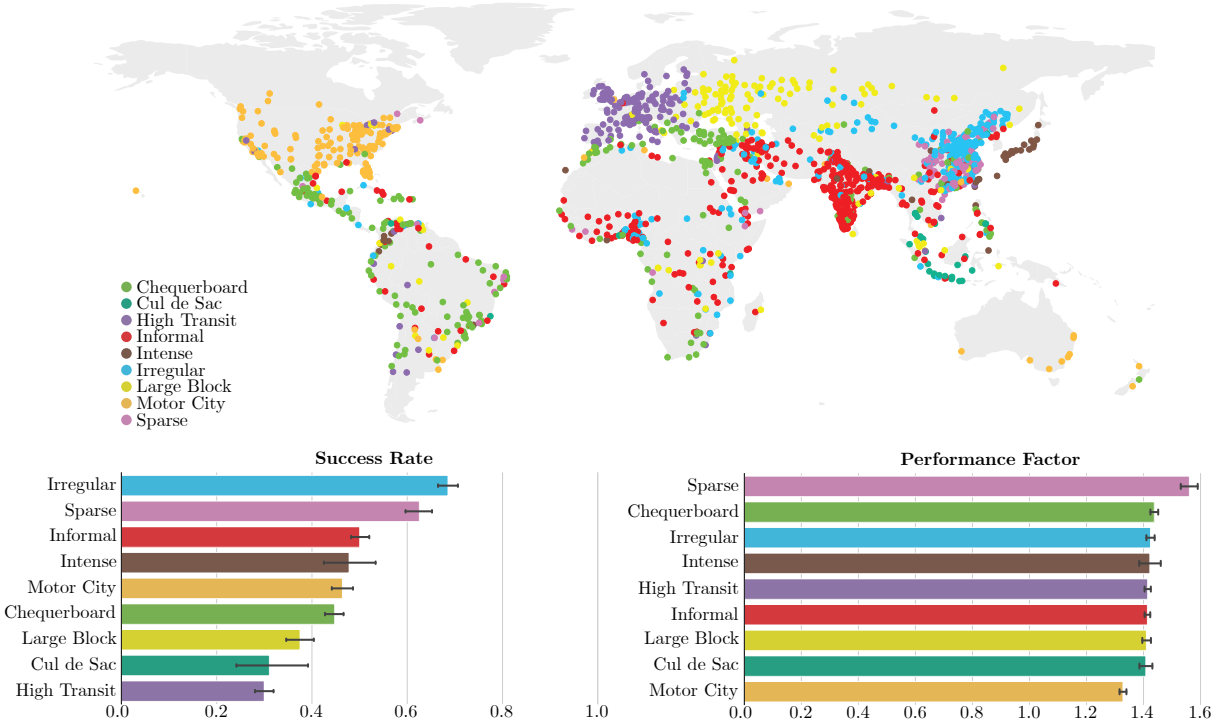


Fig. 4.4 Success rate and performance factor based on the different city types by Thompson et al [219].

cities with no significant difference between them. However, *Chequerboard* cities (45%) have a significantly higher success rate ($p < 0.01$) than *Large Block* (38%) cities. The lowest success rates were found in the *Cul de Sac* (31%) and *High Transit* (29%) cities, showing no significant difference between both but with *High Transit* (29%) cities having a significantly lower success rate than *Large Block* (38%) cities ($p < 0.001$).

Performance Factor

The performance factor was, on average, very similar between all city types (see Figure 4.4). A one-way ANOVA found significant differences between the city types ($F = 43.02$, $p < 0.001$). *Sparse* cities had the significantly highest performance factor (1.56), with a p-value of 0.0001 or smaller compared to all other city types. In contrast, *Motor City* cities had the significantly lowest performance factor (1.33), with a p-value of 0.000002 or smaller compared to all other city types. The remaining city types showed a performance factor from 1.41 (*Cul de Sac*) to 1.44 (*Chequerboard*) with no significant differences.

4.5 Discussion

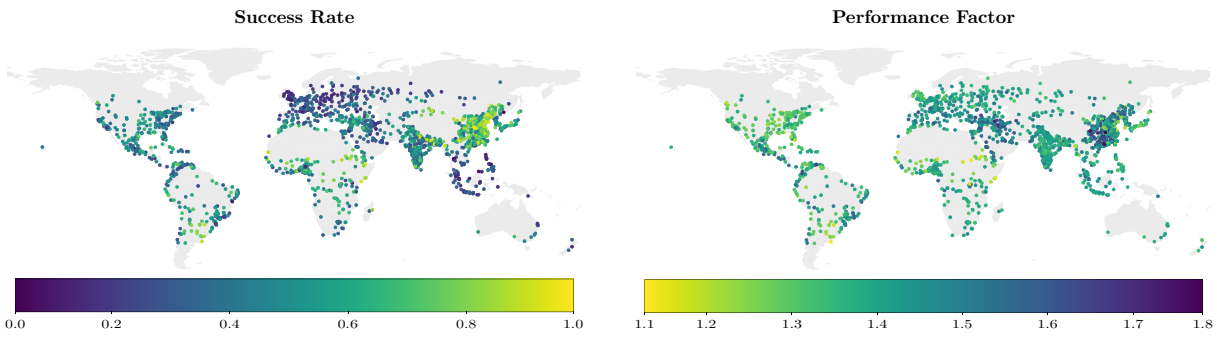
In this section, we discuss the simulation results and their consequences for the design and application of the ATCF navigation method. As an alternative to TBT navigation, ATCF navigation offers the freedom to explore one's environment. This allows cyclists to attend more to their surroundings and make decisions as they see fit. Still, according to the least-angle strategy (LAS), people will follow the "right" direction as closely as possible. From our results, we learn that some environments make this harder than others, as can be seen in the different success rates and performance factors across cities worldwide (Figure 4.5). Thus, we should consider these differences when designing for the people who try to navigate these places. Finally, navigation is a part of how people interact with their surrounding city infrastructure. Therefore, we should not only design navigation methods to suit different environments. We should also understand how different city environments developed, what constraints they have, and think about designing them to support more flexible navigation methods that foster exploration and humans' abilities to find their way through them [98].

4.5.1 Human Error? No, Bad Street Network Design

A central assumption in human-computer interaction (HCI) is that people make mistakes [153]. However, as HCI researchers, we have the tools to ask and understand what causes these mistakes. For ATCF navigation, related work has identified problems people encounter when using it across different modalities. Some of these problems are accounted for by the novelty factor of the method as described in Pielot et al. [167], where participants did not understand the method as they were so used to TBT navigation instructions. Thus, it is only normal that participants would make mistakes using a new technology. However, as our results show, there are differences in how the least-angle strategy works in different cities. As the user experience of the ATCF navigation is dependent on the successful application of the LAS, we need to consider these differences carefully and evaluate their consequences. In the following subsections, we discuss how the street network influences the identified problems.

Ending Up in Dead Ends

With no map available, participants in the previous studies sometimes ended up running into dead ends [184, 196]. This is frustrating and, in principle, increases the route length and thus the performance factor due to the backtracking necessary to get out of the dead



(a) **(b)**

Fig. 4.5 (a) Success rate and (b) performance factor for all 1,633 cities in the dataset. The color map is flipped for the performance factor. For both scales, brighter colors indicate a better result.

end and resume the navigation. As our data shows, dead ends impact the success rate as well as the performance factor. While for the success rate we see a high negative correlation (the higher the proportion of dead ends, the lower the success rate), we do not see the same for the performance factors. A reason for this could be that routes of the agent reach the stopping criterion in a complex dead end, and thus successful routes only contain limited dead ends. Furthermore, the proportion of dead ends differs between different city types (see appendix B).

It comes as no surprise that the city type featuring the highest proportion of dead ends (24.0%) across all city types is *Cul de Sac*. The city type second to that is *High Transit* with 21.6%. This is also the city type primarily found in Western Europe and appears to be where most of the previously presented studies were conducted. Thus, people driving into dead ends might be a less common problem in other areas like North America (*Motor City*, 14.6%) or China (*Sparse*, 13.1%). Based on our implementation, a future ATCF navigation system could use our simulation approach to predict the likeliness of running into dead ends on the chosen route and intervene with TBT instructions at critical decision points by, for example, temporarily changing into a map view. Another option would be to alert users that a given area has a high density of dead ends. Thus, they should be looking out for respective road signs more carefully when taking a turn instead of just following the system.

Going in the "Wrong" Direction

The feeling of going in the "wrong" direction or not being able to go where the ATCF navigation points to was a frequently reported issue in previous literature [166, 167, 196] (illustrated in Figure 4.1 (b)). In terms of street network indicators, this is influenced by the average node degree (*k_avg*) as it describes the average number of options an intersection offers. A higher average node degree thus means that more often, there will be an option that might lead in the "right" direction. When it comes to the average node degree, *Motor City* cities are the leading type with on average 5.27 in and outgoing streets per intersection compared to the lowest average being 4.68 for *High Transit* cities. While more options to turn might offer a higher likelihood of taking a turn in the "right" direction, we still need more information on how people deal with this problem in situ to offer an adequate solution.

To collect additional information on street networks regarding this problem, a future version of our agent should include the notion of going in the "wrong" direction. In the meanwhile, Savino et al. [196] presented a first approach about giving people feedback on whether they are still on the "right" track, which successfully helped people going "against" the proposed direction.

Not Knowing When to Take a Turn

Not knowing when to take a turn was another of the problems identified to be caused by the ATCF navigation (see Figure 4.1 (c)). The main reason was that participants did not have a map to consult about when a potential turn would come up [4, 196]. In *High Transit* cities this can mean that a wrong decision can cause a long detour as they have a high orientation entropy ($orientation\_entropy = 3.5$), and low average node degree ($k\_avg = 4.68$). Thus, missing a turn can mean that the current street potentially deviates more and more from the destination and that upcoming turns do not allow a person to turn in the direction of the destination. In that sense, *Motor City* cities are at an advantage through their grid-like structure ($orientation\_entropy = 3.1$). As a countermeasure, the ATCF navigation should indicate whether an upcoming turn is best taken, as the following turn might not lead in the right direction or is too far away.

Design Implications for ATCF Navigation

"At the end of the street, turn left"; The extended prevalence of TBT navigation has led to many people getting used to following instructions by navigation systems like Google

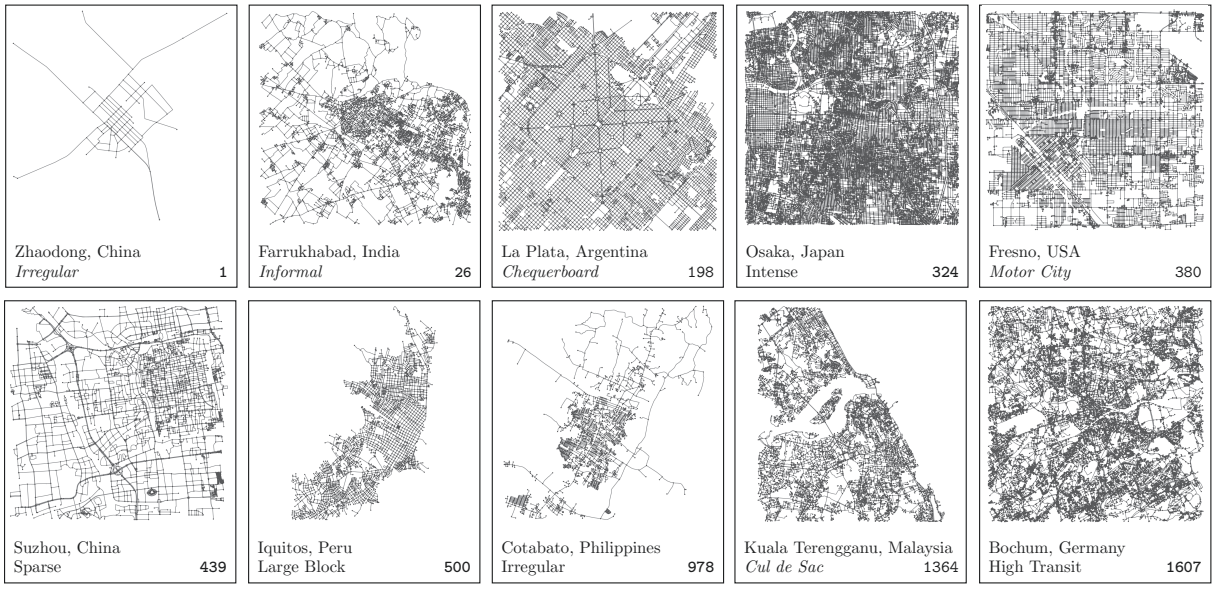


Fig. 4.6 A selection of ten cities from our dataset. It shows the name of the city, country, the city type and the rank within our data set when sorted by a combined score of performance factor and success rate. Each image shows a map section of 10x10 kilometers.

Maps. This, however, has partly led to an overtrust in navigation systems, sometimes resulting in serious casualties [126]. Due to the popularity of the navigation method, it also became the default for cyclists. Slowly, routing criteria are adapting to account for the needs of specific user groups [106]. Still, ATCF navigation presents the only currently used alternative navigation method that uses peoples' own ability to navigate and takes advantage of their own decision-making.

Current implementations of the ACTF navigation benefit from being simple. A system offering ATCF navigation does not use resource-intensive online calculations and updates as TBT navigation does. However, given a poorly suited environment, this study shows that this lack of flexibility can negatively impact the user experience. In this paper, we propose making ATCF navigation smarter in order to overcome this issue. Using the insights from this section, we can build predictive models that continuously assess the situation during a navigation task and intervene when a person likely runs into a problem. This way, the best of both ATCF and TBT navigation could be combined. Letting people freely navigate whenever possible but prevent them from running into problems.

Design Implications	
Issue	Design Implication
Ending Up in Dead Ends	Use agent to predict likeliness of running into dead ends; Change to map view at critical decision points; Alert user of high density of dead ends.
Going in the "Wrong" Direction	Include the notion of going in the "wrong" direction into the agent for further investigation.
Not Knowing When to Take a Turn	Indicate whether an upcoming turn is best taken, as the following turn might not lead in the right direction or is too far away.

Table 4.3 Design implications relating to the three identified difficulties across modalities from Section 4.2.2.

4.5.2 Geographic Differences

Different cities come with various sizes, shapes, and, most importantly, street networks. Many cities in Europe grew and developed organically with their street network usually focused on local geography. Inversely, many cities in the USA were planned using geometric grids [131]. Beyond the implications for the ATCF navigation method, our work offers a unique view of geographic differences in urban structures worldwide with implications on future study designs in the domain of navigation. Related work is already acknowledging that different cities come with different environments and proposes increasing comparability between results by identifying similar routes across cities [143]. With this work, we add to this argument by highlighting that geographic differences can influence peoples' navigation tasks which we encourage future studies to report and take into account.

Most of the studies presented in the related works in this paper appear to have been conducted in Western Europe. They, therefore, might have been exposed to the environment of a *High Transit* like street network, which we found to be not very suitable for applying the LAS. *High Transit* cities have the lowest average (undirected) node degree (*k_avg*) with 4.68 in and outgoing streets per node. While these cities feature a large absolute intersection count (due to their intense network structure [219]), their proportions of 3-way (62.8%) and 4-way (14.2%) intersections are at the lower end of the spectrum (for a full comparison, see Appendix B). Together with the high proportion of dead ends (21.6%), these indicators help explain a low success rate for our agent.

Figure 4.6 shows an example of a typical *High Transit* (#1607) from Western Europe. According to Thompson et al. [219], additionally to their intense network structure, these cities also showed a high level of railed massed transit networks.

As described before, European cities developed mostly organically [131]. *High Transit*, being the most prominent city type in this area, they feature the highest orientation entropy (*orientation_entropy*, 3.50) and are thus the least ordered. In contrast, *Motor City* cities are ordered, grid-like networks found in North America and Australia [219]. In our analysis, they stand out, having the significantly lowest (i.e., best) performance factor, meaning that routes found by the agent were on average the shortest in these types of cities compared to the shortest path. Figure 4.6 shows a typical North American *Motor City* city (#380). While they had the best performance factor *Motor City* cities featured not the best success rate. Like many other cities, they had a low mean (undirected) edge length (*length_mean*, 83 meters), which, according to our results, is an important feature that correlates with the success rate.

When it comes to the success rate *Irregular* cities had significantly the highest. This had two reasons: (1) some cities featured a very low node count making it almost impossible for the agent to get stuck given the limited possibilities in the street network. A good example of this can be seen in Figure 4.6 (#1). The feature importance analysis showed that a low number of nodes is advantageous for the success rate, and we believe it is for the previously mentioned reason. That means smaller or lower density graphs should be easier to traverse for the agent. However, examples like Figure 4.6 (#26) show that the node count itself cannot tell the full story. (2) The second reason we see is the high mean (undirected) edge length, meaning *Irregular* cities often feature long streets with an average length of 210 meters. This is backed up by Thompson et al.'s [219] visual analysis showing that they showed the lowest number of blocks per map tile. Furthermore, they characterize *Irregular* cities being irregular shaped, high level of green space and rectangular blocks of varying sizes [219]. This description fits well to the second example of an *Irregular* city shown in Figure 4.6 (#978).

Looking at these different examples, we should bear in mind that the influence of the environment can be very noticeable between different city types when evaluating novel navigation methods. Therefore, we need more geographically diverse evaluations when it comes to evaluating them. With this paper, we present the evaluation of a simulation and a way to evaluate the experiment site beforehand and check if the environment could

influence the user experience by introducing structural problems like a high density of dead ends or very high orientation entropy.

4.6 Ways Forward

This section presents and discusses the limitations of our approach and presents related and future work that builds upon our results. We discuss the agent's shortcomings and how to make its performance more human-like in the future. Furthermore, we reflect on the data quality of our study and how it affects the quality of our results. Finally, we look at how city size affects our model, what makes a bike-friendly city, and how ATCF navigation applies beyond the bicycle.

4.6.1 Modeling Human Behavior

Throughout this study, we use our agent as a proxy for human navigation performance. Given that the agent implements the LAS based on Hochmair's work from 2005 [95], we can assume that, in many cases, it will decide similarly to a human given the bearing information they need for a given task. Still, the agent differs in two crucial ways from humans, which are subject to continuous improvement: (1) the agent is too precise, and (2) it gives up too fast. The agent will make a difference even if two possible street angles differ by only 0.1 degree. It will choose the street with the 0.1 better angle over the other one. The notion that humans will not realize such differences builds on research about the perception of angularity during navigation [190]. However, for the specific case of ATCF navigation, we need more fine-grained evidence to add this behavior to our implementation. The second drawback is the stopping criterion. When stuck or caught in a loop, the agent will stop the navigation. A human will continue the task and build up a certain level of frustration with continued errors [196]. Furthermore, humans will use additional information such as road signs to cope with problematic situations. With these limitations, one should be aware that the performance of our LAS agent does not yet perfectly reflect real cyclists' performance. In his paper, Hochmair already suggests possible changes to the original algorithm to make the agent more human-like (e.g., visiting the node with the least number of pasts visits first). In addition, we learn from the related work presented in this paper that many different behaviors can be observed when people use the ATCF navigation method [4, 166, 196]. Participants, for example, had problems turning around when riding "against" the proposed direction for too long or not being able to differentiate between minor angular differences. In order to make the

agent more human-like, future work should study these behaviors even more closely to be able to formalize them. A recent study by Savino et al. [193] for example explores the effect of angle perception of humans at intersections and how this behavior can be implemented into an ATCF agent. However, extending the ATCF navigation in such a way would make it more complex. Existing implementations do not need a lot of data or calculations to work. Once a destination is chosen, a system needs to calculate the angle deviation and communicate it to the user via, e.g., a compass bearing. This approach makes ATCF navigation work even without an internet connection but, on the other hand, makes it less flexible. A smarter implementation could pre-calculate routes based on the LAS to predict possible problems in advance and give more concrete instructions where necessary.

4.6.2 Data Quality

An important aspect of our study design is that the results are only as good as the underlying graph data. Wherever the data collected by Open Street Map (OSM) [158] is incomplete, our model might make wrong assumptions. The results will be accurate given the graph used for the analysis, but the graph might not actually represent the real world. Barrington-Leigh et al. [14] analyzed the completeness of OSM and found an overall completeness of 80% across the world. However, China, a prominent country in our results, was found less than one-third complete. This might be a reason for some of its cities' low node count and thus the high success rate. Furthermore, we had to disregard 59 cities from the total dataset, resulting in 1,633 cities. This was due to several mismatches between the 2014 UN world urbanization prospects [224] and the dataset provided by Thompson et al. [219].

4.6.3 Street Network Radius

We chose a radius of five kilometers for the street networks to achieve route lengths of average commute lengths for cyclists [36]. However, a fixed radius means that the area might include only a portion of the center or some of the outer rural areas for different sized cities. To counter this circumstance, we tried to use an adaptive radius that grows with the size of the population [15, 219]. This approach resulted in the disadvantage that the area of the map was different for each city, as was the graph. This affected street network indicators that work with absolute numbers like $node\_count$, $street\_segment\_count$, $length\_total$, and $intersect\_count$ making them difficult to compare between cities. Thus,

we chose to keep the area fixed even though some graphs only feature a smaller part of a city's center region (for very large cities) or include some of the outer rural areas (for smaller cities). Since all cities in our dataset had at least 300,000 inhabitants, very small cities where this effect would have been most severe were excluded, to begin with.

Still, future work should improve the distinction between urban and rural areas even more. In this work, we evaluated the 1,633 largest cities by population size. Necessarily, this means that our data set contains mostly urban areas. While these areas are important to investigate how suited ATCF navigation is for shorter distances and commuting, larger rural areas could yield additional insights which can further our understanding of ATCF navigation for longer cycling trips.

4.6.4 Bike-Friendly Cities

Our results demonstrate that cities that developed in certain regions seem to be categorically better or worse suited for ATCF navigation. As this result is solely based on the street network, it is important to note that a well-suited street network alone does not necessarily make for a bike-friendly city. To test this assumption, we looked at some of the most bike-friendly cities worldwide and checked how they scored on our combined score of performance factor and success rate. One possible way to measure the bike-friendliness of cities is proposed by the Copenhagenize Index(CI) [48]. Initiated by the Copenhagenize Design Company [48] in 2011, CI is a holistic measure for rating cities on streetscape, biking culture and ambition. This index ranks the 118 most bicycle-friendly cities in the world on 14 parameters, of which one is the bicycle infrastructure. Here, the focus is on the protected and separated infrastructure (like cycling highways) [125], which increases the general bicycle adaptability and convenience but not necessarily ease of navigation. Moreover, it may counter the ease of navigation as the bicycle pathways may be separated from other road infrastructure for safety at the cost of limited intersections. Thus, users may have to take longer or more complicated routes with fewer intersections, resulting in an increased (worse) ATCF performance factor. Looking at the top ten most bike-friendly cities according to the CI, we find that seven out of ten cities rank above 1,000 in our metric (see Figure 4.6 for reference), with Paris ranking the best at rank 721 while at the same time ranking eight on the CI. This means that cities that are particularly unsuited for ATCF navigation, according to our metric, can still feature lots of benefits for cyclists in general. At the time of writing, navigation is not included in the CI. Thus, a high CI does not necessarily mean high navigability. We argue that ease of navigation is a

relevant part of any transport modality and the CI and other measures for bike-friendliness should be extended to include navigability especially suited for cyclists, as one of the parameters. Our study finds that some cities are highly ATCF navigation-friendly, but they might lack biking culture or infrastructure limiting its applicability in such places.

While further investigation goes beyond the scope of this paper, this insight shows that bike-friendliness and suitability for ATCF navigation are not necessarily related. Especially dedicated cycling infrastructure could take away from the suitability or usefulness of ATCF navigation as it replaces the flexibility of choosing one's route with safe but dedicated cycle paths. Here a hybrid approach could be a viable solution. ATCF navigation can be used until reaching a dedicated cycling highway. TBT instructions could be then used while riding on it, switching back to ATCF navigation after leaving the cycling highway. However, further research is needed to investigate such scenarios.

4.6.5 As-The-Crow-Flies Navigation Beyond the Bicycle

Most of the related work on ATCF navigation and current commercial applications [17, 210] are concerned with cycling [4, 166, 196]. For that reason, we also chose to make cycling the focus of our study, and we were able to strengthen that focus by using OSM data specifically for bikes. Thus, our results apply to cyclists only. However, this is not to say that ATCF navigation can solely be used by cyclists. Pedestrians [4] and scooterists are two other groups that would benefit from the same arguments having been made in this and related work for ATCF navigation. To extend the results of this study to those groups, appropriate map data should be used in future work to run the same or similar simulations.

4.7 Conclusion

As-the-crow-flies navigation utilizes cyclists' freedom to move beyond the confines of the dedicated car road network and people's own ability to navigate their environment [98] by providing a sense of orientation [204]. However, related work finds problems with the user experience that hinder its widespread adoption. Improving upon existing ATCF navigation approaches will help make the bicycle an even more attractive way of getting around and promote it further as a sustainable mode of transportation. In this paper, we find that the street network can affect the successful application of the LAS and thus, make the ATCF navigation method more challenging to use in different cities. By acknowledging and understanding these differences, we can consider them when

designing new technologies around this method and pick diverse and suitable study locations for future research. These insights will help make the navigation method more usable in all kinds of environments and thus encourage cycling around the world. In turn, making cycling not only a more sustainable mode of transportation in environmental terms but could also have a lasting effect on cyclists' spatial abilities [204], escaping the tyranny of TBT navigation [184].

5 Simulating Human Behavior for As-The-Crow-Flies Navigation

Turn-by-turn (TBT) route guidance allows users to follow navigation instructions based on a precomputed path. However, for novel route guidance, like as-the-crow-flies (ATCF), there is no precomputed path that users can follow. ATCF's distinctive feature is that users make their own decisions, removing the exclusive focus on finding the fastest or shortest path. When we turn away from these wide spread measures as the requirements for successful navigation, novel ways to improve user experience are needed. In this chapter we explore improving the simulation of human ATCF-based navigation behavior in order to predict and to prevent common navigation errors (e.g. walking or cycling into dead ends). Our study improved on our virtual agent (Chapter 4) making the agent's navigation decisions more human-like. We extended the agent's behavioral options to include an angle estimation error. This angle estimation error was calculated on the basis of the results of our online survey with sixty-four respondents. This added calculation improved the similarity between the agents' routes and the routes chosen by the participants (Chapter 3). As part of our work, we analyzed the **empirical** results concerning the angle estimation error of the participants in ATCF navigation situations and we expanded the behavioral options of the virtual navigation agent.

The contents of this chapter originally appeared in Savino, Gian-Luca. "Improving Agent-Based Route Predictions for As-The-Crow-Flies Navigation". In: *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 2022, pp. 1–6. ISBN: 978-1-4503-9156-6. DOI: 10.1145/3491101.3519709

5.1 Introduction & Motivation

Many people rely on mobile navigation apps for their everyday commute, leisure trips, and generally getting from A to B. For car drivers, cyclists, and pedestrians, these apps often use turn-by-turn (TBT) instructions of in-car navigation systems and navigation apps on smartphones or smartwatches. However, in the field of pedestrian and cyclist navigation, the trend is moving away from classical turn-by-turn navigation and towards other navigation methods. One example is the as-the-crow-flies (ATCF) navigation method (see Figure 5.1). The ATCF navigation method provides users with a constant indication of the direction to the destination. Given such information, users will choose the street with the least angle deviation to the destination at decision points. While being found suitable in many use cases [4, 167, 196] and providing an alternative navigation and user experience, the ATCF navigation method also has disadvantages compared to the TBT method. These problems include users ending up in dead ends [184, 196], going in the "wrong" direction [166, 167, 196], and not knowing when to take a turn [4, 196]. To prevent such errors, mobile ATCF navigation systems need to better predict and anticipate their users' potential routes and navigation behavior. This poses a challenge as there is no fixed precomputed route as, for example, there is with turn-by-turn navigation. Existing methods to predict these routes use heuristics like the least-angle strategy (LAS), which describes how humans navigate given only the direction to the destination [95]. However, existing implementations of this heuristic show a mismatch between the heuristic's prediction and actual human behavior [196]. One reason for this mismatch is the task of actually choosing the least angle at any decision point. User studies with ATCF navigation have shown that this decision can be very difficult [4, 196]. While an agent will always choose the better angle, no matter how small the deviation is, a human might not even realize the difference between a 20° and 23° angle and potentially choose a sub-optimal path. While related work has successfully explored software-agent-based simulation based on the LAS [95], this work extends existing approaches by creating and including a model for this angle estimation error into the agent's decision process, making its performance closer to that of humans. In the context of this work, we test a novel uncertainty (UC) agent against an existing LA agent. We compared the routes of our novel agent with route data of humans using the ATCF navigation. The results show that our novel agent better represents human navigation behavior under ATCF navigation guidance than existing LAS approaches. With this work, we contribute a model that simulates a human error when judging angles at decision points. Furthermore, we extend



Fig. 5.1 A comparison of visual as-the-crow-flies and turn-by-turn navigation methods for a typical navigation situation.

existing agents and thus improve potential agent-based modeling of human navigation behavior.

5.2 Related Work

This section presents insights into how humans perceive angles in navigation, how this perception affects their behavior, and discuss existing approaches of agent-based modeling of ATCF navigation behavior and applications of the navigation methods in related studies.

5.2.1 Perception of Angles by Humans

People in unknown environments need three essential components to find a destination: their location, orientation, and the metric properties of the environment (e.g. how many kilometers am I away from my destination) [63]. Based on these components, people form a cognitive map of their environment and use it to find their way around [63]. To do that, humans rely on their perception for wayfinding and navigation [78]. The environment is perceived and processed visually, which can lead to misjudging distances and distorting the cognitive map of the environment [78]. This results in navigation and wayfinding being shaped differently by the underlying individual model. This was already suggested in 1992, when it was shown in a small experimental setup that people, even with good local knowledge, are not able to locate places using distances or angles [79]. In order to compensate for these inaccuracies when navigating through an unknown environment, humans employ different strategies. Dalton [51] observed that they strive to choose the least possible angular deviation from their current path on the way to their destination, i.e., to walk straight ahead for as long as possible. This preference is consistent with the experiments of Bailenson et al. [11] conducted in 2000. Here it was shown that people

chose routes that contained the longest possible straight sections. If several routes had an equal proportion of straight sections, those were preferred which contained the least number of turns at the beginning of the route [11]. This strategy is also known as “longest leg first”.

When it comes to the perception of angles, Sadalla and Montello suggested in 1989 that humans are very good at estimating right angles and probably diagonal angles (45°, 135°, 225°, and 315°) because the Earth’s gravitational field provides a fixed point [190]. An experiment showed that humans could estimate angles close to 90° well, while angles between 0° and 90° are overestimated and angles between 90° and 180° are underestimated. This suggests that human perception tends to bias angles toward 90° [190]. In 1993, Loomis et al. conducted further experiments on the precision of human estimated angles confirming the findings of Sadalla and Montello [129]. The studies above suggest that perceiving angles as part of a navigation method could cause some inaccuracies for certain angles. How exactly these inaccuracies affect ATCF navigation has been found by the following two studies. Both Albrecht et. al. [4] and Savino et al. [196] tested how well participants were able to navigate given ATCF navigation instructions. However, the studies differed in the modality used to communicate the direction to the destination. While Albrecht et al. [4] used spatial audio, Savino et al. [196] used a visual interface. Still, both studies found that participants had difficulties making the right call for minor angular deviations between two streets.

In this paper, we are quantifying this difficulty with the help of a pre-study in which participants have to make a call between two streets given ATCF instructions with minor angular deviations. This specific task is essential for ATCF navigation because the correct interpretation of angles is central to successfully using the navigation method. A better understanding of this error will help us develop a better agent-based model to predict human wayfinding with the ATCF navigation method.

5.2.2 Modeling Human Wayfinding with ATCF Navigation

The most suitable model to describe people’s navigation behavior with ATCF navigation is the least-angle strategy proposed by Hochmair and Frank in 2000 [96]. Here, a person selects the street with the least angle deviation from the direct target direction at each turn when navigating to a visible location like a tall building or other landmark [96]. To evaluate the LAS, Hochmair [95] conducted a virtual simulation. In order to build an agent that was able to traverse a street network with close to human-like performance,



(a) **(b)**

Fig. 5.2 Two of the five intersections which participants saw in the online survey. (a) Shows an intersection without a navigation aid, where participants had to choose the street that would lead them to the destination, which was "exactly straight ahead". (b) Shows an intersection with the instruction angle pointing to the right.

he presents the memorized least-angle strategy as the basis for his agent. In addition to the above-described behavior, the agent could memorize the last node visited but could not return to this last node in a subsequent step (except when in a dead end) [95]. In this paper, we will use this implementation as the basis for implementing our own agents.

While the LAS is a heuristic describing human wayfinding behavior, the ATCF navigation method utilizes the LAS by providing the direction to the destination throughout the navigation task for better orientation and fewer estimation errors. However, field studies have shown that the ATCF method has a few drawbacks. A recent study by Savino et al. [196] on ATCF navigation found that cyclists had problems going into a direction that deviated from the indicated direction to the destination, similar to what Pielot et al. [166] found for pedestrians. Furthermore, participants were unsure when to take a turn due to the lack of a map, similar to the results of Albrecht et al.[4]. Finally, participants ran into dead ends while exploring possible routes to the destination, as also seen in the study of Robinson et al. [184]. In order to anticipate and circumvent these problems, we need to predict someone's path when using ATCF navigation successfully. Since there is no precomputed path, we have to closely model human decision-making to calculate a possible path they might take to be able to react to problems they might run into. Based on the previously described difficulty to assess small angle deviations, in this work, we will investigate whether an agent using the LAS together with a human-like angular estimation error can represent the navigation behavior of participants using the ATCF navigation method [196] better than existing implementations from the literature [95].

5.3 Pre-Study

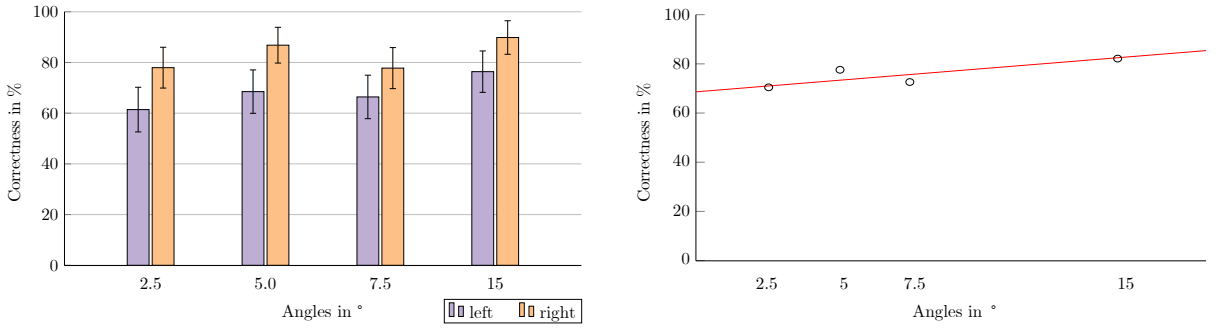
In this pre-study, we examine the difficulty of choosing the turn with the least angle deviation to the destination, as suggested by the LAS. The study explores how well humans can make navigation decisions based on estimating small angles of less than 15°, possibly identifying other influencing factors, and deriving a function from the collected data that models human decisions uncertainty in this task.

5.3.1 Study Design

Five traffic intersections were photographed to carry out the study, each with two possible turns. The perspective of the photos was chosen, as best as possible, from the apex of the two outgoing roads so that the subject's point of view would not later dictate any tendency about the direction (see Figure 5.2). In an online survey, participants were asked to decide which street they would take, given the information shown on the smartphone. The smartphone showed an ATCF navigation interface with a compass needle pointing towards the destination. Whenever there was no smartphone, the instruction was that the destination was precisely straight ahead. The angles shown on the phone were: 0° (straight ahead), 2,5°, 5,0°, 7.5°, and 15°. All angles greater than zero were once pointing to the right, and the left with each road intersection. Combined with the "no smartphone" situation, this made for ten different situations per intersection. Based on five intersections, this results in a combination of 50 different situations. In total, 64 respondents participated in the study via an online survey. The study itself was conducted in English. Participants ranged in age from 18 to 54, with an average age of 27 (SD=7.67). The participant pool consisted of 32 females, 30 males, and two non-binary participants. The 50 situations were divided into five groups, each with ten different situations to keep the survey time short while still guaranteeing an even distribution of results for each configuration of road intersections and associated angles. Each of these groups includes each of the available angles, once pointing to the left and once to the right and an image without instructions in randomized order. During the survey, each participant evaluated two groups (20 situations).

5.3.2 Results

Based on participants' responses, we calculated the percentage of correct decisions per angle and direction. Figure 5.3 shows the percentage of the correct decisions broken down by angle and direction, so the quantities include all underlying intersections in



(a) **(b)**

Fig. 5.3 The correctness of participants judging the angles on the pictures. (a) Scores for the different angles point left and right. (b) The uncertainty function which we derived from the data.

equal amounts. For the instructions oriented to the right, at 2.5° a total of 77.95 % of the responses were correct, at 5.0° we saw 86.82 % correct responses, at 7.5° 77.78 % of the responses were correct, and at 15° a total of 89.84 % were correct. For the left-facing instructions, at 2.5° 61.42 % of the responses were correct, the instructions at 5.0° again had more correct responses at 68.50 % than 7.5° at 66.41 %, while the 15° angle had 76.38 %. Based on the collected data, we used linear regression to construct an uncertainty function that maps human error to decisions with small angles. For this purpose, the data of the angles from Figure 5.3a were combined into angle classes in Figure 5.3b. From this, the following function can be derived: $f(x) = 0.009319 \cdot x + 0.686236$.

In the following section, we will extend the existing LAS agent from Hochmair [95] with the derived uncertainty function to introduce an error in the assessment of the angles for the decision making of the agent. We will compare this new agent to the existing agent to test which one achieves a higher overlap of route decisions when compared to human navigators in an ATCF navigation task.

5.4 Simulation & Agents

To evaluate how the uncertainty function influences the least-angle agent and to test whether it makes its decisions more human-like, we create a simulation environment similar to that of Hochmair [95]. In this section, we will introduce OSMnx [29] for the simulation environment and our custom LA agents.

5.4.1 Simulation Environment

The basis of the least-angle simulation is provided by OSMnx by Geoff Boeing [28, 29]. OSMnx provides the functionality to create and analyze directed graphs from Open Street Map (OSM) data [158]. The directed graph itself consists of nodes and edges with information about their latitude, longitude, the number of connected edges and other road traffic specific meta information. OSMnx provides information about the entry and exit degree of the node, incoming and outgoing edges, and information about traffic, road, and environment data. The edges have attributes about their start and destination node, the euclidean distance, as well as the bearing (compass direction), which describes the geographic orientation of an edge. This can be used to determine the angle between two edges or an edge and the target node. Our agent uses this functionality to decide which node to visit next at each decision point and will be affected by our uncertainty function.

5.4.2 Least-Angle Agent & Uncertainty Agent

The following subsections describe the two agents we built. The first one is a replication of Hochmair's original agent [95] and the second one with the extended angle error implementation.

Least-Angle Agent

The implementation of our least-angle (LA) agent is based upon the implementation by Hochmair [95]. When finding its destination, the agent follows the following principle: The agent starts at an initial node, knowing its destination. Starting from its location, all further reachable options are considered in the form of nodes connected via edges. The direct predecessor node is then removed from this set, and the remaining nodes are sorted in ascending order according to their angular deviation from the destination. The agent then travels to the node with the least angular deviation from the target that is still unvisited (has not been visited before). If all nodes have already been visited, the agent returns to the previous node of its location. This principle is repeated until the given destination is reached or one of the termination criteria is met. Termination occurs if the starting node has no neighbors or all available neighbors have already been visited, and the predecessor node has been visited more than once.

Uncertainty Agent

To examine and compare the findings from the preliminary study, we extend the above described LA agent. This new uncertainty (UC) agent should also use the least-angle

strategy as a basic structure. In addition, the findings from the study are integrated into the agent in the form of the described uncertainty function. This works with the help of the function from the regression model in Figure 5.3b, which is incorporated into the decision making of the uncertainty agent. The model describes the correctness of the decision, as a function of the angle difference, between two potential route options. Therefore, during the agent's pathfinding, we calculate the likelihood of the agent making a wrong decision for each decision between unvisited neighbours. Therefore, we take the difference of the angle deviation to the destination of the next two best neighbors and calculate the probability of error based on our error function. For example, if one option has an angle deviation of 20° to the destination and another 23° to the destination, resulting in a difference of 3°, the probability of making a correct decision would be 0.71%. Based on this probability, if the agent actually makes a mistake, the "worse" neighbor (in our example, the one with the 20° deviation) is chosen to be visited next. This example is depicted in Figure 5.4.

5.5 Results

In this section, we will present the results of the comparison between the LA Agent and the UC Agent regarding the overlap of their routes with human performance. For this comparison, we use the data set from Savino et al.'s [196] study with a total of 13 participants across two experiments. To compare how similar the two agents performed

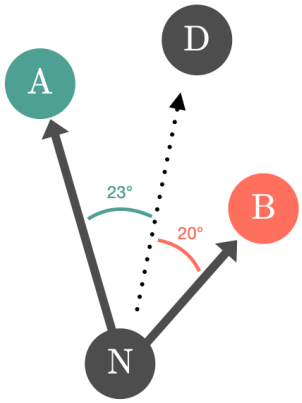
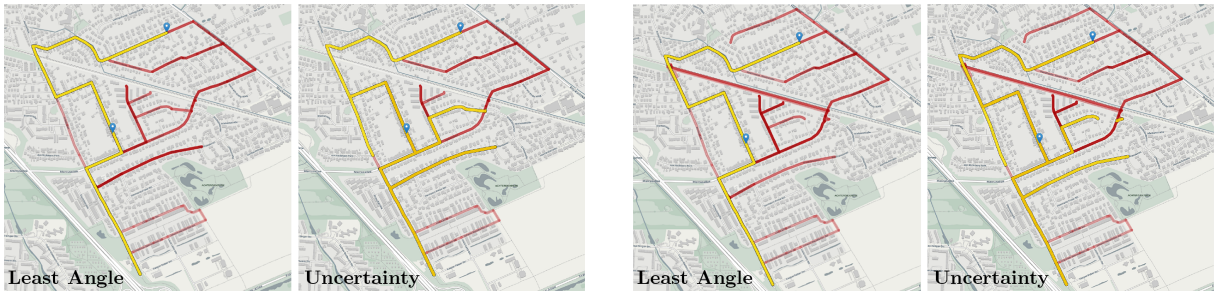


Fig. 5.4 Example of an angle-decision situation for the agents. At node *N* with destination *D*, the agent can visit node *A* or *B*. Node *B* has a smaller angle deviation of 20°. The least-angle agent will always choose to visit node *B*. However, the uncertainty agent will have a probability of 29% to choose node *A* and make a wrong decision.



(a) **(b)**

Fig. 5.5 The visualized overlap between the participant data from Savino et al. [196] and the respective agent. (a) Shows the result for experiment 1 and (b) the results of experiment 2 in Savino et al.'s [196] data.

against the human participants, we looked at the number of identical edges between participants and agents. In addition, a coverage factor of the routes is compared, which is calculated from the proportion of the route distance covered. Figure 5.5 shows the congruence of the route of the LA agent with the routes of the user data. To illustrate the scale of comparison, the subjects' route data are superimposed and drawn in red on the map. The parts of the route that were also traversed by the LA and UC agents are highlighted in yellow. While the LA agent behaves deterministic, coverage equality with the UC agent is not sufficient by simply comparing a single produced route. Instead, we produced a coverage graph from multiple routes of the UC agent. By comparing node pair by node pair from the study data with the data of the agents, we obtain coverage values that are shown in Table 5.1. Here, the UC agent covers 12.8% more edges in the first experiment and 15.5% more distance, respectively. In the second experiment, the UC agent covers 11.3% more edges and 12.8% more distance of the participants' paths. Overall, the built-in angle estimation error improved the coverage by 51 % on average compared to the LA agent. Which means that the UC agent had a more human like performance than the existing LA agent.

	Experiment	Least-Angle	Uncertainty
Overlap of edges in %	#1	24,6	37,4
	#2	20,0	31,3
Overlap of length in %	#1	34,2	49,7
	#2	25,0	37,8

Table 5.1 Overlap of the agent routes with the participant routes.

5.6 Discussion & Conclusion

Often humans are not the perfect machines we want them to be. Related work has shown that ATCF navigation sometimes relies on making very precise and, therefore, difficult angle estimations, resulting in bad navigation decisions [4, 196]. In some instances, a navigation decision that is obvious for a simple software agent is ambiguous for a human. In this work, we show (1) that there is a measurable effect of the difficulty to detect differences in small angles and (2) that this ability affects how humans use the navigation method. Subsequently, we learn that heuristics like the least-angle strategy [96] are not sufficient to model this complex human behavior. Adding an angle estimation uncertainty lets the agent produce more similar routes to those of human participants in a navigation experiment than existing agents based on just the least-angle strategy. While this result allows us to model human wayfinding with ATCF navigation better than before, our approach has some limitations that we discuss in the following paragraph.

The angle estimation error of our UC agent is based on the results of our pre-study. During the analysis of the results, we used the non-smartphone version of the decision task to check for biases towards left or right turns for each of the five intersections. We found that eventually, not only the compass direction had an effect on the decision process, but also other factors such as the direction cars are parked in, visible traffic signs, as well as the surface of the street (e.g. cobblestone versus asphalt). This led to an asymmetry in the results, shifting the majority of decisions in one or the other direction. While limiting the results, this gives us meaningful insights into potential aspects to further improve our agent. Furthermore, we limited our estimation task to a maximum of 15°. This means we can not know if our assumption of a linear function holds for larger degrees. However, we tested our setup initially with degrees up to 30° and found that participants correctly interpreted degrees larger than 15. Our results motivate further experiments with more than the one aspect that has been discussed in this work. Future work should consider these complex aspects and test them in a real-world environment.

In the context of this work, we explored the effect of the human angle estimation error for agent-based modeling of human wayfinding. For this purpose, we investigated human decision-making behavior, with compass instructions, at intersections in a pre-study and derived an angle estimation error function. This function was integrated into the decision making of a least-angle agent. Simulations showed that the angle estimation error led to more human-like route choices than the existing LA heuristic. The UC agent model could be used in an ACTF+ [196] like interface to predict navigators' errors and reduce

navigating into dead ends or taking non-target detours. This could help prevent user frustration and increase trust in the navigation device.

6 Safely Interacting With Technology While Cycling

When designing novel mobile applications, researchers and practitioners must be aware of the safety risks associated with "interaction in motion" [134]. One of the ongoing challenges in Human-Computer Interaction is keeping the balance between ecological validity of the research results and the safety of participants during experiments [198]. This chapter presents a study concerned with this problem by investigating suitable interaction modalities for cyclists to report traffic incidents. As cyclists' hands and feet are busy during cycling, the interaction modalities we developed needed to account for this and adapt to the cyclists' needs and possibilities. We found that talking to voice assistants, when compared to touch input and basic voice recognition, allowed cyclists' attention to remain focused on their environment while reporting traffic incidents. As part of our work, we built an **artifact** in the form of a custom iOS application. In this chapter, we also present the **empirical** results of a comparison of three interaction modalities for our iOS-based traffic reporting application for cyclists.

The contents of this chapter originally appeared in Savino, Gian-Luca, Moraes Braga, Jessé, and Schöning, Johannes. "VeloCity: Using Voice Assistants for Cyclists to Provide Traffic Reports". In: *Proceedings of the 29th ACM International Conference on Multimedia*. 2021, pp. 3482–3491. ISBN: 978-1-4503-8651-7. DOI: 10.1145/3474085.3475509

6.1 Introduction & Motivation

Bicycles are becoming an increasingly important means of transport in many cities as they complement or replace the car or public transport as a viable option [179, 180, 236]. Cities worldwide already have dedicated cycling infrastructure and more cities are following to implement car-free areas or so-called cycle highways [125, 148]. As the number of cyclists rises and cycling becomes one of the main transportation methods for daily commutes, cyclists need and use navigation applications more often. In the first half of the year 2020, Google Maps saw a worldwide increase of 69% in routing requests for bicycles [116]. Not only specific cycling modes are implemented within existing navigation applications (e.g. Google Maps or Strava [215]), but also apps or new devices (e.g. Komoot [113], Beeline [17], SmartHalo [210]) are developed, which aim to improve the overall cycling experience and provide navigation instructions tailored to cyclists.

However, navigation apps for cyclists still lack information on real-time traffic, incidents and obstacles. Car drivers can get such information through various services which report traffic jams, closed lanes or roads, construction sites, dangerous objects on the road or other incidents. Most of the time such information is embedded directly within the navigation app. For example, the navigation app Waze [229] uses volunteered geographical information (VGI) [81], which is mainly provided by its users to improve their routing and inform drivers about traffic-related incidents. This information can also be shared with public authorities (as Waze does in some cases) to see where road infrastructure needs improvement. We see an emergent need for similar services for cyclists, to improve routing and infrastructure in the future. However, interacting with such a service while riding could pose security risks as most cycling applications are operated using touch interaction. They either require a person to hold a smartphone or strap it to their handlebar similar to how dedicated devices are usually fixed to the bicycle's handlebar [17, 210]. Therefore, we explore the voice as a possible interaction technique that is suited to safely report traffic incidents and obstacles while cycling. While audio has been proven to work well for cyclists to receive information [53, 137, 185] (e.g. turn-by-turn instructions), there is only limited work on voice as a method to input data while cycling. Thus, these efforts do not only improve the safety of cyclists but also enable them to interact with more complex data than before. Consequently, in this paper we investigate the following research question:

RQ1: Which inputs methods are suited for cyclists to safely report real-time traffic, incidents, and obstacles?

In a pre-study, we used a user-centered design process to identify participants needs and behaviors, which informed the design of our application as well as the comparison of viable interaction techniques. Based on our findings we developed an app called VeloCity that allows users to report real-time traffic information for cyclists. In a user study (n=21) we compared three interaction techniques (touch, in-app speech recognition, and using the operating systems' voice assistant), that enable cyclists to provide this information during live traffic.

We found that voice-based interaction was preferred over touch to interact with the reporting app VeloCity. Still, both touch and speech recognition were similarly distracting for participants, while only the voice assistant allowed them to pay more attention to traffic. This was due to the hands- and eyes-free interaction that the voice assistant offered, which even novices, who have not been using voice assistants before, quickly learned to take advantage of. There was no significant difference between the usability of all three techniques. Based on these results we formulate five guidelines for designing voice user interfaces (VUIs) for cyclists to provide traffic reports. Consequently, this paper contributes (1) the first, to our knowledge, study on viable interaction techniques to report live traffic data while cycling; (2) the use of voice assistants specifically for cycling tasks to enable safe, hands- and eyes-free interaction.

6.2 Related Work

To identify interaction techniques suitable for reporting live traffic incidents while cycling, we review previous work on cycling in HCI and interaction in motion.

6.2.1 HCI & Cycling

Research on cycling in HCI looks at two perspectives: Input from a user to a system or output from the system to the user. Especially in the domain of navigation, there is a lot of related work on how to inform the user through different kinds of output methods. Pielot and Poppinga et al. [167, 168] for example used vibrating handlebars in a navigation setting. Through the vibration of the left and right handle, they communicate the direction to a destination in an as-the-crow-flies manner. Albrecht et al. [4] used spatial audio and Savino et al. [196] a visual display to convey similar information. Another approach to tactile information is Vibrobelt. The belt, worn around the waist, gives waypoint, distance and endpoint information using directional tactile cues and was able to successfully navigate participants over an unfamiliar route [214]. For a

pure turn-by-turn style approach, Huxtable et al. [103] present a tactile interface for wayfinding devices designed for cyclists. It is made up of two wristbands that vibrate to signal left and right turns. In terms of improved visual map approaches, as many navigation applications use them, Dancu et al. [52] investigate to move this visualisation into the environment through a map which is projected in front of the bicycle with the goal to make cyclists more attentive to their environments. All of these systems do not only enable cyclists to interact with information while cycling, most of them also aim towards making this interaction as safe as possible by directing the user's visual attention away from the mobile device. Because, not only are cyclists victims of bicycle-motor vehicle crashes, single-bicycle crashes (i.e. a fall or obstacle collision) are as well a serious problem that needs to be kept in mind when designing interactive systems for cyclists [201]. About half of all single-bicycle crashes are related to infrastructure such as collision with an obstacle, riding off the road or skidding due to slippery surfaces [201]. To counter bicycle-motor vehicle crashes, Carton [42] presents a solution to improve the visibility of the rider's hand gestures. LED's attached to gloves will illuminate, depending on the gesture the gloves recognized, and thus amplify the gesture, especially at night times. An approach to warn cyclists themselves was tested by Matviienko et al. [136]. They used multimodal warning signals for child cyclists and found that reaction times could be reduced when using a combination of tactile, visual, and auditory feedback over unimodal warnings. After presenting systems that make the output available to users and care for their safety, we now look at systems that actively enable cyclists to interact not only with the information mobile systems provide but also with the systems themselves through an appropriate interface.

6.2.2 Interaction in Motion

Interacting with mobile devices on a bicycle can be very dangerous [226]. Still, people interact with these systems while in motion, including cycling [134]. To better understand the reasons and consequences behind this phenomenon, Marshall et al. [134] classify interactions in motion with regards to the locomotion's inhibition on interaction and the interactions related to the locomotion. Within this taxonomy, cycling is classified as a strongly constrained activity as hands and feet are occupied with operating a vehicle. And even though mobile devices are increasingly portable, most systems are not designed for meaningful two-way interaction whilst moving [135]. Because except for navigation applications, most interactions on the bicycle are unrelated to locomotion. The constraints

on hand (and foot) interaction, which cycling creates, are especially relevant at points when one may wish to maneuver. Related work takes on this problem from many different angles. Especially when you are confronted with an obstacle, fast maneuvers can be necessary. Thus, touch interaction seems unfitted for the task of logging these obstacles while riding. While using large user interface elements (like buttons) has been shown to work for pedestrians while walking [108], studies have found that cyclists prefer techniques where they do not have to take their hands off the handlebar [53]. Voice-based interactions, therefore, seem like a good fit. However, they come with the disadvantage of potentially being masked by traffic noise or the necessity to wear headphones, which in return mask traffic noise and are thus a potential safety hazard [185].

Aside from touch and voice as input methods, related work has explored a variety of ways how cyclists can interact with mobile devices. Dancu et al. [53] explore gesture-based input. Through hand gestures, cyclists can control a turn indicator that is mounted to the bicycle. This is an example of a "Tailored Solution" regarding the taxonomy by Marshall et al., as the turn gesture (stretching one arm outwards to signal a turn) is encouraged by the locomotion itself. Vechev et al. [225] investigated an interface that allows tapping different areas on the user's body to interact with a mobile system while cycling. This, as well as the above strategy, however, require removing one's hands from the handlebar. In response to this disadvantage, Woźniak et al. [233] created custom handlebar controllers. These feature buttons as well as moving parts to interact with the most common smartphone features like accepting a phone call or play/pause music.

To expand the research on existing interaction techniques, we explore leveraging the possibilities of built-in voice assistants to report live traffic incidents for cyclists. Voice assistants are being successfully used in other domains [5] to interact with multimedia data and are already widely available and easy to connect to existing systems.

6.3 Pre-Study

The goal of the pre-study was to build an in-depth understanding of what interaction techniques people naturally use while cycling. In this study, we used a contextual inquiry [21] approach (similar to [216]). This allowed us to observe users in a real-life situation, and learn how they would use an application to report live traffic information for cyclists. Therefore, an experimenter together with a participant embarked on a bike ride and introduced *imaginary* obstacles along the road which the participant should log using an imaginary application. We made sure all participants were experienced bike

riders and explained that they should only interact in ways they felt safe and comfortable with. Since we focused on a smartphone application we mounted a smartphone that was turned off to the handlebar. The goal of this method was to observe participants in-situ to learn what kind of incidents/obstacles they would report and what interaction techniques they would use doing so.

6.3.1 Participants

We used convenience sampling to recruit six participants to take part in the pre-study. All participants were equipped with an omnidirectional lapel microphone connected to a smartphone that was used to record them *thinking aloud* [152]. All of the participants reported riding bicycles on a casual (at least once a week) to regular (3 or more times a week) basis. Everyone took part voluntarily and was not compensated for their participation.

6.3.2 Procedure

The entire experiment lasted for 30 minutes. Participants were familiarized with the experiment which asked them to use an *imaginary* mobile application for reporting live traffic incidents while riding a bicycle in real-life conditions (i.e. sharing traffic with cars, other bicycles, and e-scooters, dodging construction sites, roadblocks, pedestrians, etc.). They were asked to think aloud during the whole experiment. During the ride, participants encountered *imaginary* obstacles introduced by the experimenter which were inspired by the ADFC "Mängelmelder", a web platform where citizens can report obstacles and incidents for cyclists [1]. In addition to those, real-life obstacles were encountered which participants should also report to the app. They imagined their own version of the application including how it looked and how the interaction worked. As such, we could observe the challenges of the reporting task and the constraints they dealt with while cycling. Participants were offered to ride the same route a second time, which allowed them to get used to the demanding conditions and think more creatively. In the end, we used an unstructured interview to ask them about specific events, their reasons for the chosen interaction technique, and their general opinion on a traffic reporting application for cyclists.

6.3.3 Results

Once participants were familiar with the task, they felt comfortable making suggestions and interacting with the app in a way that felt natural to them. They changed from

stopping to interact via touch to using voice commands and voice assistants while in motion. Regarding voice commands, they mainly used short words to describe the obstacle and mentioned that "[...] it would be nice if the app could translate what you say into categories" (participant 6) or that "it would be just easier to say keywords that are already a category in the app, so the app would understand me" (participant 6). Another participant commented that he would prefer to communicate with short sentences, but the assistant should understand full sentences. An example phrase for a voice assistant was "Hey bicycle app, please log shattered glass to my position" (participant 3). These insights helped us to develop and design the VeloCity application as well as the main study.

6.4 VeloCity Application

VeloCity was developed in Swift 5 and is compatible with iOS 13.2 and newer. The application consists of four main sections: (1) The map-view features a map that shows the users current location. This view features an action button that, depending on the condition, is used to report incidents via touch or speech recognition (see Figure 6.1b and 6.1e). The live location feature and the map, although not necessary for the experiment, were included to give a realistic look and feel of the app, as this was how participants imagined the app to look like in the pre-study. Additionally, a recording button on the screen is used to mark the start and end timestamps in the application logs during the experiment. This way we were able to differentiate between trial runs and the actual conditions. (2) The incident list features all incidents which have been reported during a session (see Figure 6.1i). It serves as a visualization of the result of each condition and allows participants to correct their inputs afterwards. This was used to check how many times participants realized they made a mistake and wanted to correct it after a session. (3) The survey view contains the surveys for the main study. These can be filled in right in the app. (4) In the settings participants can input their participant-ID, change the input method and the language of the application (see Figure 6.1a). The input method could be changed between touch input and speech recognition. This changes the action button in the map view which then triggers the corresponding input when tapped. The experiment was conducted in two languages depending on the participant's preferences. The language could be switched between German and English in the settings.

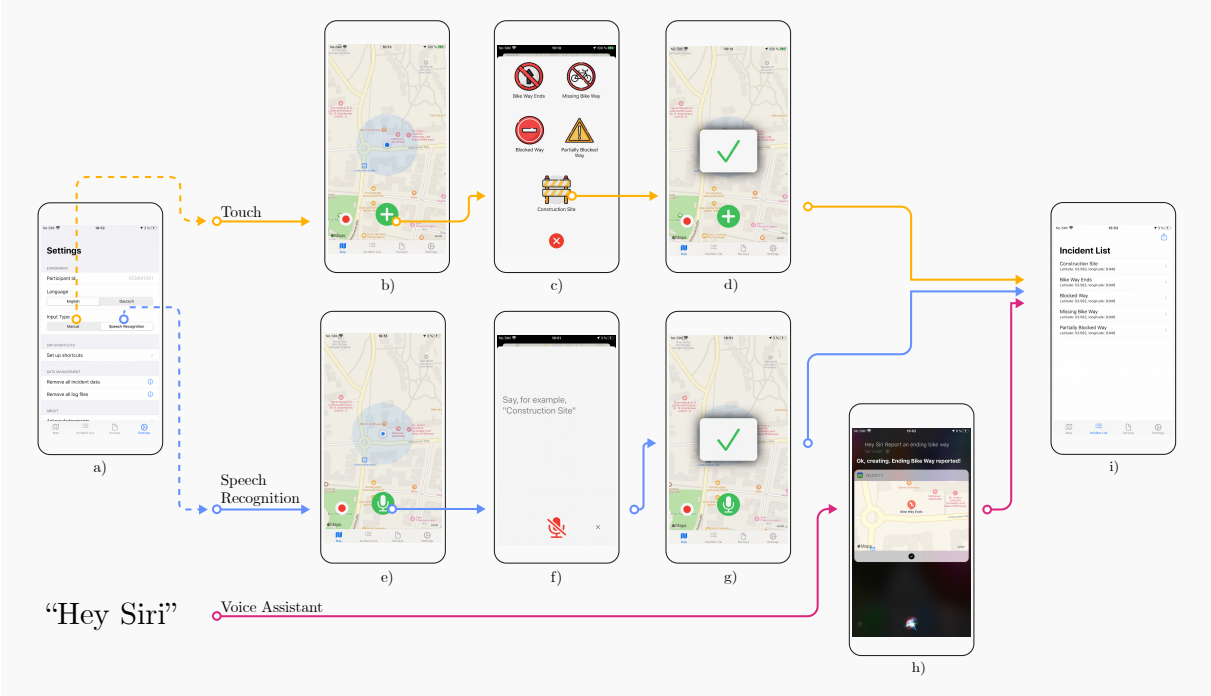


Fig. 6.1 User Story of the VeloCity application. Depending on the condition, the participant switched on either "Manual" (touch) or "Speech Recognition" in the Settings. The green action button then changes to a plus sign (touch) or a microphone (speech recognition). The participant can then report an obstacle as shown above and gets visual as well as auditory feedback (only in the speech recognition condition) after a successful report. The activation phrase "Hey Siri" can be used from anywhere, even when the device is locked. Eventually all reports are saved to the Incident List.

6.4.1 Input Methods

Based on the pre-study we identified three input methods that are relevant for cyclists when reporting live traffic information: touch, in-app speech recognition, and the built-in voice assistant (Siri). These were implemented into the VeloCity application. Touch is state of the art in other comparable applications such as Waze and functions as a baseline. Speech recognition and the built-in voice assistant were proposed by participants in the pre-study as a successful technique to interact while cycling. Since it was not clear which one they would favor, and how exactly they would perform, we implemented and tested them in our main study.

Touch

Figure 6.1b-6.1d shows the user story for adding an incident using touch. The user taps the action button, selects a category, and is presented with the confirmation that the incident was added. The look and feel of the touch condition were inspired by Waze. We used a similar layout using expressive icons to present the obstacles that can be reported. This was also in line with how participants imagined the application in the pre-study. If a participant accidentally pressed the action button, the incident view (Figure 6.1c) could be dismissed by pulling it down.

Speech Recognition

Reporting an incident via speech recognition is similar to the touch input (see Figure 6.1e-6.1g). After the user taps the action button, the app will play a sound to cue the user that it is ready to record. Similarly, the app will play sounds when the user cancels or dismisses the view (by pulling down on it), as well as when the speech recognition is able to recognize a voice command. The latter case also dismisses the voice recognition view and displays a confirmation on the map view (see Figure 6.1g). To make for a robust implementation, we use iOS's built-in speech recognizer in combination with the fuzzywuzzy_swift library [132] which uses Levenshtein distance to find the most similar incident category to the spoken input. If the input roughly matches one of the categories the app finds a match and saves the incident. This meant that the speech recognition would understand even short phrases like "construction" and map them to the appropriate category (in this case "construction site"). This resulted in very few cases where the speech recognition did not recognize the correct category.

Voice Assistant (Siri)

For the voice assistant condition, we implemented six shortcuts that can be added to Siri – one for each incident category and a generic one, that can add any category. Shortcuts offer the possibility to add custom commands to Siri and connect them with your own application. These shortcuts must be set up once but can then be used from anywhere on the device. Thus, the app could be running in the background, or even be completely out of iOS' memory. In our experiment, we instructed participants to use the "Hey Siri" command in combination with the custom shortcuts such as "Hey Siri, report an ending bikeway" (see Figure 6.1h). As this example highlights, in contrast to our speech

recognition, Siri needed a full sentence to understand the command. This was to make it as conversational as possible.

6.5 Study

Using the VeloCity application, the study addresses the research question (RQ1: Which input methods are suited for cyclists to report traffic incidents?) by looking into which of the investigated input methods participants prefer and how they perform in regards to attention and usability.

6.5.1 Study Design

In order to reach a diverse sample and control for hard to control factors like weather, traffic and the type of bicycle, the study was conducted remotely and under lab settings at a desk meaning that participants did not actually ride a bike in traffic. This was done to minimized safety risks as participants would use real interaction techniques designed by us, which could harm them when used in real traffic and without sufficient training. Participants installed the VeloCity application on their own iOS devices and were sent three videos of the experimenter riding a bicycle through an urban environment, one for each of the three conditions. Using a within-subjects design each participant went through each of the three conditions using the three different input methods respectively. The order of the conditions was randomized using a Latin square design, keeping the order of the videos and permuting the input methods.

6.5.2 Participants

We used convenience sampling to recruited 21 participants from different backgrounds such as five different countries (Brazil, Canada, Belgium, Denmark, Germany) and six nationalities (Russian, Turkish, Brazilian, Irish, Maltese, German). Of our participants, 52% identify as female, 43% identify as male, and 5% identify as diverse. Moreover, 19% are aged 18 to 24, 48% 25 to 30, 24% 31 to 40, and 9% over 40. When it comes to participants' cycling habits, most of them cycle on a weekly basis (38% of respondents answered with "1–2 days a week" or "3 to 7 days a week") and have their own bicycle. When asked about the reasons for cycling we found that cycling is still often seen as a hobby, but health and environment-related reasons also play a role alongside. With regards to the technology used while cycling, apps are more popular among our sample than dedicated cycling gadgets (like Beeline [17]). 8 participants use smartphone apps, 1



Fig. 6.2 Screenshot of one of the videos participants saw during the experiment. In order to remember the five different obstacle categories and the respective commands to report them, they were always included in the video on the left side of the screen.

participant uses a sports watch, 1 participant uses a smartwatch and 1 participant a bike computer. When asked how they carry their smartphone while cycling, 8 replied that they carry it in their pockets and take it out, when needed. When it comes to voice assistants like Siri, Alexa or Google Home, about half of our sample (10 out of 21) reported using some kind of assistants, mainly to automate simple tasks, such as setting an alarm or timer, play music, or check the weather.

6.5.3 Procedure

The entire experiment lasted for about one hour and was video recorded for later analysis. Previous to the session, participants were sent information material on how to install and set up the application. The experiment started with a greeting and a brief explanation of the study. All participants were informed that their participation is voluntary and that they can choose to end the experiment at any given time. The experimenter then ran through a checklist, checking the in-app settings and settings of the operating system (e.g. whether “Hey Siri” was activated). A brief explanation of the app was given, showing the

user an introductory video of a sample reporting task. The different incident categories were explained and how to report them correctly using the different input methods. For the main task, participants were asked to set up the respective input method and place their phone on a flat surface in front of them. They were asked to not hold the phone in their hands as we wanted to imitate the phone being strapped to the handlebar. Before each condition participants were given time for a dedicated training phase and were able to ask questions until they felt comfortable using the input method. They were then asked to open a link to a video of an experimenter driving a bicycle through an urban environment (see Figure 6.2). In order to remember the different incident categories, they were displayed in the video at all times. While watching the video, participants were asked to report any of the five obstacles they noticed. Each video was 5 minutes long and participants were asked to report all incidents without stopping it. After each video participants answered a questionnaire asking them about their experience with the just used input method and its usability. Finally, a short, unstructured interview with participants has conducted at the end of the study.

6.5.4 Measures

Using a mixed-methods approach, we collected data from the application logs, the experiments' recordings, the surveys and the interviews (which were loosely transcribed for the analysis). The app itself logs all user interactions and settings in a text file as soon as it is opened for the first time. This log data includes language used to complete the conditions, timestamps of when a reported obstacle was added, edited, or deleted, etc. The main measures that are taken to answer our research question are:

Personal Preference: We compared identical questions from the questionnaire among all three input methods, in order to determine which one users liked best.

Attention: Participant's visual attention is measured by counting how many times they looked at the device's screen. Video recordings of the call were used for the analysis.

System Usability Scale: We use the System Usability Scale (SUS) [38], to assess which of the three input methods was better rated by users, in regards to usability.

6.5.5 Results

All 21 participants were able to complete the experiment. The data presented in this section were statistically analyzed in R using the following methods: The Shapiro test plus

Question	Median Answer			Kruskal-Wallis			Wilcoxon-Pratt Z-Value			Wilcoxon-Pratt p-Value			Effect Size		
	TO	SR	VA	X2	Df	P-value	TO-SR	TO-VA	SR-VA	TO-SR	TO-VA	SR-VA	TO-SR	TO-VA	SR-VA
Rate this input method based on its usefulness when riding a bicycle - *very useful (5) to not useful at all (1)*	3	4	4	7.0965	2	0.029 *	-2.464	-2.7	-0.288	0.009 **	0.006 **	0.792	-0.380	-0.416	-0.044
I could keep my eyes on the road most of the time - *strongly agree (5) to strongly disagree (1)*	2	4	5	18.339	2	0.0001 ***	-3.095	-3.578	-1.909	0.0009 ***	0.0001 ***	0.062	-0.477	-0.552	-0.294
I felt like the phone distracted me - *strongly agree (5) to strongly disagree (1)*	4	3	2	25.612	2	0.0027 **	2.626	3.853	3.014	0.008 **	0.0153 *	0.002 **	0.405	0.594	0.465
How do you classify logging incidents to the VeloCity App with said input type, while watching the recording of someone else riding a bicycle? - *very easy (5) to very hard (1)*	4	4	4	1.997	2	0.368	-1.315	-1.056	0.088	0.213	0.32	0.9500	-0.203	-0.163	0.013
The haptic feedback helped me notice I had tapped a button - *strongly agree (5) to strongly disagree (1)*	3	4	NA	NA	NA	NA	-0.892	NA	NA	0.388	NA	NA	-0.137	NA	NA
The feature is accurate - *strongly agree (5) to strongly disagree (1)*	NA	5	5	NA	NA	NA	NA	NA	0.858	NA	NA	0.5	NA	NA	0.132
I felt like the feature really understood what I said - *strongly agree (5) to strongly disagree (1)*	NA	5	5	NA	NA	NA	NA	NA	0.972	NA	NA	0.433	NA	NA	0.15
The feature was able to classify incidents correctly most of the times - *strongly agree (5) to strongly disagree (1)*	NA	5	5	NA	NA	NA	NA	NA	0.904	NA	NA	0.548	NA	NA	0.139

Table 6.1 Results of the survey. TO = Touch, SR = Speech Recognition, VA = Voice Assistant. Questions with cells marked as NA were compared between only two conditions. Significant results are marked with a gray fill.

visual analysis of histograms were used to determine normal and not normal distributions. Comparisons between groups were done using the Kruskal-Wallis test with Wilcoxon tests for pairwise comparisons for not normally distributed data. For normally distributed data we used the Student's t-test. All tests use an alpha of 0.05. Effect sizes were calculated according to Robertson and Kaptein [183].

Personal Preference

We used surveys after each condition to ask participants about different aspects of the input method they just used. They answered using a five-point Likert scale. We analysed the answers to each of the statements using a Kruskal-Wallis test and a Wilcoxon-Pratt test for pairwise comparisons. We also provide effect sizes for all of those results. For a complete overview of the statements, answers and results please refer to Table 6.1. Overall we find that participants rate both speech recognition (median: 4, p-value: 0.009) and voice assistant (median: 4, p-value: 0.006) more useful than touch (median: 3). Furthermore, we find participants could better keep their eyes on the road in the speech recognition (median: 4, p-value: 0.0009) and voice assistant (median: 5, p-value: 0.0001) condition than in the touch condition (median: 2) (see Table 6.1). There is no significant difference between speech recognition and voice assistant (p-value: 0.062) but a medium effect size (-0.294) suggests that we might find a difference with a bigger sample. Regarding the question of whether participants felt distracted by the input method, we find significant differences between all conditions. Touch was rated more distracting than

speech recognition (p-value: 0.008) and more distracting than the voice assistant (p-value: 0.0153). The voice assistant was rated less distracting than speech recognition (p-value: 0.002). Thus, participants were most distracted by their phone in the touch condition (median: 4). The second most distracting input method was speech recognition (median: 3) and the least distracting the voice assistant (median: 2) (see Table 6.1). Participants had the option to correct wrong inputs after each video. We find that participants in total reported having corrected 5 incident reports created via touch, 12 via speech recognition and 15 via voice assistant. Thus touch seemed to be the most accurate input method.

Attention

We analyze visual attention to investigate if participants actually did not look at the screen if they did not have to. Siri can be used completely without looking at the device, which can be crucial for cyclists whose visual attention should be on the environment and the traffic at all times. From related work, we learn that such interfaces are more and more used in situations where complex tasks are done eyes-free [75]. Additionally, our intuition tells us that participants should have to look less or not at all at the device to report an obstacle using the voice assistant. To test this assumption we formulate the following hypothesis.

H1: Participants need fewer looks per interaction using the voice assistant compared to the other techniques.

To test our hypothesis, we used a classification method similar to Bah et al. [10]. We classified participants' looks at the screen when logging a traffic incident. We found that on average participants using touch needed 1.79 looks per interaction, with speech recognition they needed 1.71 and using the voice assistant 0.96 looks per interaction. To check whether these differences are significant, we used a Kruskal-Wallis test with posthoc pairwise Wilcoxon rank sum tests.

The Kruskal-Wallis test found a significant difference between the three conditions (p-value = 0.0003). Pairwise Wilcoxon tests showed that whereas touch and speech recognition (W = 231.5, p-value = 0.7912) did not differ significantly from one another, touch and voice assistant (W = 361.5, p-value = 0.0004) as well as speech recognition and voice assistant (W = 355, p-value = 0.0007) do differ significantly. Thus we conclude that participants needed fewer looks per interaction with the voice assistance compared to touch and speech recognition respectively, which confirms our hypothesis.

Usability

We used the SUS to identify differences between the conditions regarding usability. A Kruskal-Wallis test found no statistical difference between the conditions ($X^2 = 2,5261$, df = 2, p-value = $0,2828$). However we found medium effect sizes for the comparison between touch and speech recognition inputs (r = $-0,2177683$), as well as touch and voice assistant inputs (r = $-0,2362693$), and small effect size for speech recognition and voice assistant inputs (r = $0,04042902$). Therefore significant differences might be found between the first two mentioned comparisons with a larger sample [183].

6.6 Guidelines for Using Voice Interaction for Cyclists

Many navigation apps are designed for multiple transport modalities but do not adapt their interaction techniques accordingly. This leads to increased risk for cyclists who use these services and applications. We thus see the need for more user-specific solutions for cyclists [233] which take their movement and inhibition on interaction with hands and feet into account. Therefore, in this section, we will discuss five guidelines we identified in our study when it comes to designing VUIs for cyclists to provide traffic reports.

6.6.1 Use Hands and Eyes-Free Interaction

According to the "four strategies for mobile interaction" by Marshall et al. [134] VeloCity falls into the "Danger Zone". This is because reporting obstacles while riding a bicycle is weakly related to the locomotion itself and cycling has a high inhibition on interaction with hands and feet being occupied. One way to design for the "Danger Zone" is to choose modalities that are easily accessible whilst moving [134]. Even though our experiment was stationary, the most preferred interaction technique was the voice assistant which can be used hands and eyes-free and is thus very easily accessible whilst moving which supports their design recommendation. Participants commented on this matter also showing their immersion in the task: "With Siri, it was good that you didn't have to touch the phone. You have to have your hands on the handlebar after all" (participant 3). To the question of which input method they preferred one participant answered: "Overall Siri. The reason is that you do not need to look at the phone" (participant 6). Participants had to look on average almost twice as much at the device to report an obstacle using touch or speech recognition compared to using the voice assistant (H1). We assume that this is due to the action button (see Figure 6.1b and Figure 6.1e) that was featured in both conditions. Participants always looked at the screen before pressing it. However,

observations show that the touch condition induced longer fixations on the screen (due to the two touch events participants had to perform) whereas for the speech recognition participants used short glances to tap the action button and acknowledged the feedback shown in Figure 6.1. In contrast to the touch and speech recognition, the voice assistant (Siri) offered hands and eyes-free interaction using the activation phrase "Hey Siri". Using an activation phrase instead of a button to activate the voice interaction turned out to make a significant difference when it comes to the visual attention that participants were able to spend on traffic instead of the graphical user interface. Our observations showed that participants looked at the screen only for their first interaction with Siri in order to make sure everything worked as they expected and then adopted a complete eyes-free interaction. It was interesting to see that even novices, who stated to usually not use any kind of voice assistant, adopted this behavior quite quickly. One participant commented: "I don't use Siri as much, so I found it a little difficult at first but very intuitive". This is contrary to what Hua and Ng [99] find for car drivers. In their work visual feedback was recommended for users to know what commands had been given. In our case, Siri's feedback was informative enough to not create that need.

6.6.2 Give Informative Feedback

During the study, we realized that Siri gives different Feedback in German and in English, even though our technical implementation was identical. The English version would not only confirm that an obstacle was reported but also which kind. The German version did not mention the latter. Interestingly, German participants commented on this issue: "I think this is very important, if I don't look at it I would like to have the confirmation of what was created" (participant 2). We also asked participants in the interview if the confirmation helped them in general and most participants found it essential for the eye-free interaction: "Yes 100% if you are cycling at least then you know it has been logged. It is like a confirmation." (participant 3). From these opinions, we learn for future systems, that especially on the bicycle, informative confirmations are necessary for good and safe interactions. In our case, the feedback should not only confirm that the command was successfully executed but that the system actually executed the correct command.

6.6.3 Keep Commands Short

When it comes to the length and content of the commands, participants mentioned that they really liked the way the in-app speech recognition understood even short commands

like “construction site” instead of full sentences. The main reason for this was that they had to remember the exact phrase for Siri to execute the command, which seemed to present a difficulty even with the commands displayed on the screen. Chang et al. [43] found that for car drivers speaking to a VUI was a lot more cognitively demanding than listening to it. Furthermore, this demand increased with the information complexity of the command that was uttered. Thus commands should be short and descriptive and the assistant should be able to resolve ambiguous commands by looking for keywords instead of complete phrases.

6.6.4 Use Robust Error Handling

In case Siri misunderstood a command and was not able to resolve the issue it responded with an error telling the participants that it had not understood the command. When this happened participants looked at the screen in order to assess the problem. This is a common behavior for VUIs which display voice-to-text transcriptions on the screen to help users understand what the misunderstanding with the assistant was [169]. In the case of cycling, however, it might be safer to resolve such an error through a conversation with the assistant. Kim et al. [110] suggest using a simple “Can you repeat that please?” error handling method as participants in their study felt like this was a natural miscommunication error with only little negative impact on the interaction.

Overall, the two voice interaction techniques were more error-prone than the touch interaction. We attribute this difference mainly to the occasional error in the speech recognition as described above. However, with the ever-increasing accuracy of this technology, we expect the error rate to go down with it. For now, we argue that the increase in safety with the voice assistant outweighs the larger number of errors which can be countered by robust error handling.

6.6.5 Make It Safe

When designing for interaction in motion, safety should always be a high priority. Participants explicitly talked about safety issues during our experiments. We had multiple participants comment on the fact that they would have probably severely injured themselves trying the touch screen condition while biking: “The manual thing is a no go. I mean I would die, or kill someone within like 5 minutes if I take my hands off the handlebar” (participant 5). This is especially relevant when touch interaction is still a highly used interaction technique for cycling applications. Just recently the application

Bikemap [24] released a reporting feature similar to VeloCity (see Figure 6.1c) utilizing touch input. Not only touch input but also other modalities can severely impact users' safety while moving. Studies of (car) driving behavior have shown that listening to music can influence peoples' perception and vehicular control [37]. And that phone calls during the ride can lead to reduced visual processing capabilities [154]. In regards to cyclists de Waard et al. find that mobile phone use while cycling affects cognitive demand on speed and peripheral view [226].

We know that people interact with mobile devices while moving and cyclists are no exception. Taking on the example of phone calls, Marshall et al. argue that whilst not communicating by phone at all is safer than hands-free communication, we have to assume that people will communicate while driving regardless. Given this, there is a strong argument for hands-free systems in cars [134], and we strongly believe this argument should also hold for cyclists. In this paper, we argue that we have to identify and use sensible guidelines instead of trying to enforce "stop to interact" [134] when designing interactions for cyclists.

6.7 Limitations & Future Work

While this is the first study exploring input methods for reporting live traffic information while cycling, we recognize that our approach is prone to certain limitations. We decided to conduct the study remotely due to safety concerns. Given our results, we are convinced that participants would have been exposed to risks for which we can not take responsibility, regarding our codex as researchers as well as our local ethics board. We acknowledge that this potentially harms the ecological validity of our study. However, through the comments participants made during the experiment, we realized that participants were very often reflecting on their behavior with regard to real cycling when evaluating the different interaction techniques. To increase future ecological validity without compromising safety we suggest looking into solutions that make use of virtual reality as shown by Löchtefeld et al. [128].

When reporting the incidents during the experiment, we embedded the commands into each video as can be seen in Figure 6.2 to avoid that participants would forget them. This made for a fair comparison between the two voice-based and the touch-based conditions, as we have to assume that people know the commands they want to use. Furthermore, the study was conducted in two languages German and English. Therefore, all app features and surveys were translated. We did not encounter any peculiarities

which made us question the validity of the results. We do believe inclusive study design improves our findings as they represent a more diverse sample and let us learn from and design for different cultures and people. Lastly, we acknowledge that the usability of the voice interaction can be highly influenced by traffic noise which we were not able to test in our setup. However, new headphones like Apple's AirPods Pro, which use a so-called transparency mode to combine noise cancellation with outside sounds, start to solve the problem of masking traffic noise and may thus be a possible way for cyclists to safely interact with a VUI. Novel technologies offer the potential to improve mobile interaction on the bicycle. Therefore, we hope that future studies and researchers will keep investigating the topic of live traffic reporting for cyclists. Many participants commented that the feedback, after logging an incident, was very informative (in the English version). Since we only used Siri's standard feedback, future studies could investigate how to optimize feedback of VUIs while cycling to learn what information cyclists need when the most. Another crucial aspect of the interaction was how the commands were formulated. Most participants preferred the short commands of the speech recognition instead of the conversational nature of Siri. Future research should thus investigate the dialogue with a voice assistant while cycling. Because, while participants preferred short commands, they liked Siri's complete answer of what was reported. We think future developments will create a need for these kinds of applications and we need to make sure that they can be interacted with in a way that is safe while cycling.

6.8 Conclusion

For reporting traffic incidents when driving, touch interaction is still state of the art as-is for most other mobile applications. While the availability of general-purpose navigation applications and services for cyclists is growing, we have to find ways of designing safe interaction techniques for them. Since cycling imposes a strong inhibition on touch interaction we need to find suitable interaction techniques that can be safely used on a bicycle. Voice-based interfaces on the bicycle and especially built-in voice assistants meet these requirements quite well and are safer than touch-based methods since people have to look less at the interface during the interaction. Our guidelines will help inform future designs of mobile systems for live traffic reporting for cyclists as well as for mobile applications for cyclists in general. We hope that with this paper researchers and practitioners are inspired to contribute to this topic and do so in a safe and responsible manner.

7 Discussion

In this chapter we discuss the effects from a user perspective of decoupling the design space for mobile navigation technologies. Instead of the single-module innovations that have been common throughout the last two decades, we are recently and currently seeing multi-module innovations resulting in new navigation systems, such as the as-the-crow-flies (ATCF) based systems we investigated in our work. To understand the challenges and benefits of these new systems, we developed a systematic approach to understanding, evaluating, and improving novel mobile navigation systems. Additionally, to better understand the longevity of the rigid architecture of mobile navigation technologies throughout the last two decades and the current user-centered effects of its decoupling, we discuss the negative impacts of turn-by-turn (TBT) route guidance and the advantages of the emerging novel alternatives. We placed one of our foci on the compromise between ecological validity and safety in navigation experiments.

7.1 Decoupling the Design Space for Mobile Navigation Technologies

For more than two decades there was a rigid system architecture, depicted in Figure 1.1, that served as the design space for mobile navigation technologies. We saw many single-module innovations, but seldom was the architecture itself altered. However, this rigidity has been fading with the decoupling of the design space for mobile navigation technologies from its former underlying architecture. As an effect of the decoupling, we are seeing novel mobile navigation systems based on the ATCF route guidance. These novel systems are based on simultaneous innovation of and within multiple modules of the design space; moreover these innovations can be optimized for a specific user group. Consequently, these novel mobile navigation systems require a new systematic approach for understanding, evaluation, and improvement, while making sure users in motion can safely interact with these systems.

7.1.1 Multi-Module Innovation: An ATCF-Based Example

With ATCF-based mobile navigation systems we saw innovation in three of the eight modules of the design space [159], namely route planning, route guidance, and user interface. Figure 7.1 shows the system architecture of such a mobile navigation system. Instead of the typical route planning module, which uses routing techniques to compute paths between an origin and a destination, ATCF-based mobile navigation systems use

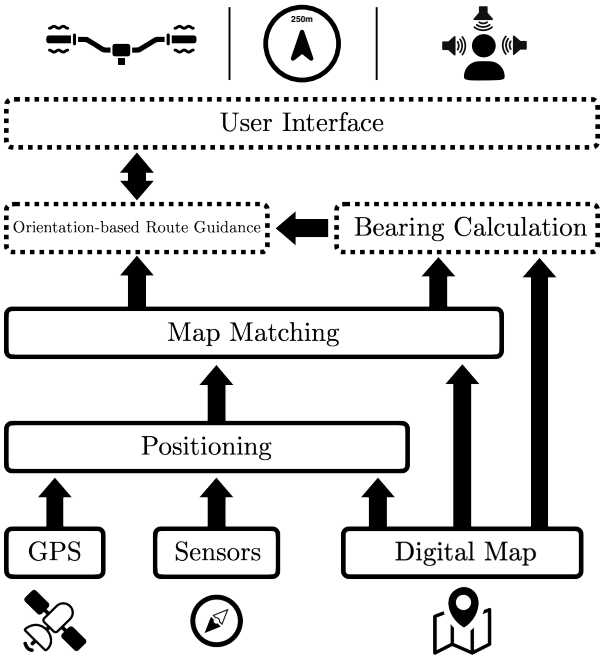


Fig. 7.1 As-the-crow-flies-based mobile navigation system architecture with three different options for the user interface (UI). Left: tactile UI by Pielot et al. [167]; Middle: visual UI by Savino et al. [196]; Right: audio-based UI by Albrecht et al. [4]. The dashed modules differ from the original architecture by Park et al. [159].

bearing calculations to compute the angle between the users direction and the direction to the destination. Using this bearing calculation, the mobile navigation system can indicate how much the user has to turn to be facing their destination. This information is then used by the route guidance module. Using orientation-based (instead of TBT) route guidance the route guidance module – at every decision point – communicates the general direction toward the destination. However, there is to-date only a limited understanding of how people make use of this route guidance. The most accurate understanding is provided by Hochmair [95], who provided a heuristic which describes human wayfinding behavior with a least-angle strategy (LAS). The LAS assumes that a navigator who knows the general direction to a destination, as is the case with orientation-based route guidance, will always choose the street with the least angle deviation toward the destination [95]. However, our work has shown that this is not necessarily an ideal proxy for actual human wayfinding behavior with ATCF-based mobile navigation systems [193]. Human abilities [193] (e.g. to interpret small angles) and the environment [195] (e.g. the number of dead ends) affect the successful application of ATCF-based mobile navigation systems. Finally, related work on orientation-based navigation explored three different

output modalities. Pielot et al. [167] used vibrating handlebars to indicate the direction to the destination, while Albrecht et al. [4] used spatial audio to communicate the direction. In our work, we tested a visual interface showing a compass needle to indicate the direction to the destination [196]. The simultaneous innovation within these three modules increases the complexity of investigating the challenges and benefits of this approach when compared to existing mobile navigation systems. Our work and this thesis constitute a systematic assessment of novel mobile navigation systems.

7.1.2 Systematic Assessment of Novel Mobile Navigation Systems

The exploration of decoupling the design space for mobile navigation systems has shown that in order to assess their challenges and benefits a comprehensive evaluation of the resulting mobile navigation systems is required. This section presents and discusses five aspects of our systematic assessment.

Understanding Usage Behavior of Mobile Navigation Technologies (RQ1)

The first aspect emphasizes the importance of understanding people's usage behavior, when employing mobile navigation technologies. Researchers and practitioners might have misconceptions about how users interact with devices and applications. Our study [199] presented in Chapter 2, outlines a method to collect in-app usage behavior by utilizing a wrapper application. This method can be applied to novel mobile navigation applications, thereby avoiding the carrying over of any misconceptions about the usage behavior from one user group to another.

Identifying User Experience Issues for Specific User Groups (RQ2)

The second aspect includes identifying common usability and user experience issues with the mobile navigation system. Our results, described in Chapter 3, revealed that cyclists benefited from ATCF navigation, even though they were inexperienced with this novel ATCF-based mobile navigation system. We saw navigation errors caused by this novelty factor and we also identified specific user errors. These errors included: ending up in dead ends, users thinking they were going in the wrong direction, and users not knowing when to make a turn [196]. Having become familiar with these errors, we were able to implement changes in the user interface to counter these error-prone behaviors. However, not all issues could be entirely resolved by these interface changes. Therefore, we looked beyond user errors and explored the influence of the environment on the user experience.

Identifying Environmental Influences on Mobile Navigation Technologies (RQ3)

The third aspect led us to integrate the environment into the evaluation process. While the user experience issues discussed in Chapter 3 could be partially resolved by our improved design, some of the errors still remained. We then explored whether the environment itself would affect the user experience and, if so, to what extent. In our work reported in Chapter 4 we found that the street network has a significant impact on the user experience for ATCF-based mobile navigation systems. Thus, researchers and practitioners should take the environment into close consideration when designing future mobile navigation technologies. Beyond this concrete example, we have seen an increase in the number of evaluations of environments as part of new study designs [49, 143]. Such new study designs, if employed by the majority of mobile navigation researchers, can lead in the future to an easier way of comparing among results of mobile navigation studies.

Improving Mobile Navigation Systems Beyond Navigation Efficiency (RQ4)

Identifying the user experience issues and environmental influences showed that improving ATCF-based mobile navigation systems is a challenging task. Elaborating on the fourth aspect of our systematic assessment, we explored new ways to improve these mobile navigation technologies. ATCF-based mobile navigation systems do not precompute the user's route. Instead, we need to simulate people's navigation behavior in order to estimate where users will go if we are to adequately intervene in the case of error-laden behavior. Chapter 5 reports on the improvements we made to our simulation of ATCF-based navigation behavior. By analyzing people's ability to interpret small angle deviations – a critical decision-making process during ATCF-based navigation – we were able to make the decisions taken by our virtual agent more human-like [193]. In future studies for non-TBT-based mobile navigation systems, simulating human behavior should be considered a fruitful method for predicting navigation behavior and preventing navigation errors.

Using Safe Interaction Modalities in Motion (RQ5)

The fifth aspect is the recognition that novel mobile navigation systems can be dangerous to use. This recognition requires the design of safe mobile navigation technologies for each user group. In Chapter 6 we describe how we enabled cyclists to report traffic incidents while in motion. This reporting technology has been available to car drivers for a long time through the mobile application Waze [229]. However, to make this same

function available to cyclists interactions had to be specifically designed to take cyclists' restrictions/inhibitions into account [134]. This work resulted in the implementation of interaction modalities using smart assistants and voice commands. We saw the need for suitable methods to evaluate interaction modalities for specific user groups while maintaining a balance between the ecological validity of the results and the safety of the participants. This necessity gave rise to remote [197], lab [136], virtual reality [200], and augmented reality [139] experiment setups for cyclists.

7.2 The Predominance of Turn-By-Turn Navigation

From a technological perspective, the decoupling of the design space for mobile navigation technologies allowed for the development of novel mobile navigation systems without TBT-based route guidance. In this section, we discuss this decoupling in terms of effects on spatial learning and changes in societal navigation patterns by investigating the predominance of TBT navigation.

Navigation is described as coordinated and goal-directed movement through the environment [149]. It is successful if the goal is reached efficiently and accident-free. This definition by Montello [149] considers navigation to consist of two components: locomotion and wayfinding. While locomotion is concerned with the actual movement to reach a goal, wayfinding is concerned with the planning and the efficiency of the route followed [149]. The criterion most often used to measure this efficiency is distance [77]. Thus, efficient navigation is looking for the shortest path between a point of origin and a destination. Shortest path algorithms [58, 86] are used to optimize for this criterion. These algorithms compute the route through the environment with the least amount of distance between origin and destination. To communicate this route to a person, navigation instructions are used. Most commonly, these instructions are communicated turn by turn. Thus, TBT navigation effectively reduces wayfinding to comprehending instructions and interpreting them. This approach works very well for car drivers. With a limited network of streets that can be driven, finding the most efficient way is paramount [77] and is likely one of the reasons for the wide spread adoption of TBT navigation during the last two decades. However, with increasingly diverse user groups employing mobile navigation technologies, efficiency might no longer outweigh the negative impacts of mobile navigation use for certain users.

7.2.1 Negative Impact of Mobile Navigation Technologies

"Google Maps is making our brains dumb" [3]. "GPS leads Japanese tourists to drive into Australian bay" [85]. "Navigation apps are turning quiet neighborhoods into traffic nightmares" [69]. These and similar headlines can be found describing the negative effects of the use of mobile navigation technologies. Such negative phenomena can be divided into two categories: (1) detrimental effects on spatial learning and (2) the social ramifications of mobile navigation. This section presents research findings concerned with these topics and highlights how systems resulting from decoupling the design space for mobile navigation technologies offer ways to reduce these negative effects.

Detrimental Effects on Spatial Learning

When it comes to the negative effects of mobile navigation technologies on spatial learning, one of the most recent studies was conducted by Ruginski et al. [187]. In their work participants had to navigate a virtual college campus, complete a mental rotation task, and carry out a perspective-taking task. The results were compared to a self-report survey where participants commented on their general GPS use. Ruginski et al. [187] found that regular GPS use affects environmental learning abilities indirectly through the negative influence GPS has on mental rotation and perspective-taking abilities [187].

While Ruginski et al. [187] specifically state that they have not investigated which specific aspects of GPS use is causing the observed effect, Schwering et al. [204] specifically tackle issues that arise in the use TBT route guidance. Schwering et al. [204] showed that while TBT navigation is perfectly suitable to help users reach a destination through the best (e.g. fastest, shortest) route, the users might not acquire a broader orientation or overview of the route [204]. Following strict instructions, one after another, is not how humans naturally engage in spatial learning. Rather, people integrate information, learn spatial configuration during wayfinding, and thus build cognitive maps [64, 80] to orient themselves in an environment [204]. Eventually, particular instructions at decision points can help build up route knowledge [220] but these instructions do not improve the user's ability to gain orientation in an unfamiliar environment [204].

With only a handful of studies in this domain, we cannot yet say whether "Google Maps is making our brains dumb" [3] or not. However, first results point towards a negative impact of excessive assistance when it comes to everyday navigation tasks. With the orientation task described in Chapter 3, we presented results that indicate improved orientation abilities for participants using the ATCF-based mobile navigation system

when compared to users of the TBT-based system (*RQ2*) [196]. Thus, non-TBT-based mobile navigation systems could counteract some of these negative effects by supporting our spatial cognitive abilities [100] instead of diminishing them [204].

Social Ramifications of Mobile Navigation

Everyday mobile navigation systems help people plan a route and move through space to a destination [104]. However, this common, everyday activity can have fatal consequences when incorrect or wrongly interpreted navigation instructions lead people to drive into the Atlantic Ocean [85] or down a staircase [84]. This phenomenon is known as "Death By GPS" [126]. It describes catastrophic incidents caused by people following the instructions of their mobile navigation systems [126]. In a recent study, Lin et al. [126] investigated 158 news reports of catastrophic incidents associated with mobile navigation systems. From a technological perspective, the cause for many of these incidents can be traced back to missing or incorrect mobile map attributes. From a user interaction perspective, however, navigation instructions were often too simple for the spatial decisions that users had to make [126]. One solution to overcome these problems is improving the interface to better support users [126]. Our work led us to the conclusion that novel non-TBT-based mobile navigation methods (e.g. without specific instructions) might circumvent the problem altogether. Through active decision-making which increases the level of engagement with the environment [142], people are given back responsibility for navigating. This would reduce people's blind trust in their mobile navigation systems and thus eliminate some of the negative consequences. Furthermore, by improving the simulation quality (see Chapter 5), we can better predict dangerous navigation situations which might arise with the use of non-TBT-based mobile navigation, as well as prevent "Death By GPS" for individuals within novel user groups (*RQ4*).

We see ramifications of mobile navigation technologies not only for individuals but also on a society level. With increasing numbers of users [212, 213], routing algorithms of large-scale mobile navigation applications affect more and more people by deciding which routes are taken through an environment. Johnson et al. [106] have shown that this increasing use of mobile navigation applications affects community-level externalities, externalities that arise when these large-scale mobile navigation applications broadly adopt new routing criteria. Depending on the routing criteria, their results show that routes became more complex because they included a higher number of left turns. Left turns generally increase the risk of collisions [106, 144]. In addition, traffic was broadly

redistributed, increasing traffic in previously low-trafficked neighborhoods [106]. With novel non-TBT-based mobile navigation systems, we are heading toward more autonomy when it comes to making navigation decisions [167, 196]. In Chapter 3, for example, we reported that cyclists showed a personal preference for ATCF route guidance for leisure biking (*RQ1*, *RQ2*) [196]. The autonomy that comes with novel non-TBT-based mobile navigation systems (e.g. ATCF navigation) may help counteract the negative influences of large-scale mobile navigation applications and thus some of the societal effects we currently see in the case of car traffic [106].

TBT will likely remain the route guidance of choice for many mobile navigation systems. It has proven to be superior for efficient navigation in the context of escape routes and guidance in public places (e.g. subway stations, airports) where time plays a crucial role [204]. However, in this thesis we argue that there are and will be other contexts where users will prefer novel solutions to reduce the negative effects of TBT-based route guidance for individuals and societies.

7.3 Ecological Validity of Mobile Navigation Research

This thesis presents a spectrum of study designs: from in-situ field studies presented in Chapter 3, over remote lab studies elaborated in Chapter 6, to agent-based simulations discussed in Chapter 4. All three studies investigated mobile technologies for cyclists. Such a variety of study designs is common for mobile navigation research but can affect the validity of results. In this section we discuss the topic of ecological validity in the context of mobile navigation studies by highlighting two particular factors: safety and geography.

Novel mobile navigation technologies are catering to the needs of particular user groups. The variety of these technologies increases even further with decoupling the design space. When researching novel systems and designing interactions for novel user groups, we must ensure that the results are ecologically valid and are applicable beyond the confines of an experiment. For mobile navigation research this means addressing two main issues: (1) Mobile navigation technologies must be tested and evaluated in real world environments while keeping participants safe from the hazards of traffic incidents and (2) mobile navigation technologies must be evaluated in more than one environment.

7.3.1 Safety

Some of the technologies presented in this thesis were evaluated by real users in real environments [196, 197, 199]. While we ensured the safety of our participants at all times, "risks of interaction in motion" [134] is a recognized and often discussed topic within HCI. There are formal criteria for risky interactions, as for example interactions defined by driver safety standards such as the SAE 2364 [191]. These standards state that any driver interaction which is concerned with navigation technology while a vehicle is in motion should not exceed 15 seconds [191]. For car drivers these standards make sense, but pedestrians and cyclists, belonging to the group of vulnerable road users [207] (VRUs), are often at greater risk and subjected to specific restrictions/inhibitions during motion. A study by Dancu et al. [53], for example, found that cyclists prefer interaction modalities where they do not have to take their hands off the handlebar [53]. Limitations like these, coupled with the particular restrictions/inhibitions of each user group [134], make designing research studies for novel mobile navigation systems a challenge.

Researchers have been coming up with different study designs to tackle this challenge for both field studies and lab studies. In field studies, participants actually walk or ride in the real world and most often in actual traffic. This type of study offers a high ecological validity but increases the risks of injury and/or accidents. Ways to reduce the safety risks in field studies include using previously scouted environments with low levels of traffic [167, 196] and simple, straight road segments [233], riding bicycles at low speeds [233], experimenting on special outdoor practice test tracks [138], and recruiting well-versed cyclists [52]. In contrast lab studies, imitating the real world situation as best as possible, carry a very low risk of injury. Here, the level of safety is very high but results might be lacking in terms of ecological validity, depending on the fidelity of the environment. Low-cost solutions in this domain include a stationary setup, where participants – either seated or standing – observe or interact with a video or a virtual environment on a screen [76, 197]. To increase ecological validity further, researchers are building stationary simulators for cyclists and other road users. A popular method for studying cyclists is the combination of a stationary bicycle and a visualization of the traffic environment either through a virtual reality headset [140, 200] or on a large external monitor [136, 137, 168]. For pedestrians and wheelchair users, researchers have used immersive, cave-like setups to imitate the environment [44, 55]. Finally, the state of the art includes augmented or virtual reality test tracks, where people can actually navigate an environment with a considerably large movement-area. For pedestrians,

current virtual reality setups using either walking-in-place locomotion methods [194] or redirected walking [176] allow for a realistic navigation experience. Cyclists using augmented reality headsets can ride within a predefined area and experience varying traffic setups without being at risk of accidents with other road users [139].

While the improvements in lab studies have made significant progress with the introduction of high-resolution head-mounted displays, virtual reality environments can not yet mimic all the details of the real world [194]. Thus, keeping a balance between high ecological validity and a low level of safety risks will continue to be a challenge in the foreseeable future and will continue to restrict research results. In the course of our work we have had to deal with this challenge. Future challenges will also include closing the gap between real-world and virtual navigation experiences and improving our understanding of the impacts of interaction while in motion. In addition to using the more traditional field and lab studies approach, we also introduced simulation studies into our research on mobile navigation systems (Chapters 4 and 5). While or rather because simulation studies lack participants' engagement with actual mobile navigation technology in the real world, they are completely safe (*RQ5*). Combined with field and lab studies, simulations are a valuable addition to a systematic assessment of novel mobile navigation systems.

7.3.2 Geography

Our results show that for novel mobile navigation systems not only the user experience of a system itself matters but also the environment in which it is used (see Chapter 4). The prevalence of dead ends in the study reported on in Chapter 3 caused problems for participants when they were navigating with the ATCF-based navigation system [196]. However, our study discussed in Chapter 4 showed that areas with fewer dead ends might see a less problematic application of the mobile navigation system. This illustrates the second major issue in achieving high ecologically valid results when researching mobile navigation technologies: Results must be valid beyond the confines of the area in which a study takes place.

The safety issues discussed above are one reason why navigation technologies are usually tested under very strict and limited conditions. Participants navigate on an island [167], in a zoo [8], in specifically chosen city centers [98] and neighborhoods [104, 194, 196]. Furthermore, these studies usually last for a limited amount of time, because experimenters predetermine the time a navigation task will roughly last [4] and/or the

distance of the route that is to be navigated [19, 196]. These criteria and restrictions are necessary for properly controlling variables during the experiment and keeping participants safe. However, at the same time they limit the generalizability of the results. Efforts to improve the levels of generalizability and comparability for mobile navigation studies are few. Some studies mention the experiment area or the specific surroundings of the study as a limitation of their research [167, 196], others discuss [109] or work on improving the current situation [143]. In a recent study, Mazurkiewicz et al. presented an approach to systematically choose suitable routes for navigation experiments based on street network data. This not only eases the previously described attempts to control for important variables, but it also allows for the discovery of similar routes in various geographical areas [143].

The results of our work, presented in this thesis, reveal that especially for novel mobile navigation systems that do not rely on TBT route guidance, the environment (i.e. the street network) can significantly affect how users apply and use specific novel mobile navigation systems (*RQ3*). To understand and account for the variety of environments that mobile navigation technologies can and will be used in, we introduced simulation as a study method (see Chapter 4). Making use of this and similar methods, like the one by Mazurkiewicz et al. [143], future work should focus on making research results for mobile navigation technologies generalizable across multiple environments.

8 Conclusion

In this thesis, we have reported on our systematic approach to understanding, evaluating, and improving novel mobile navigation systems. The development of these systems resulted from the decoupling of the design space for mobile navigation technologies. These systems have brought about many innovations within multiple modules of the design space, innovations tailored to the needs of specific user groups. We have argued that understanding the challenges and benefits of these multi-module innovations from a user perspective requires a more complex approach than the approach used to study the single-module innovations we have seen in the past. Our studies focused on (1) understanding how people use mobile navigation technologies, (2) researching how different navigation methods empower specific user groups, (3) investigating whether street network structures affect the use of novel mobile navigation systems, (4) exploring how to improve the user experience of those novel mobile navigation systems beyond navigation efficiency, and (5) evaluating the safety risks of decoupling the design space for mobile navigation technologies.

Navigation does not merely serve the purpose of efficiently getting from one location to another via the shortest path. While navigating efficiently will remain a central use-case of mobile navigation technologies, facilitated by turn-by-turn (TBT) based navigation, we are starting to move away from predefined route planning and toward more user autonomy as part of the navigation experience [167, 196]. This shift allows mobile navigation systems to better support spatial cognitive abilities [100] and to alleviate some of the societal effects caused by large-scale route guidance [106].

One particular outcome of the decoupling of the design space for mobile navigation technologies is the development of as-the-crow-flies (ATCF) based mobile navigation systems for cyclists. Three of the five publications in this thesis (Chapters 3 - 5) investigate user experience with ATCF-based mobile navigation systems. Through our research, we were able to understand the advantages and disadvantages of ATCF route guidance. This led us to the conclusion that a combination of TBT and ATCF-based navigation could solve many of the user errors discussed in this thesis. Such a combined navigation system would allow users to navigate freely and without interruption. By using simulation, the navigation system can predict when or where user errors during the ATCF route guidance will most likely occur. When the likelihood of navigation errors increases, the combined navigation system could then take precautionary action by using TBT

route guidance to efficiently guide users turn by turn. Closely tied to the ongoing development of novel mobile navigation systems, as well as the partial integration of TBT into these novel systems, is the question of maintaining and/or increasing the ecological validity of experiments. The two building blocks of ecological validity in mobile navigation experiments, as discussed in Chapter 7, are (1) maintaining high levels of safety for participants and (2) conducting experiments in a variety of environments. To contribute to these two building blocks, we developed voice assistant-based interaction modalities for cyclists. This increased their safety while they were interacting with mobile navigation technologies in real traffic. For other experiments, we developed an approach to simulate navigation behavior during the use of ATCF-based mobile navigation systems. This enabled us to evaluate mobile navigation systems in a variety of experimental environments without exposing cyclists to the dangers of road traffic.

During our work we have witnessed how classical TBT-based navigation is beginning to be replaced by alternative navigation methods designed for various user groups. While there are still many open challenges, the exploration of novel mobile navigation technologies, like the ones developed and analyzed during our work and presented in this thesis, will get us from a one-architecture-fits-all approach to custom-fit mobile navigation systems for specific user groups.

References

[1] ADFC. *ADFC Mängelmelder*. 2019. URL: https://adfc-bremen.xn--mngelmelder-l8a.de/ (visited on 05/23/2022).

[2] Adrados, Christophe, Girard, Irène, Gendner, Jean-Paul, and Janeau, Georges. "Global Positioning System (GPS) location accuracy improvement due to Selective Availability removal". In: *Comptes Rendus Biologies* 325.2 (2002), pp. 165–170. ISSN: 1631-0691. DOI: 10.1016/S1631-0691(02)01414-2.

[3] Alba, Alejandro. *Google Maps Is Making Our Brains Dumb*. 2017. URL: https://www.vocativ.com/418342/google-maps-gps-navigation/index.html (visited on 05/22/2022).

[4] Albrecht, Robert, Väänänen, Riitta, and Lokki, Tapio. "Guided by music: pedestrian and cyclist navigation with route and beacon guidance". In: *Personal and Ubiquitous Computing* 20.1 (2016), pp. 121–145. DOI: 10.1007/s00779-016-0906-z.

[5] Ammari, Tawfiq, Kaye, Jofish, Tsai, Janice Y., and Bentley, Frank. "Music, Search, and IoT: How People (Really) Use Voice Assistants". In: *ACM Trans. Comput.-Hum. Interact.* 26.3 (2019), pp. 1–28. ISSN: 1073-0516. DOI: 10.1145/3311956.

[6] Apple. *Apple Maps*. 2022. URL: https://www.apple.com/maps/ (visited on 04/26/2022).

[7] Arikawa, Masatoshi, Konomi, Shin'ichi, and Ohnishi, Keisuke. "Navitime: Supporting Pedestrian Navigation in the Real World". In: *IEEE Pervasive Computing* 6.3 (2007), pp. 21–29. ISSN: 1558-2590. DOI: 10.1109/MPRV.2007.61.

[8] Aslan, Ilhan, Schwalm, Maximilian, Baus, Jörg, Krüger, Antonio, and Schwartz, Tim. "Acquisition of Spatial Knowledge in Location Aware Mobile Pedestrian Navigation Systems". In: *Proceedings of the 8th conference on Human-computer interaction with mobile devices and services*. 2006, pp. 105–108. ISBN: 978-1-59593-390-4. DOI: 10.1145/1152215.1152237.

[9] Azimi, Seyed Majid, Fischer, Peter, Körner, Marco, and Reinartz, Peter. "Aerial LaneNet: Lane-Marking Semantic Segmentation in Aerial Imagery Using Wavelet-Enhanced Cost-Sensitive Symmetric Fully Convolutional Neural Networks". In: *IEEE Transactions on Geoscience and Remote Sensing* 57.5 (2019), pp. 2920–2938. ISSN: 1558-0644. DOI: 10.1109/TGRS.2018.2878510.

[10] Ba h, Kenneth Majlund, Jæger, Mads Gregers, Skov, Mikael B., and Thomassen, Nils Gram. "You Can Touch, but You Can't Look: Interacting with in-Vehicle Systems". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2008, pp. 1139–1148. ISBN: 9781605580111. DOI: 10.1145/1357054.1357233.

[11] Bailenson, Jeremy N., Shum, Michael S., and Uttal, David H. "The initial segment strategy: A heuristic for route selection". In: *Memory & Cognition* 28.2 (2000), pp. 306–318. ISSN: 1532-5946. DOI: 10.3758/BF03213808.

[12] Baltrunas, Linas, Church, Karen, Karatzoglou, Alexandros, and Oliver, Nuria. "Frappe: Understanding the Usage and Perception of Mobile App Recommendations In-The-Wild". In: *arXiv* (2015). DOI: https://doi.org/10.48550/arXiv.1505.03014.

[13] Banovic, Nikola, Brant, Christina, Mankoff, Jennifer, and Dey, Anind. "Proactive-Tasks: The Short of Mobile Device Use Sessions". In: *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices & Services*. 2014, pp. 243–252. ISBN: 978-1-4503-3004-6. DOI: 10.1145/2628363.2628380.

[14] Barrington-Leigh, Christopher and Millard-Ball, Adam. "The world's user-generated road map is more than 80% complete". In: *PLOS ONE* 12.8 (2017). ISSN: 1932-6203. DOI: 10.1371/journal.pone.0180698.

[15] Barthelemy, Marc. *The Structure and Dynamics of Cities: Urban Data Analysis and Theoretical Modeling*. Cambridge University Press, 2016. ISBN: 978-1-107-10917-9. DOI: 10.1017/9781316271377.

[16] Bayer, Christoph. *Navigate with komoot – the app that helps you to discover new trails*. 2019. URL: https://enduro-mtb.com/en/navigate-with-komoot/ (visited on 04/26/2022).

[17] Beeline. *Beeline Velo*. 2019. URL: https://beeline.co/pages/beeline-velo (visited on 05/23/2022).

[18] Bellino, Alessio. "Two New Gestures to Zoom: Enhancing Online Maps Services". In: *Proceedings of the 24th International Conference on World Wide Web*. 2015, pp. 167–170. ISBN: 978-1-4503-3473-0. DOI: 10.1145/2740908.2742823.

[19] Bertel, Sven, Dressel, Thomas, Kohlberg, Tom, and Jan, Vanessa von. "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. ISBN: 978-1-4503-5075-4. DOI: 10.1145/3098279.3098543.

[20] Bétaille, David and Toledo-Moreo, Rafael. "Creating Enhanced Maps for Lane-Level Vehicle Navigation". In: *IEEE Transactions on Intelligent Transportation Systems* 11.4 (2010), pp. 786–798. ISSN: 1558-0016. DOI: 10.1109/TITS.2010.2050689.

[21] Beyer, Hugh and Holtzblatt, Karen. *Contextual Design: Defining Customer-Centered Systems*. Morgan Kaufmann Publishers Inc., 1997. ISBN: 978-0-08-050304-2.

[22] Bhavnani, Yash, Rodden, Kerry, Guarnotta, Laura Cuozzo, Lynn, Margaret T., Chizari, Sara, and Granka, Laura. "Understanding Mobile Phone Activities via Retrospective Review of Visualizations of Usage Data". In: *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2017, pp. 1–10. ISBN: 978-1-4503-5075-4. DOI: 10.1145/3098279.3119841.

[23] Bi, Lei, Cao, Juan, Li, Guohui, Viet Hung, Nguyen Quoc, Jensen, Christian S., and Zheng, Bolong. "SpeakNav: A Voice-based Navigation System via Route Description Language Understanding". In: *2021 IEEE 37th International Conference on Data Engineering (ICDE)*. 2021, pp. 2669–2672. DOI: 10.1109/ICDE51399.2021.00300.

[24] Bikemap. *Bikemap*. 2021. URL: https://www.bikemap.net/de/apps/ (visited on 08/11/2021).

[25] Blades, Mark and Spencer, Christopher. “How Do People Use Maps to Navigate Through the World”. In: *Cartographica: The International Journal for Geographic Information and Geovisualization* 24 (1987), pp. 64–75.

[26] Blauert, Jens. *Spatial Hearing: The Psychophysics of Human Sound Localization*. The MIT Press, 1996. ISBN: 978-0-262-26868-4. DOI: 10.7551/mitpress/6391.001.0001.

[27] Blubel. *Blubel*. 2019. URL: https://blubel.co/ (visited on 07/24/2019).

[28] Boeing, Geoff. *OSMnx*. 2021. URL: https://github.com/gboeing/osmnx (visited on 05/30/2022).

[29] Boeing, Geoff. “OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks”. In: *Computers, Environment and Urban Systems* 65 (2017), pp. 126–139. ISSN: 0198-9715. DOI: https://doi.org/10.1016/j.compenvurbsys.2017.05.004.

[30] Boeing, Geoff. “Street Network Models and Indicators for Every Urban Area in the World”. In: *Geographical Analysis* Special Issue (2021), pp. 1–17. ISSN: 1538-4632. DOI: 10.1111/gean.12281.

[31] Boeing, Geoff. “The right tools for the job: The case for spatial science tool-building”. In: *Transactions in GIS* 24.5 (2020), pp. 1299–1314. DOI: 10.1111/tgis.12678.

[32] Boeing, Geoff. “Urban spatial order: street network orientation, configuration, and entropy”. In: *Applied Network Science* 4.1 (2019), pp. 1–19. ISSN: 2364-8228. DOI: 10.1007/s41109-019-0189-1.

[33] Böhmer, Matthias, Hecht, Brent, Schöning, Johannes, Krüger, Antonio, and Bauer, Gernot. “Falling asleep with Angry Birds, Facebook and Kindle: a large scale study on mobile application usage”. In: *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*. 2011, pp. 47–56. ISBN: 978-1-4503-0541-9. DOI: 10.1145/2037373.2037383.

[34] Boriboonsomsin, Kanok, Barth, Matthew J., Zhu, Weihua, and Vu, Alexander. “Eco-Routing Navigation System Based on Multisource Historical and Real-Time Traffic Information”. In: *IEEE Transactions on Intelligent Transportation Systems* 13.4 (2012), pp. 1694–1704. ISSN: 1558-0016. DOI: 10.1109/TITS.2012.2204051.

[35] Brena, Ramon F., García-Vázquez, Juan Pablo, Galván-Tejada, Carlos E., Muñoz-Rodriguez, David, Vargas-Rosales, Cesar, and Fangmeyer, James. “Evolution of Indoor Positioning Technologies: A Survey”. In: *Journal of Sensors* 2017 (2017), pp. 1–21. ISSN: 1687-725X. DOI: 10.1155/2017/2630413.

[36] Broach, Joseph, Dill, Jennifer, and Gliebe, John. “Where do cyclists ride? A route choice model developed with revealed preference GPS data”. In: *Transportation Research Part A: Policy and Practice* 46.10 (2012), pp. 1730–1740. ISSN: 0965-8564. DOI: 10.1016/j.tra.2012.07.005.

[37] Brodsky, Warren and Kizner, Micha. “Exploring an alternative in-car music background designed for driver safety”. In: *Transportation Research Part F: Traffic Psychology and Behaviour* 15.2 (2012), pp. 162–173. ISSN: 1369-8478. DOI: https://doi.org/10.1016/j.trf.2011.12.001.

[38] Brooke, John. *"SUS-A quick and dirty usability scale." Usability evaluation in industry*. CRC Press, 1996. ISBN: 978-0-7484-0460-5.

[39] Brown, Barry and Laurier, Eric. "The normal natural troubles of driving with GPS". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2012, pp. 1621–1630. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2208285.

[40] Brügger, Annina, Richter, Kai-Florian, and Fabrikant, Sara Irina. "How does navigation system behavior influence human behavior?" In: *Cognitive Research: Principles and Implications* 4.1 (2019), pp. 1–5. ISSN: 2365-7464. DOI: 10.1186/s41235-019-0156-5.

[41] Carrascal, Juan Pablo and Church, Karen. "An In-Situ Study of Mobile App & Mobile Search Interactions". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2015, pp. 2739–2748. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702486.

[42] Carton, Anthony. "Design of a Context Aware Signal Glove for Bicycle and Motorcycle Riders". In: *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*. 2012, pp. 635–636. ISBN: 9781450312240. DOI: 10.1145/2370216.2370341.

[43] Chang, Chun-Cheng, Sodnik, Jaka, and Boyle, Linda Ng. "Don't Speak and Drive: Cognitive Workload of In-Vehicle Speech Interactions". In: *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 2016, pp. 99–104. ISBN: 9781450346542. DOI: 10.1145/3004323.3004351.

[44] Christou, Chris, Tzanavari, Aimilia, Herakleous, Kyriakos, and Poullis, Charalambos. "Navigation in virtual reality: Comparison of gaze-directed and pointing motion control". In: *2016 18th Mediterranean Electrotechnical Conference (MELECON)*. 2016, pp. 1–6. DOI: 10.1109/MELCON.2016.7495413.

[45] Chua, Alton Y. K., Balkunje, Radhika Shenoy, and Goh, Dion Hoe-Lian. "Fulfilling Mobile Information Needs: A Study on the Use of Mobile Phones". In: *Proceedings of the 5th International Conference on Ubiquitous Information Management and Communication*. 2011, pp. 1–7. ISBN: 9781450305716. DOI: 10.1145/1968613.1968721.

[46] Church, Karen, Cherubini, Mauro, and Oliver, Nuria. "A large-scale study of daily information needs captured in situ". In: *ACM Transactions on Computer-Human Interaction* 21.2 (2014), pp. 1–46. ISSN: 1073-0516, 1557-7325. DOI: 10.1145/2552193.

[47] Church, Karen, Ferreira, Denzil, Banovic, Nikola, and Lyons, Kent. "Understanding the Challenges of Mobile Phone Usage Data". In: *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2015, pp. 504–514. ISBN: 978-1-4503-3652-9. DOI: 10.1145/2785830.2785891.

[48] Copenhagenize Design Company. *Copenhagenize Index*. 2019. URL: https://copenhagenizeindex.eu/ (visited on 05/17/2022).

[49] Coutrot, Antoine, Manley, Ed, Goodroe, Sarah C., Gahnstrom, Christoffer J., Filomena, Gabriele, Yesiltepe, Demet, Dalton, Ruth C., Wiener, Jan M., Hölscher, Christoph, Hornberger, Michael, and Spiers, Hugo. "Entropy of city street networks linked to future spatial navigation ability". In: *Nature* 604.7904 (2022), pp. 104–110. ISSN: 1476-4687. DOI: 10.1038/s41586-022-04486-7.

[50] Curzon, Paul, Blandford, Ann, Butterworth, Richard, and Bhogal, Ravinder. *Interaction design issues for car navigation systems*. Proceedings paper. 2002.

[51] Dalton, Ruth Conroy. "The Secret Is To Follow Your Nose: Route Path Selection and Angularity". In: *Environment and Behavior* 35.1 (2003), pp. 107–131. DOI: 10.1177/0013916502238867.

[52] Dancu, Alexandru, Franjcic, Zlatko, and Fjeld, Morten. "Smart flashlight: map navigation using a bike-mounted projector". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014, pp. 3627–3630. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557289.

[53] Dancu, Alexandru, Vechev, Velko, Ünlüer, Adviye Ayça, Nilson, Simon, Nygren, Oscar, Eliasson, Simon, Barjonet, Jean-Elie, Marshall, Joe, and Fjeld, Morten. "Gesture Bike: Examining Projection Surfaces and Turn Signal Systems for Urban Cycling". In: *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces - ITS '15*. 2015, pp. 151–159. ISBN: 978-1-4503-3899-8. DOI: 10.1145/2817721.2817748.

[54] De Waard, Dick, Lewis-Evans, Ben, Jelijs, Bart, Tucha, Oliver, and Brookhuis, Karel. "The effects of operating a touch screen smartphone and other common activities performed while bicycling on cycling behaviour". In: *Transportation Research Part F: Traffic Psychology and Behaviour* 22 (2014), pp. 196–206. ISSN: 1369-8478. DOI: 10.1016/j.trf.2013.12.003.

[55] Devigne, Louise, Babel, Marie, Nouviale, Florian, Narayanan, Vishnu K., Pasteau, François, and Gallien, Philippe. "Design of an immersive simulator for assisted power wheelchair driving". In: *2017 International Conference on Rehabilitation Robotics (ICORR)*. 2017, pp. 995–1000. DOI: 10.1109/ICORR.2017.8009379.

[56] Diaz, Melvin. "Integrating GPS receivers into consumer mobile electronics". In: *IEEE MultiMedia* 6.4 (1999), pp. 88–90. ISSN: 1941-0166. DOI: 10.1109/93.809238.

[57] Dicker, Russell. *3 new ways to navigate more sustainably with Maps*. 2021. URL: https://blog.google/products/maps/3-new-ways-navigate-more-sustainably-maps/ (visited on 04/26/2022).

[58] Dijkstra, E. W. "A note on two problems in connexion with graphs". In: *Numerische Mathematik* 1.1 (1959), pp. 269–271. ISSN: 0945-3245. DOI: 10.1007/BF01386390.

[59] Dingus, Thomas A., Antin, Jonathan P., Hulse, Melissa C., and Wierwille, Walter W. "Human Factors Issues Associated with in-Car Navigation System Usage: An Overview of Two in-Car Experimental Studies". In: *Proceedings of the Human Factors Society Annual Meeting* 32.19 (1988), pp. 1448–1452. ISSN: 0163-5182. DOI: 10.1177/154193128803201930.

[60] Do, Trinh Minh Tri, Blom, Jan, and Gatica-Perez, Daniel. "Smartphone usage in the wild: a large-scale analysis of applications and context". In: *Proceedings of the 13th international conference on multimodal interfaces*. 2011, pp. 353–360. ISBN: 978-1-4503-0641-6. DOI: 10.1145/2070481.2070550.

[61] Dube, Ryan. *Google Maps Voice Guidance is Great for Walking City Streets*. 2019. URL: https://www.groovypost.com/howto/google-maps-voice-guidance-is-great-for-walking-city-streets/ (visited on 04/26/2022).

[62] Duckham, Matt and Kulik, Lars. "'Simplest' Paths: Automated Route Selection for Navigation". In: *Spatial Information Theory. Foundations of Geographic Information Science*. 2003, pp. 169–185. ISBN: 978-3-540-39923-0.

[63] Ekstrom, Arne D., Spiers, Hugo J., Bohbot, Véronique D., and Rosenbaum, R. Shayna. "The Neural Basis of Spatial Navigation". In: *Human Spatial Navigation*. 2018, pp. 45–65. ISBN: 9780691171746.

[64] Epstein, Russell A., Patai, Eva Zita, Julian, Joshua B., and Spiers, Hugo J. "The cognitive map in humans: spatial navigation and beyond". In: *Nature Neuroscience* 20.11 (2017), pp. 1504–1513. ISSN: 1546-1726. DOI: 10.1038/nn.4656.

[65] Falaki, Hossein, Mahajan, Ratul, Kandula, Srikanth, Lymberopoulos, Dimitrios, Govindan, Ramesh, and Estrin, Deborah. "Diversity in Smartphone Usage". In: *Proceedings of the 8th International Conference on Mobile Systems, Applications, and Services*. 2010, pp. 179–194. ISBN: 978-1-60558-985-5. DOI: 10.1145/1814433.1814453.

[66] Faul, Franz, Erdfelder, Edgar, Lang, Albert-Georg, and AG, Buchner. "G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences". In: *Behavior Research Methods Instruments & Computers* 39 (2007), pp. 175–191.

[67] Federation, European Cyclists'. *Annual Report 2020*. 2015. URL: https://ecf.com/system/files/ECF_Annual_Report_2020.pdf (visited on 09/07/2021).

[68] Ferreira, Denzil, Kostakos, Vassilis, Beresford, Alastair R., Lindqvist, Janne, and Dey, Anind K. "Securacy: An Empirical Investigation of Android Applications' Network Usage, Privacy and Security". In: *Proceedings of the 8th ACM Conference on Security & Privacy in Wireless and Mobile Networks*. 2015, pp. 1–11. ISBN: 978-1-4503-3623-9. DOI: 10.1145/2766498.2766506.

[69] Foderaro, Lisa W. *Navigation Apps Are Turning Quiet Neighborhoods Into Traffic Nightmares*. 2017. URL: https://www.nytimes.com/2017/12/24/nyregion/traffic-apps-gps-neighborhoods.html (visited on 06/11/2022).

[70] Frommer, Dan. *These are the 10 most popular mobile apps in America*. 2017. URL: http://www.recode.net/2017/8/24/16197218/top-10-mobile-apps-2017-comscore-chart-facebook-google (visited on 08/28/2017).

[71] Fu, Kaiqun, Lu, Yen-Cheng, and Lu, Chang-Tien. "TREADS: a safe route recommender using social media mining and text summarization". In: *Proceedings of the 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. 2014, pp. 557–560. ISBN: 978-1-4503-3131-9. DOI: 10.1145/2666310.2666368.

[72] Fujihara, Akihiro and Yanagizawa, Takuma. "Proposing an Extended iBeacon System for Indoor Route Guidance". In: *2015 International Conference on Intelligent Networking and Collaborative Systems*. 2015, pp. 31–37. DOI: 10.1109/INCoS.2015.72.

[73] Gagnon, Kyle T., Thomas, Brandon J., Munion, Ascher, Creem-Regehr, Sarah H., Cashdan, Elizabeth A., and Stefanucci, Jeanine K. "Not all those who wander are lost: Spatial exploration patterns and their relationship to gender and spatial memory". In: *Cognition* 180 (2018), pp. 108–117. ISSN: 0010-0277. DOI: 10.1016/j.cognition.2018.06.020.

[74] Galbrun, Esther, Pelechrinis, Konstantinos, and Terzi, Evimaria. “Urban navigation beyond shortest route: The case of safe paths”. In: *Information Systems* 57 (2016), pp. 160–171. ISSN: 0306-4379. DOI: 10.1016/j.is.2015.10.005.

[75] Ghosh, Debjyoti, Liu, Can, Zhao, Shengdong, and Hara, Kotaro. “Commanding and Re-Dictation: Developing Eyes-Free Voice-Based Interaction for Editing Dictated Text”. In: *ACM Trans. Comput.-Hum. Interact.* 27.4 (2020), pp. 1–31. ISSN: 1073-0516. DOI: 10.1145/3390889.

[76] Giannopoulos, Ioannis, Kiefer, Peter, and Raubal, Martin. “GazeNav: Gaze-Based Pedestrian Navigation”. In: *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2015, pp. 337–346. ISBN: 978-1-4503-3652-9. DOI: 10.1145/2785830.2785873.

[77] Golledge, Reginald G. “Defining the Criteria Used in Path Selection”. *UC Berkeley: University of California Transportation Center*. 1995.

[78] Golledge, Reginald G. “Path selection and route preference in human navigation: A progress report”. In: *Spatial Information Theory A Theoretical Basis for GIS*. 1995, pp. 207–222. ISBN: 978-3-540-45519-6. DOI: 10.1007/3-540-60392-1_14.

[79] Golledge, Reginald G. “Place recognition and wayfinding: Making sense of space”. In: *Geoforum* 23.2 (1992), pp. 199–214. ISSN: 0016-7185. DOI: https://doi.org/10.1016/0016-7185(92)90017-X.

[80] Golledge, Reginald G. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. JHU Press, 1999. ISBN: 978-0-8018-5993-9.

[81] Goodchild, Michael F. and Li, Linna. “Assuring the quality of volunteered geographic information”. In: *Spatial Statistics* 1 (2012), pp. 110–120. ISSN: 2211-6753. DOI: https://doi.org/10.1016/j.spasta.2012.03.002.

[82] Google. *Google Maps*. 2022. URL: https://play.google.com/store/apps/details?id=com.google.android.apps.maps&hl=en&gl=US (visited on 04/26/2022).

[83] Gu, Weixi, Zhou, Zimu, Zhou, Yuxun, Zou, Han, Liu, Yunxin, Spanos, Costas J., and Zhang, Lin. “BikeMate: Bike Riding Behavior Monitoring with Smartphones”. In: *Proceedings of the 14th EAI International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services*. 2017, pp. 313–322. ISBN: 978-1-4503-5368-7. DOI: 10.1145/3144457.3144462.

[84] Hanauer, Florian. *Navi führt Autofahrerin auf Treppen am Polizeihaus*. 2016. URL: https://weserreport.de/2016/09/bremen-bremen/panorama/navi-fuehrt-autofahrerin-auf-treppen-polizeihaus/ (visited on 04/05/2022).

[85] Hanson, Hilary. *GPS Leads Japanese Tourists To Drive Into Australian Bay*. 2012. URL: https://www.huffpost.com/entry/gps-tourists-australia_n_1363823 (visited on 04/05/2022).

[86] Hart, Peter E., Nilsson, Nils J., and Raphael, Bertram. “A Formal Basis for the Heuristic Determination of Minimum Cost Paths”. In: *IEEE Transactions on Systems Science and Cybernetics* 4.2 (1968), pp. 100–107. DOI: 10.1109/TSSC.1968.300136.

[87] Hasan, Layla, Morris, Anne, and Probets, Steve. “Using Google Analytics to Evaluate the Usability of E-Commerce Sites”. In: *Human Centered Design*. 2009, pp. 697–706. ISBN: 978-3-642-02806-9. DOI: 10.1007/978-3-642-02806-9_81.

[88] Hecht, Brent, Carton, Samuel H., Quaderi, Mahmood, Schöning, Johannes, Raubal, Martin, Gergle, Darren, and Downey, Doug. "Explanatory semantic relatedness and explicit spatialization for exploratory search". In: *Proceedings of the 35th international ACM SIGIR conference on Research and development in information retrieval*. 2012, pp. 415–424. ISBN: 978-1-4503-1472-5. DOI: 10.1145/2348283.2348341.

[89] HeiGIT gGmbH. *Openrouteservice*. 2022. URL: https://news.wheelmap.org/en/ (visited on 05/21/2022).

[90] Heller, Florian and Schöning, Johannes. "NavigaTone: Seamlessly Embedding Navigation Cues in Mobile Music Listening". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–7. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3174211.

[91] Hewett, Thomas T., Baecker, Ronald, Card, Stuart, Carey, Tom, Gasen, Jean, Mantei, Marilyn, Perlman, Gary, Strong, Gary, and Verplank, William. *ACM SIGCHI Curricula for Human-Computer Interaction*. Association for Computing Machinery, 1992. ISBN: 0-89791-474-0.

[92] Hintze, Daniel, Hintze, Philipp, Findling, Rainhard D., and Mayrhofer, René. "A Large-Scale, Long-Term Analysis of Mobile Device Usage Characteristics". In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1.2 (2017), pp. 1–21.

[93] Hipp, Markus, Schaub, Florian, Kargl, Frank, and Weber, Michael. "Interaction Weaknesses of Personal Navigation Devices". In: *Proceedings of the 2Nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 2010, pp. 129–136. ISBN: 978-1-4503-0437-5. DOI: 10.1145/1969773.1969796.

[94] Hochmair, Hartwig H. *'Least Angle' Heuristic: Consequences of errors during navigation*. 2000.

[95] Hochmair, Hartwig H. "Investigating the effectiveness of the least-angle strategy for wayfinding in unknown street networks". In: *Environment and Planning B: Planning and Design* 32.5 (2005), pp. 673–691. DOI: 10.1068/b31160.

[96] Hochmair, Hartwig H. and Frank, Andrew. "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. DOI: 10.1023/A:1015566423907.

[97] Holland, Simon, Morse, David R., and Gedenryd, Henrik. "AudioGPS: Spatial Audio Navigation with a Minimal Attention Interface". In: *Personal Ubiquitous Comput.* 6.4 (2002), pp. 253–259. ISSN: 1617-4909. DOI: 10.1007/s007790200025.

[98] Hölscher, Christoph, Tenbrink, Thora, and Wiener, Jan M. "Would you follow your own route description? Cognitive strategies in urban route planning". In: *Cognition* 121.2 (2011), pp. 228–247. ISSN: 0010-0277. DOI: 10.1016/j.cognition.2011.06.005.

[99] Hua, Zhang and Ng, Wei Lieh. "Speech Recognition Interface Design for In-Vehicle System". In: *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 2010, pp. 29–33. ISBN: 978-1-4503-0437-5. DOI: 10.1145/1969773.1969780.

[100] Huang, Haosheng, Mathis, Thomas, and Weibel, Robert. "Choose your own route – supporting pedestrian navigation without restricting the user to a predefined route". In: *Cartography and Geographic Information Science* 49.2 (2022), pp. 95–114. ISSN: 1523-0406, 1545-0465. DOI: 10.1080/15230406.2021.1983731.

[101] Huang, Haosheng, Schmidt, Manuela, and Gartner, Georg. "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. ISSN: 1523-0406. DOI: 10.1559/15230406392107.

[102] Hurst, Paul and Clough, Paul. "Will we be lost without paper maps in the digital age?" In: *Journal of Information Science* 39.1 (2013), pp. 48–60. ISSN: 0165-5515. DOI: 10.1177/0165551512470043.

[103] Huxtable, Brianna Jean, Lai, Carlo Ka-Ho, Zhu, Johnson Wen Jun, Lam, Paulina Mun-Yee, Choi, Yeseul Tracy, Neustaedter, Carman, and Corness, Greg J. "Ziklo: Bicycle Navigation through Tactile Feedback". In: *CHI '14 Extended Abstracts on Human Factors in Computing Systems*. 2014, pp. 177–178. ISBN: 9781450324748. DOI: 10.1145/2559206.2579481.

[104] Ishikawa, Toru, Fujiwara, Hiromichi, Imai, Osamu, and Okabe, Atsuyuki. "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. ISSN: 0272-4944. DOI: 10.1016/j.jenvp.2007.09.002.

[105] Javadi, Amir-Homayoun, Emo, Beatrix, Howard, Lorelei R., Zisch, Fiona E., Yu, Yichao, Knight, Rebecca, Pinelo Silva, Joao, and Spiers, Hugo J. "Hippocampal and prefrontal processing of network topology to simulate the future". In: *Nature Communications* 8.1 (2017). ISSN: 2041-1723. DOI: 10.1038/ncomms14652.

[106] Johnson, Isaac, Henderson, Jessica, Perry, Caitlin, Schöning, Johannes, and Hecht, Brent. "Beautiful but at What Cost? An Examination of Externalities in Geographic Vehicle Routing". In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1.2 (2017), pp. 1–21. DOI: 10.1145/3090080.

[107] Kamvar, Maryam and Baluja, Shumeet. "A Large Scale Study of Wireless Search Behavior: Google Mobile Search". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2006, pp. 701–709. DOI: 10.1145/1124772.1124877.

[108] Kane, Shaun K., Wobbrock, Jacob O., and Smith, Ian E. "Getting off the Treadmill: Evaluating Walking User Interfaces for Mobile Devices in Public Spaces". In: *Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services*. 2008, pp. 109–118. ISBN: 9781595939524. DOI: 10.1145/1409240.1409253.

[109] Kedron, Peter, Frazier, Amy E., Trgovac, Andrew B., Nelson, Trisalyn, and Fotheringham, A. Stewart. "Reproducibility and Replicability in Geographical Analysis". In: *Geographical Analysis* 53.1 (2021), pp. 135–147. ISSN: 1538-4632. DOI: 10.1111/gean.12221.

[110] Kim, Jihyun, Jeong, Meuel, and Lee, Seul Chan. “"Why did this voice agent not understand me?": error recovery strategy for in-vehicle voice user interface”. In: *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings*. 2019, pp. 146–150. ISBN: 978-1-4503-6920-6. DOI: 10.1145/3349263.3351513.

[111] Kim, Kyungwan and Bock, Otmar. “Acquisition of landmark, route, and survey knowledge in a wayfinding task: in stages or in parallel?” In: *Psychological Research* 85.5 (2021), pp. 2098–2106. ISSN: 1430-2772. DOI: 10.1007/s00426-020-01384-3.

[112] Klatzky, Roberta L., Loomis, Jack M., and Golledge, Reginald G. “Encoding Spatial Representations Through Nonvisually Guided Locomotion: Tests of Human Path Integration”. In: *Psychology of Learning and Motivation: Advances in Research and Theory* 37 (1997), pp. 41–54.

[113] Komoot. *Komoot*. 2022. URL: https://www.komoot.com/ (visited on 04/26/2022).

[114] Kraak, Menno-Jan. “The Cartographic Visualization Process: From Presentation to Exploration”. In: *The Cartographic Journal* 35.1 (1998), pp. 11–15. DOI: 10.1179/000870498787074100.

[115] Kraak, Menno-Jan and Ormeling, Ferjan. *Cartography: Visualization of Geospatial Data, Fourth Edition*. CRC Press, 2021. ISBN: 978-1-138-61395-9.

[116] Krone, Stephanie. *Suchen nach Fahrradrouten in Corona-Zeiten boomt*. 2020. URL: https://twitter.com/FrauKrone/status/1285624861600231424 (visited on 08/11/2020).

[117] Krüger, Antonio, Aslan, Ilhan, and Zimmer, Hubert. “The Effects of Mobile Pedestrian Navigation Systems on the Concurrent Acquisition of Route and Survey Knowledge”. In: *Mobile Human-Computer Interaction - MobileHCI 2004*. 2004, pp. 446–450. ISBN: 978-3-540-28637-0. DOI: 10.1007/978-3-540-28637-0_54.

[118] Kuipers, Benjamin. “Modeling spatial knowledge”. In: *Cognitive Science* 2.2 (1978), pp. 129–153. ISSN: 0364-0213. DOI: 10.1016/S0364-0213(78)80003-2.

[119] Kumar, Sameer and Moore, Kevin B. “The Evolution of Global Positioning System (GPS) Technology”. In: *Journal of Science Education and Technology* 11.1 (2002), pp. 59–80. ISSN: 1573-1839. DOI: 10.1023/A:1013999415003.

[120] Kunhoth, Jayakanth, Karkar, AbdelGhani, Al-Maadeed, Somaya, and Al-Ali, Abdulla. “Indoor positioning and wayfinding systems: a survey”. In: *Human-centric Computing and Information Sciences* 10.1 (2020), pp. 1–18. ISSN: 2192-1962. DOI: 10.1186/s13673-020-00222-0.

[121] Kuo, Ting-Yu, Chu, Hung-Kuo, and Chang, Yung-Ju. “Comparing the effects of reference-based, orientation-based, and turn-by-turn navigation guidance on users’ independent navigation”. In: *Adjunct Proceedings of the 2020 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2020 ACM International Symposium on Wearable Computers*. 2020, pp. 63–66. ISBN: 978-1-4503-8076-8. DOI: 10.1145/3410530.3414424.

[122] Lee, Uichin, Lee, Joonwon, Ko, Minsam, Lee, Changhun, Kim, Yuhwan, Yang, Subin, Yatani, Koji, Gweon, Gahgene, Chung, Kyong-Mee, and Song, Junehwa. "Hooked on Smartphones: An Exploratory Study on Smartphone Overuse Among College Students". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014, pp. 2327–2336. DOI: 10.1145/2556288.2557366.

[123] Leo, Bagrow and Skelton, Raleigh A. *History of Cartography*. 2nd ed. Routledge, 2019. ISBN: 978-0-203-79000-7. DOI: 10.4324/9780203790007.

[124] Lettner, Florian and Holzmann, Clemens. "Automated and unsupervised user interaction logging as basis for usability evaluation of mobile applications". In: *Proceedings of the 10th International Conference on Advances in Mobile Computing & Multimedia - MoMM '12*. 2012, pp. 118–127. ISBN: 978-1-4503-1307-0. DOI: 10.1145/2428955.2428983.

[125] Lierop, Dea van, Soemers, Judith, Hoeke, Lisette, Liu, George, Chen, Zheyan, Ettema, Dick F., and Kruijf, Joost. "Wayfinding for cycle highways: Assessing e-bike users' experiences with wayfinding along a cycle highway in the Netherlands". In: *Journal of Transport Geography* 88 (2020). ISSN: 0966-6923. DOI: https://doi.org/10.1016/j.jtrangeo.2020.102827.

[126] Lin, Allen Yilun, Kuehl, Kate, Schöning, Johannes, and Hecht, Brent. "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. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025737.

[127] Lin, Sophia. *Explore and eat your way around town with Google Maps*. 2018. URL: https://www.blog.google/products/maps/explore-around-town-google-maps/ (visited on 06/05/2018).

[128] Löchtefeld, Markus, Krüger, Antonio, and Gellersen, Hans. "DeceptiBike: Assessing the Perception of Speed Deception in a Virtual Reality Training Bike System". In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. 2016, pp. 1–10. ISBN: 978-1-4503-4763-1. DOI: 10.1145/2971485.2971513.

[129] Loomis, Jack M, Klatzky, Roberta L, Golledge, Reginald G, Cicinelli, Joseph G, Pellegrino, James W, and Fry, Phyllis A. "Nonvisual navigation by blind and sighted: assessment of path integration ability." In: *Journal of Experimental Psychology: General* 122.1 (1993), pp. 73–91.

[130] Loomis, Jack M., Golledge, Reginald G., and Klatzky, Roberta L. "Navigation System for the Blind: Auditory Display Modes and Guidance". In: *Presence: Teleoperators and Virtual Environments* 7.2 (1998), pp. 193–203. DOI: 10.1162/105474698565677.

[131] Louf, Rémi and Barthelemy, Marc. "A typology of street patterns". In: *Journal of The Royal Society Interface* 11.101 (2014), pp. 1–17. DOI: 10.1098/rsif.2014.0924.

[132] lxian. *Fuzzywuzzy_swift*. 2019. URL: https://github.com/lxian/Fuzzywuzzy%5C_swift (visited on 07/11/2019).

[133] Lynch, Kevin. *The Image of the City*. MIT Press, 1964. ISBN: 978-0-262-62001-7.

[134] Marshall, Joe, Dancu, Alexandru, and Mueller, Florian "Floyd". “Interaction in Motion: Designing Truly Mobile Interaction”. In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. 2016, pp. 215–228. ISBN: 978-1-4503-4031-1. DOI: 10.1145/2901790.2901844.

[135] Marshall, Joe and Tennent, Paul. “Mobile Interaction Does Not Exist”. In: *CHI ’13 Extended Abstracts on Human Factors in Computing Systems*. 2013, pp. 2069–2078. ISBN: 978-1-4503-1952-2. DOI: 10.1145/2468356.2468725.

[136] Matviienko, Andrii, Ananthanarayan, Swamy, Borojeni, Shadan Sadeghian, Feld, Yannick, Heuten, Wilko, and Boll, Susanne. “Augmenting bicycles and helmets with multimodal warnings for children”. In: *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2018, pp. 1–13. ISBN: 978-1-4503-5898-9. DOI: 10.1145/3229434.3229479.

[137] Matviienko, Andrii, Ananthanarayan, Swamy, Brewster, Stephen, Heuten, Wilko, and Boll, Susanne. “Comparing unimodal lane keeping cues for child cyclists”. In: *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*. 2019, pp. 1–11. ISBN: 978-1-4503-7624-2. DOI: 10.1145/3365610.3365632.

[138] Matviienko, Andrii, Ananthanarayan, Swamy, El Ali, Abdallah, Heuten, Wilko, and Boll, Susanne. “NaviBike: Comparing Unimodal Navigation Cues for Child Cyclists”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019, pp. 1–12. ISBN: 978-1-4503-5970-2. DOI: 10.1145/3290605.3300850.

[139] Matviienko, Andrii, Müller, Florian, Schön, Dominik, Seesemann, Paul, Günther, Sebastian, and Mühlhäuser, Max. “BikeAR: Understanding Cyclists’ Crossing Decision-Making at Uncontrolled Intersections using Augmented Reality”. In: *CHI Conference on Human Factors in Computing Systems*. 2022, pp. 1–15. ISBN: 978-1-4503-9157-3. DOI: 10.1145/3491102.3517560.

[140] Matviienko, Andrii, Müller, Florian, Zickler, Marcel, Gasche, Lisa Alina, Abels, Julia, Steinert, Till, and Mühlhäuser, Max. “Reducing Virtual Reality Sickness for Cyclists in VR Bicycle Simulators”. In: *CHI Conference on Human Factors in Computing Systems*. 2022, pp. 1–14. ISBN: 978-1-4503-9157-3. DOI: 10.1145/3491102.3501959.

[141] May, Andrew J., Ross, Tracy, Bayer, Steven H., and Tarkiainen, Mikko J. “Pedestrian Navigation Aids: Information Requirements and Design Implications”. In: *Personal Ubiquitous Comput.* 7.6 (2003), pp. 331–338. ISSN: 1617-4909. DOI: 10.1007/s00779-003-0248-5.

[142] Mazurkiewicz, Bartosz, Kattenbeck, Markus, and Giannopoulos, Ioannis. “Navigating Your Way! Increasing the Freedom of Choice During Wayfinding”. In: *11th International Conference on Geographic Information Science (GIScience 2021) - Part II*. Vol. 208. 2021, 9:1–9:16. ISBN: 978-3-95977-208-2. DOI: 10.4230/LIPIcs.GIScience.2021.II.9.

[143] Mazurkiewicz, Bartosz, Kattenbeck, Markus, Kiefer, Peter, and Giannopoulos, Ioannis. “Not Arbitrary, Systematic! Average-Based Route Selection for Navigation Experiments”. In: *11th International Conference on Geographic Information Science (GIScience 2021) - Part I*. Vol. 177. 2020, 8:1–8:16. ISBN: 978-3-95977-166-5. DOI: 10.4230/LIPIcs.GIScience.2021.I.8.

[144] McFarland, Matt. *The case for almost never turning left while driving*. 2014. URL: https://www.washingtonpost.com/news/innovations/wp/2014/04/09/the-case-for-almost-never-turning-left-while-driving/ (visited on 06/20/2022).

[145] McGregor, Moira, Brown, Barry, and McMillan, Donald. "100 Days of iPhone Use: Mobile Recording in the Wild". In: *CHI '14 Extended Abstracts on Human Factors in Computing Systems*. 2014, pp. 2335–2340. ISBN: 978-1-4503-2474-8. DOI: 10.1145/2559206.2581296.

[146] McMillan, Donald, Morrison, Alistair, Brown, Owain, Hall, Malcolm, and Chalmers, Matthew. "Further into the Wild: Running Worldwide Trials of Mobile Systems". In: *Pervasive Computing*. 2010, pp. 210–227. ISBN: 978-3-642-12654-3. DOI: 10.1007/978-3-642-12654-3_13.

[147] Medial Journal Editors, International Committee of. *Defining the Role of Authors and Contributors*. 2022. URL: https://www.icmje.org/recommendations/browse/roles-and-responsibilities/defining-the-role-of-authors-and-contributors.html (visited on 04/26/2022).

[148] Minh, Nguyen Quang. "Application of "Car-Free City" and "City of Short Walks" to Living Quarters in Hanoi Towards Sustainable Mobility and Logistics". In: *Procedia Engineering* 142 (2016), pp. 284–291. ISSN: 1877-7058. DOI: https://doi.org/10.1016/j.proeng.2016.02.043.

[149] Montello, Daniel R. "Navigation". In: *The Cambridge Handbook of Visuospatial Thinking*. 1st ed. 2005, pp. 257–294. ISBN: 978-0-511-61044-8. DOI: 10.1017/CBO9780511610448.008.

[150] Nakhimovsky, Yelena, Miller, Andrew T, Dimopoulos, Tom, and Siliski, Michael. "Behind the scenes of google maps navigation: enabling actionable user feedback at scale". In: *CHI'10 Extended Abstracts on Human Factors in Computing Systems*. 2010, pp. 3763–3768.

[151] NASA. *NASA TLX application*. 2019. URL: https://humansystems.arc.nasa.gov/groups/tlx/tlxapp.php (visited on 01/31/2019).

[152] Nielsen, Janni, Clemmensen, Torkil, and Yssing, Carsten. "Getting Access to What Goes on in People's Heads? Reflections on the Think-Aloud Technique". In: *Proceedings of the Second Nordic Conference on Human-Computer Interaction*. 2002, pp. 101–110. ISBN: 1581136161. DOI: 10.1145/572020.572033.

[153] Norman, Donald A. *The Design of Everyday Things*. Basic Books, Inc., 2002. ISBN: 978-0-465-06710-7.

[154] Nunes, Luis and Recarte, Miguel Angel. "Cognitive demands of hands-free-phone conversation while driving". In: *Transportation Research Part F: Traffic Psychology and Behaviour* 5.2 (2002), pp. 133–144. ISSN: 1369-8478. DOI: https://doi.org/10.1016/S1369-8478(02)00012-8.

[155] O'Beirne, Justin. *A Year of Google & Apple Maps*. 2017. URL: https://www.justinobeirne.com/a-year-of-google-maps-and-apple-maps (visited on 09/14/2017).

[156] O'Keefe, John and Nadel, Lynn. *The hippocampus as a cognitive map*. Clarendon Press, 1978. ISBN: 978-0-19-857206-0.

[157] openrouteservice. *openrouteservice*. 2019. URL: https://maps.openrouteservice.org/ (visited on 08/25/2019).

[158] OpenStreetMap. *OpenStreetMap*. 2017. URL: https://www.openstreetmap.org (visited on 06/12/2022).

[159] Park, Chang-Won, Joe, Moon-Jeung, Byun, Seong-Chan, Choi, Hyun-Woo, Jung, Mun-Ho, and Kim, Young-In. "A turn-by-turn navigation system for automotive telematics terminals". In: *IEEE IV2003 Intelligent Vehicles Symposium. Proceedings*. 2003, pp. 21–24. DOI: 10.1109/IVS.2003.1212876.

[160] Patras, Vaios, Fudos, Ioannis, Koritsoglou, Kyriakos, and Tsoumanis, Georgios. "Revisiting shortest path algorithms for navigation systems". In: *2021 6th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM)*. 2021, pp. 1–5. DOI: 10.1109/SEEDA-CECNSM53056.2021.9566273.

[161] Peng, Zhe, Gao, Shang, Xiao, Bin, Guo, Songtao, and Yang, Yuanyuan. "CrowdGIS: Updating Digital Maps via Mobile Crowdsensing". In: *IEEE Transactions on Automation Science and Engineering* 15.1 (2018), pp. 369–380. ISSN: 1558-3783. DOI: 10.1109/TASE.2017.2761793.

[162] Perkins, Chris. "Cartography: mapping theory". In: *Progress in Human Geography* 27.3 (2003), pp. 341–351. ISSN: 0309-1325. DOI: 10.1191/0309132503ph430pr.

[163] Pielot, Martin and Boll, Susanne. "'In Fifty Metres Turn Left': Why Turn-by-turn Instructions Fail Pedestrians". In: *Proceedings of Using Audio and Haptics for Delivering Spatial Information via Mobile Devices*. 2010, pp. 2–4.

[164] Pielot, Martin and Boll, Susanne. "Tactile Wayfinder: Comparison of Tactile Waypoint Navigation with Commercial Pedestrian Navigation Systems". In: *Pervasive Computing*. 2010, pp. 76–93. ISBN: 978-3-642-12654-3. DOI: 10.1007/978-3-642-12654-3_5.

[165] Pielot, Martin, Church, Karen, and Oliveira, Rodrigo de. "An in-situ study of mobile phone notifications". In: *Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services*. 2014, pp. 233–242. ISBN: 978-1-4503-3004-6. DOI: 10.1145/2628363.2628364.

[166] Pielot, Martin, Poppinga, Benjamin, Heuten, Wilko, and Boll, Susanne. "A Tactile Compass for Eyes-Free Pedestrian Navigation". In: *Human-Computer Interaction – INTERACT 2011*. 2011, pp. 640–656. ISBN: 978-3-642-23771-3. DOI: 10.1007/978-3-642-23771-3_47.

[167] Pielot, Martin, Poppinga, Benjamin, Heuten, Wilko, and Boll, Susanne. "Tacticycle: Supporting Exploratory Bicycle Trips". In: *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services - MobileHCI '12*. 2012, pp. 369–378. ISBN: 978-1-4503-1105-2. DOI: 10.1145/2371574.2371631.

[168] Poppinga, Benjamin, Pielot, Martin, and Boll, Susanne. "Tacticycle: a tactile display for supporting tourists on a bicycle trip". In: *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '09*. 2009, pp. 1–4. ISBN: 978-1-60558-281-8. DOI: 10.1145/1613858.1613911.

[169] Porcheron, Martin, Fischer, Joel E., Reeves, Stuart, and Sharples, Sarah. "Voice Interfaces in Everyday Life". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3174214.

[170] Potuck, Michael. *iOS 14: How to use detailed cycling directions in Apple Maps*. 2021. URL: https://9to5mac.com/2021/05/05/how-to-use-apple-maps-cycling-directions-ios-14/ (visited on 04/26/2022).

[171] Prasad, Manoj, Taele, Paul, Goldberg, Daniel, and Hammond, Tracy A. "HaptiMoto: Turn-by-turn Haptic Route Guidance Interface for Motorcyclists". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014, pp. 3597–3606. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557404.

[172] Pucher, John and Buehler, Ralph. "Cycling towards a more sustainable transport future". In: *Transport Reviews* 37.6 (2017), pp. 689–694. ISSN: 0144-1647. DOI: 10.1080/01441647.2017.1340234.

[173] Quddus, Mohammed A., Ochieng, Washington Y., and Noland, Robert B. "Current map-matching algorithms for transport applications: State-of-the art and future research directions". In: *Transportation Research Part C: Emerging Technologies* 15.5 (2007), pp. 312–328. ISSN: 0968-090X. DOI: 10.1016/j.trc.2007.05.002.

[174] Rahaman, Mohammad Saiedur, Mei, Yi, Hamilton, Margaret, and Salim, Flora D. "CAPRA: A contour-based accessible path routing algorithm". In: *Information Sciences* 385-386 (2017), pp. 157–173. ISSN: 0020-0255. DOI: 10.1016/j.ins.2016.12.041.

[175] Rahmati, Ahmad and Zhong, Lin. "Studying Smartphone Usage: Lessons from a Four-Month Field Study". In: *IEEE Transactions on Mobile Computing* 12.7 (2013), pp. 1417–1427. ISSN: 1536-1233. DOI: 10.1109/TMC.2012.127.

[176] Razzaque, Sharif. "Redirected Walking". Ph.D. The University of North Carolina at Chapel Hill, 2005.

[177] Reid, Carlton. *Bike boom: the unexpected resurgence of cycling*. Island Press, 2017. ISBN: 978-1610918169.

[178] Renaudin, Valérie, Dommes, Aurélie, and Guilbot, Michèle. "Engineering, Human, and Legal Challenges of Navigation Systems for Personal Mobility". In: *IEEE Transactions on Intelligent Transportation Systems* 18.1 (2017), pp. 177–191. ISSN: 1558-0016. DOI: 10.1109/TITS.2016.2563481.

[179] Richter, Felix. *Infographic: COVID-19 Pandemic Fuels Bicycle Boom*. en. May 2020. URL: https://www.statista.com/chart/21794/year-over-year-change-in-bicycle-sales-in-the-us/ (visited on 07/20/2020).

[180] Richter, Felix. *The Global Rise of Bike-Sharing*. 2018. URL: https://www.statista.com/chart/13483/bike-sharing-programs/ (visited on 09/08/2020).

[181] Richter, Kai-Florian, Klippel, Alexander, and Freksa, Christian. *Shortest, fastest,- but what next? a different approach to route directions*. 2004.

[182] Riegelsberger, Jens and Nakhimovsky, Yelena. "Seeing the bigger picture: a multimethod field trial of google maps for mobile". In: *CHI '08 Extended Abstracts on Human Factors in Computing Systems*. 2008, pp. 2221–2228. ISBN: 978-1-60558-012-8. DOI: 10.1145/1358628.1358655.

[183] Robertson, Judy and Kaptein, Maurits. *Modern Statistical Methods for HCI*. 1st. Springer, 2016. ISBN: 978-3-319-26631-2. DOI: 10.1007/978-3-319-26633-6.

[184] Robinson, Simon, Jones, Matt, Eslambolchilar, Parisa, Murray-Smith, Roderick, and Lindborg, Mads. “"I did it my way": moving away from the tyranny of turn-by-turn pedestrian navigation”. In: *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services - MobileHCI ’10*. 2010, pp. 341–344. ISBN: 978-1-60558-835-3. DOI: 10.1145/1851600.1851660.

[185] Rowland, Duncan, Flintham, Martin, Oppermann, Leif, Marshall, Joe, Chamberlain, Alan, Koleva, Boriana, Benford, Steve, and Perez, Citlali. “Ubikequitous Computing: Designing Interactive Experiences for Cyclists”. In: *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2009, pp. 1–11. ISBN: 978-1-60558-281-8. DOI: 10.1145/1613858.1613886.

[186] Ruginski, Ian, Giudice, Nicholas, Creem-Regehr, Sarah, and Ishikawa, Toru. “Designing mobile spatial navigation systems from the user’s perspective: an interdisciplinary review”. In: *Spatial Cognition & Computation* 22.1-2 (2022), pp. 1–29. ISSN: 1387-5868. DOI: 10.1080/13875868.2022.2053382.

[187] Ruginski, Ian T., Creem-Regehr, Sarah H., Stefanucci, Jeanine K., and Cashdan, Elizabeth. “GPS use negatively affects environmental learning through spatial transformation abilities”. In: *Journal of Environmental Psychology* 64 (2019), pp. 12–20. ISSN: 0272-4944. DOI: 10.1016/j.jenvp.2019.05.001.

[188] Rümelin, Sonja, Rukzio, Enrico, and Hardy, Robert. “NaviRadar: a novel tactile information display for pedestrian navigation”. In: *Proceedings of the 24th annual ACM symposium on User interface software and technology*. 2011, pp. 293–302. ISBN: 978-1-4503-0716-1. DOI: 10.1145/2047196.2047234.

[189] Runge, Nina, Samsonov, Pavel, Degraen, Donald, and Schöning, Johannes. “No more Autobahn!: Scenic Route Generation Using Googles Street View”. In: *Proceedings of the 21st International Conference on Intelligent User Interfaces*. 2016, pp. 147–151. ISBN: 978-1-4503-4137-0. DOI: 10.1145/2856767.2856804.

[190] Sadalla, Edward K. and Montello, Daniel R. “Remembering Changes in Direction”. In: *Environment and Behavior* 21.3 (1989), pp. 346–363. ISSN: 0013-9165. DOI: 10.1177/0013916589213006.

[191] SAE. *SAE Recommended Practice Navigation and Route Guidance Function Accessibility While Driving (SAE 2364)*. Article. 2001.

[192] Sahami Shirazi, Alireza, Henze, Niels, Dingler, Tilman, Pielot, Martin, Weber, Dominik, and Schmidt, Albrecht. “Large-scale assessment of mobile notifications”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014, pp. 3055–3064. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557189.

[193] Savino, Gian-Luca. “Improving Agent-Based Route Predictions for As-The-Crow-Flies Navigation”. In: *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 2022, pp. 1–6. ISBN: 978-1-4503-9156-6. DOI: 10.1145/3491101.3519709.

[194] Savino, Gian-Luca, Emanuel, Niklas, Kowalzik, Steven, Kroll, Felix, Lange, Marvin C., Laudan, Matthis, Leder, Rieke, Liang, Zhanhua, Markhabayeva, Dayana, Schmeißer, Martin, Schütz, Nicolai, Stellmacher, Carolin, Xu, Zihe, Bub, Kerstin, Kluss, Thorsten, Maldonado, Jaime, Kruijff, Ernst, and Schöning, Johannes. "Comparing Pedestrian Navigation Methods in Virtual Reality and Real Life". In: *2019 International Conference on Multimodal Interaction*. 2019, pp. 16–25. ISBN: 978-1-4503-6860-5. DOI: 10.1145/3340555.3353741.

[195] Savino, Gian-Luca, Kariryaa, Ankit, and Schöning, Johannes. "Free as a Bird, but at What Cost? The Impact of Street Networks on the User Experience of As-The-Crow-Flies Navigation for Cyclists". In: *Proceedings of the ACM on Human-Computer Interaction* 6.MHCI (2022), 209:1–209:24. DOI: 10.1145/3546744.

[196] Savino, Gian-Luca, Meyer, Laura, Schade, Eve Emily Sophie, Tenbrink, Thora, and Schöning, Johannes. "Point Me In the Right Direction: Understanding User Behaviour with As-The-Crow-Flies Navigation". In: *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2020, pp. 1–11. ISBN: 978-1-4503-7516-0. DOI: 10.1145/3379503.3403539.

[197] Savino, Gian-Luca, Moraes Braga, Jessé, and Schöning, Johannes. "VeloCity: Using Voice Assistants for Cyclists to Provide Traffic Reports". In: *Proceedings of the 29th ACM International Conference on Multimedia*. 2021, pp. 3482–3491. ISBN: 978-1-4503-8651-7. DOI: 10.1145/3474085.3475509.

[198] Savino, Gian-Luca, Sawitzky, Tamara von, Matviienko, Andrii, Sturdee, Miriam, Woźniak, Paweł W., Löchtefeld, Markus, Kun, Andrew L., Riener, Andreas, and Häkkilä, Jonna. "Cycling@CHI: Towards a Research Agenda for HCI in the Bike Lane". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–5. ISBN: 978-1-4503-8095-9. DOI: 10.1145/3411763.3441316.

[199] Savino, Gian-Luca, Sturdee, Miriam, Rundé, Simon, Lohmeier, Christine, Hecht, Brent, Prandi, Catia, Nunes, Nuno Jardim, and Schöning, Johannes. "MapRecorder: analysing real-world usage of mobile map applications". In: *Behaviour & Information Technology* 40.7 (2020), pp. 646–662. ISSN: 0144-929X, 1362-3001. DOI: 10.1080/0144929X.2020.1714733.

[200] Sawitzky, Tamara von, Wintersberger, Philipp, Löcken, Andreas, Frison, Anna-Katharina, and Riener, Andreas. "Augmentation Concepts with HUDs for Cyclists to Improve Road Safety in Shared Spaces". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–9. ISBN: 978-1-4503-6819-3. DOI: 10.1145/3334480.3383022.

[201] Schepers, Paul and Klein Wolt, Karin. "Single-Bicycle Crash Types and Characteristics". In: *Cycling Research International* 2 (2012), pp. 119–135. ISSN: 2200-5366.

[202] Schmidt, Albrecht, Dey, Anind K., Kun, Andrew L., and Spiessl, Wolfgang. "Automotive user interfaces: human computer interaction in the car". In: *CHI '10 Extended Abstracts on Human Factors in Computing Systems*. 2010, pp. 3177–3180. ISBN: 978-1-60558-930-5. DOI: 10.1145/1753846.1753949.

[203] Schwab, Philipp. *How do I navigate with Komoot? A detailed look at all the functions*. 2021. URL: https://granfondo-cycling.com/komoot-know-how-2021/ (visited on 04/26/2022).

[204] Schwering, Angela, Krukar, Jakub, Li, Rui, Anacta, Vanessa Joy, and Fuest, Stefan. "Wayfinding Through Orientation". In: *Spatial Cognition & Computation* 17.4 (2017), pp. 273–303. ISSN: 1387-5868. DOI: 10.1080/13875868.2017.1322597.

[205] Selbst, Steven M., Alexander, David, and Ruddy, Richard. "Bicycle-Related Injuries". In: *JAMA Pediatrics* 141.2 (1987), pp. 140–144. ISSN: 2168-6203. DOI: 10.1001/archpedi.1987.04460020030021.

[206] Shin, Choonsung, Hong, Jin-Hyuk, and Dey, Anind K. "Understanding and Prediction of Mobile Application Usage for Smart Phones". In: *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*. 2012, pp. 173–182. ISBN: 978-1-4503-1224-0. DOI: 10.1145/2370216.2370243.

[207] Shinar, David. "Safety and mobility of vulnerable road users: Pedestrians, bicyclists, and motorcyclists". In: *Accident Analysis & Prevention* 44.1 (2012), pp. 1–2. ISSN: 0001-4575. DOI: 10.1016/j.aap.2010.12.031.

[208] Siegel, Alexander W. and White, Sheldon H. "The Development of Spatial Representations of Large-Scale Environments". In: *Advances in Child Development and Behavior*. Vol. 10. 1975, pp. 9–55. DOI: 10.1016/S0065-2407(08)60007-5.

[209] Skog, Isaac and Handel, Peter. "In-Car Positioning and Navigation Technologies—A Survey". In: *IEEE Transactions on Intelligent Transportation Systems* 10.1 (2009), pp. 4–21. ISSN: 1558-0016. DOI: 10.1109/TITS.2008.2011712.

[210] SmartHalo. *SmartHalo 2*. 2019. URL: https://www.youtube.com/watch?v=ZNDrGw7Bxjw (visited on 08/11/2020).

[211] Srinivasan, Vijay, Moghaddam, Saeed, Mukherji, Abhishek, Rachuri, Kiran K., Xu, Chenren, and Tapia, Emmanuel Munguia. "MobileMiner: Mining Your Frequent Patterns on Your Phone". In: *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 2014, pp. 389–400. ISBN: 978-1-4503-2968-2. DOI: 10.1145/2632048.2632052.

[212] Statista Survey (Global Consumer Survey). *Share of Americans who used their cell phone for online map or navigation services in the last four weeks in 2018, by age*. 2018. URL: https://www.statista.com/statistics/231615/people-who-use-their-cell-phone-for-maps-gps-navigation-usa/ (visited on 05/22/2022).

[213] Statistisches Bundesamt. *Share of private households that owned a navigation device in Germany from 2005 to 2021*. 2021. URL: https://www.statista.com/statistics/468928/navigation-devices-household-penetration-rate-germany/ (visited on 05/22/2022).

[214] Steltenpohl, Haska and Bouwer, Anders. "Vibrobelt: tactile navigation support for cyclists". In: *Proceedings of the 2013 international conference on Intelligent user interfaces - IUI '13*. 2013, pp. 417–426. ISBN: 978-1-4503-1965-2. DOI: 10.1145/2449396.2449450.

[215] Strava. *Strava*. 2019. URL: https://www.strava.com (visited on 08/11/2021).

[216] Szymczak, Delphine, Rassmus-Gröhn, Kirsten, Magnusson, Charlotte, and Hedvall, Per-Olof. "A Real-World Study of an Audio-Tactile Tourist Guide". In: *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2012, pp. 335–344. ISBN: 9781450311052. DOI: 10.1145/2371574.2371627.

[217] Tannert, Benjamin, Kirkham, Reuben, and Schöning, Johannes. "Analyzing Accessibility Barriers Using Cost-Benefit Analysis to Design Reliable Navigation Services for Wheelchair Users". In: *Human-Computer Interaction – INTERACT 2019*. 2019, pp. 202–223. ISBN: 978-3-030-29381-9. DOI: 10.1007/978-3-030-29381-9_13.

[218] Tannert, Benjamin and Schöning, Johannes. "Disabled, but at what cost? an examination of wheelchair routing algorithms". In: *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2018, pp. 1–7. ISBN: 978-1-4503-5898-9. DOI: 10.1145/3229434.3229458.

[219] Thompson, Jason, Stevenson, Mark, Wijnands, Jasper S., Nice, Kerry A., Aschwanden, Gideon DPA, Silver, Jeremy, Nieuwenhuijsen, Mark, Rayner, Peter, Schofield, Robyn, Hariharan, Rohit, and Morrison, Christopher N. "A global analysis of urban design types and road transport injury: an image processing study". In: *The Lancet Planetary Health* 4.1 (2020), pp. 32–42. DOI: 10.1016/S2542-5196(19)30263-3.

[220] Thorndyke, Perry W and Hayes-Roth, Barbara. "Differences in spatial knowledge acquired from maps and navigation". In: *Cognitive Psychology* 14.4 (1982), pp. 560–589. ISSN: 0010-0285. DOI: 10.1016/0010-0285(82)90019-6.

[221] Tlauka, Michael and Wilson, Paul N. "The effect of landmarks on route-learning in a computer-simulated environment". In: *Journal of Environmental Psychology* 14.4 (1994), pp. 305–313. ISSN: 0272-4944. DOI: 10.1016/S0272-4944(05)80221-X.

[222] Tseng, Hung-Yu, Liang, Rong-Hao, Chan, Liwei, and Chen, Bing-Yu. "LEaD: Utilizing Light Movement As Peripheral Visual Guidance for Scooter Navigation". In: *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2015, pp. 323–326. ISBN: 978-1-4503-3652-9. DOI: 10.1145/2785830.2785831.

[223] United Nations. *Sustainable Development Goals: 17 Goals to transform our world*. 2015. URL: www.un.org/sustainabledevelopment/sustainable-development-goals/ (visited on 09/07/2021).

[224] United Nations, Department of Economic and Social Affairs, Population Division. *World Urbanization Prospects: The 2014 Revision*. 2015.

[225] Vechev, Velko, Dancu, Alexandru, Perrault, Simon T., Roy, Quentin, Fjeld, Morten, and Zhao, Shengdong. "Movespace: On-Body Athletic Interaction for Running and Cycling". In: *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*. 2018, pp. 1–9. ISBN: 9781450356169. DOI: 10.1145/3206505.3206527.

[226] Waard, Dick de, Schepers, Paul, Ormel, Wieke, and Brookhuis, Karel. "Mobile phone use while cycling: Incidence and effects on behaviour and safety". In: *Ergonomics* 53.1 (2010), pp. 30–42. DOI: 10.1080/00140130903381180.

[227] Waard, Dick de, Westerhuis, Frank, Joling, Danielle, Weiland, Stella, Stadtbäumer, Ronja, and Kaltofen, Leonie. "Visual map and instruction-based bicycle navigation: a comparison of effects on behaviour". In: *Ergonomics* 60.9 (2017), pp. 1283–1296. DOI: 10.1080/00140139.2017.1282628.

[228] *Handbook of Spatial Cognition*. American Psychological Association, 2013. ISBN: 978-1-4338-1204-0.

[229] Waze. *Waze*. 2019. URL: https://www.waze.com/ (visited on 08/11/2021).

[230] Wenig, Dirk, Schöning, Johannes, Hecht, Brent, and Malaka, Rainer. "StripeMaps: Improving Map-based Pedestrian Navigation for Smartwatches". In: *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2015, pp. 52–62. ISBN: 978-1-4503-3652-9. DOI: 10.1145/2785830.2785862.

[231] Widdicks, Kelly, Bates, Oliver, Hazas, Mike, Friday, Adrian, and Beresford, Alastair R. "Demand Around the Clock: Time Use and Data Demand of Mobile Devices in Everyday Life". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017, pp. 5361–5372. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025730.

[232] Willis, Katharine S., Hölscher, Christoph, Wilbertz, Gregor, and Li, Chao. "A comparison of spatial knowledge acquisition with maps and mobile maps". In: *Computers, Environment and Urban Systems* 33.2 (2009), pp. 100–110. ISSN: 01989715. DOI: 10.1016/j.compenvurbsys.2009.01.004.

[233] Woźniak, Paweł W., Dekker, Lex, Kiss, Francisco, Velner, Ella, Kuijt, Andrea, and Donker, Stella F. "Brotate and Tribike: Designing Smartphone Control for Cycling". In: *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. 2020, pp. 1–12. ISBN: 978-1-4503-7516-0. DOI: 10.1145/3379503.3405660.

[234] Yang, Chouchang and Shao, Huai-rong. "WiFi-based indoor positioning". In: *IEEE Communications Magazine* 53.3 (2015), pp. 150–157. ISSN: 1558-1896. DOI: 10.1109/MCOM.2015.7060497.

[235] Yang, Yiyang, Wu, Xueying, Zhou, Peiling, Gou, Zhonghua, and Lu, Yi. "Towards a cycling-friendly city: An updated review of the associations between built environment and cycling behaviors (2007–2017)". In: *Journal of Transport & Health* 14 (2019). ISSN: 2214-1405. DOI: 10.1016/j.jth.2019.100613.

[236] YouGov Italy. *Italy: bicycle use intentions post-lockdown 2020*. 2020. URL: https://www.statista.com/statistics/1123452/future-bicycle-general-use-patterns-after-the-lockdown-in-italy/ (visited on 07/20/2020).

[237] Zhu, Shanjiang and Levinson, David. "Do People Use the Shortest Path? An Empirical Test of Wardrop's First Principle". In: *PLOS ONE* 10.8 (2015), pp. 1–18. DOI: 10.1371/journal.pone.0134322.

[238] Zwinderman, Matthijs, Zavialova, Tanya, Tetteroo, Daniel, and Lehouck, Paul. "Oh Music, Where Art Thou?" In: *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*. 2011, pp. 533–538. ISBN: 978-1-4503-0541-9. DOI: 10.1145/2037373.2037456.

Appendix A: MapRecorder - Interview Guide

Thank you for taking the time for this interview. The data collected here is for a research project of the University of Bremen and will be used exclusively for this purpose. Therefore it is important that this conversation is recorded. Your personal data will be anonymized so that the information you provide here cannot be traced back to you. Is that all right with you?

Personal background:

1. Can you briefly tell me something about your life situation? (age, education, profession)
2. What were or are the most important places in your life? (childhood, favorite places, place of residence ..., spending time)

Map use:

1. What do you use Google Maps for? (To find new places in the city, only for long distances (highways), ...)
2. On which devices do you use Google Maps? (Do the occasions differ/when do you use it on your laptop/cell phone/PC?)
3. What is your experience with Google Maps? (Good, bad, would recommend/delay using it, because ...)
4. What features, apart from navigation, do you use on Google Maps? (Ratings restaurants, current traffic news, public transport information, sightseeing)
5. What setting or feature are you missing on Google Maps? (What could be improved?)
6. What other navigation services have you used in the past?
7. Do you still have old-fashioned paper maps? (Still in use, in the car, in the house, why are they still used or no longer used)
8. I can see from your usage data that you looked around a lot in the map view. So you scrolled around in the map view without entering a specific location or destination. Can you tell me something about that?

9. Possibly more questions about the data

Perception of space:

1. What do you concentrate on when planning a route with Google Maps? (Settings -shortest/fastest route, avoid motorway, ...)

2. Have you ever planned an excursion/a walk with a navigation service? (To what extent have you used the navigation service for this?)

3. Do you have the feeling that by using Google Maps you are getting to know your surroundings better or in a different way? How do you perceive your surroundings while navigating with Google Maps? (New streets discovered or beautiful places / has your space 'enlarged'?)

4. You probably know such situations: You're at a big event with a lot of people on big premises (Christmas market, festival...). Suppose you wanted to meet a friend. How would you arrange the meeting place? How would you have done that ten years ago?

5. Have you ever shared your point of view with friends/family? (If so, in which situations and through which ministry?

6. Do you know Google Street View? Have you used this feature before or do you use it sometimes? (If so, in which situations?)

Linking to other services:

1. When you use navigation, do you trust Google Maps to find the best route for you? (Do you trust the route calculation or do you rather let it run while paying attention to signs/maps?)

2. What would you think if Google Maps cooperated with other services such as Facebook, giving you more personalized routes? (E.g. if your workplace is specified on Facebook and Google Maps creates the optimal route to work on each working day with calculated arrival time depending on the current traffic situation).

3. Can you imagine further links with navigation apps?

Data privacy:

1. Are there situations where you don't want to use Google Maps?
2. What settings have you made on your smartphone regarding location/GPS (Smartphone/Tablet: Always on/is consciously switched on/off...)
3. If the GPS is on, what do you think about Google (and other services) having access to your location?

Views and opinions:

1. How would you describe the importance of navigation apps in your everyday life?
2. There has been a change from map navigation to mobile navigation devices and now navigation apps in the last 10-15 years. How do you see the future of navigation in another ten years? (And does this idea scare you/If so, why?)
3. The future will probably be even more computer-based. There are smart cars that only need an address or an instruction like 'I want to visit my friend Ben' and the car will know where to navigate and may even drive without our help. What do you think?
4. Is there anything else you would like to add? Is there perhaps an aspect that is important to you that has not yet been covered in this conversation?
5. Thank you again for your time.

Appendix B: Street Network Indicators Across Cities

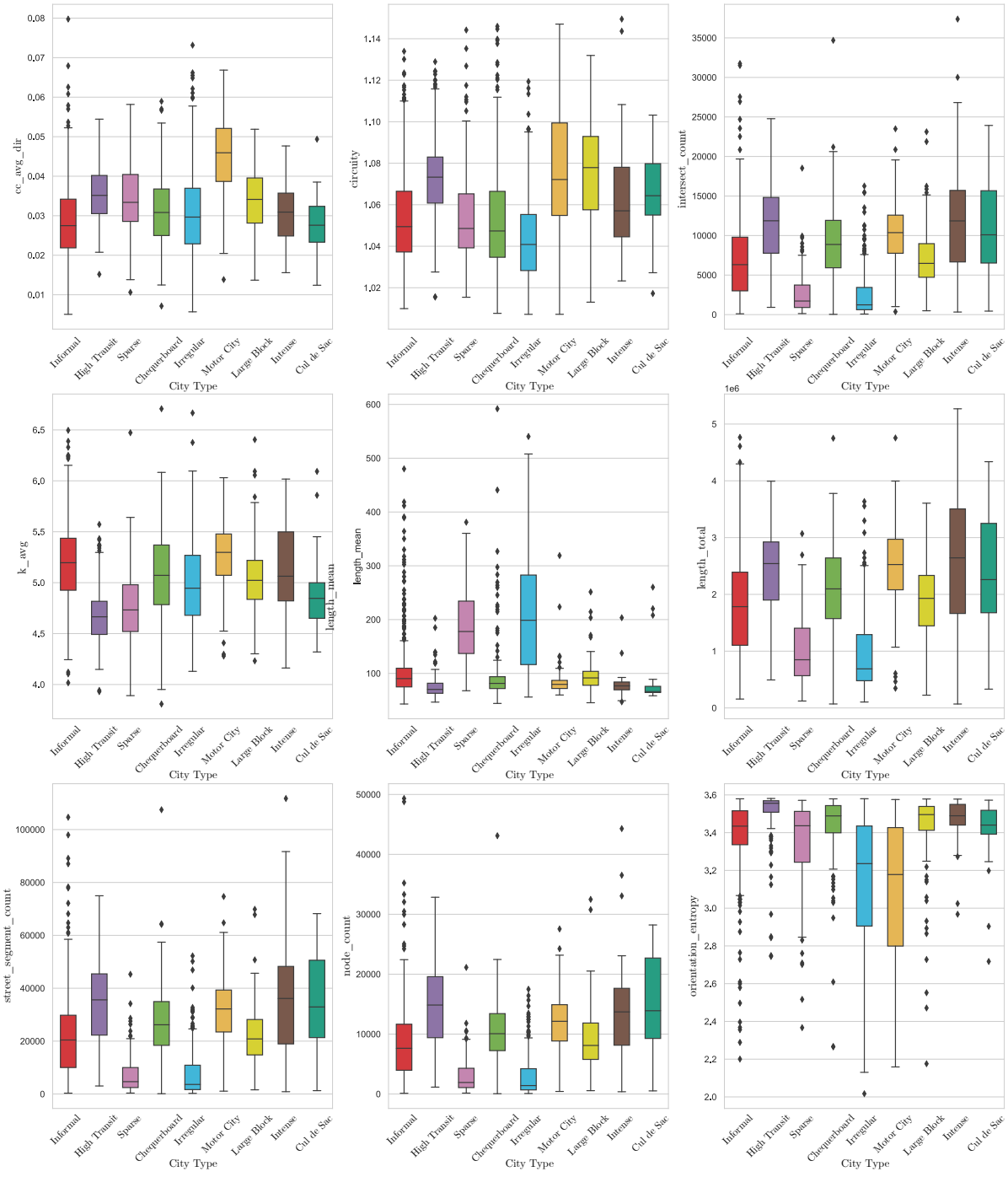


Fig. B.1 Street network indicators across city types (1-9).

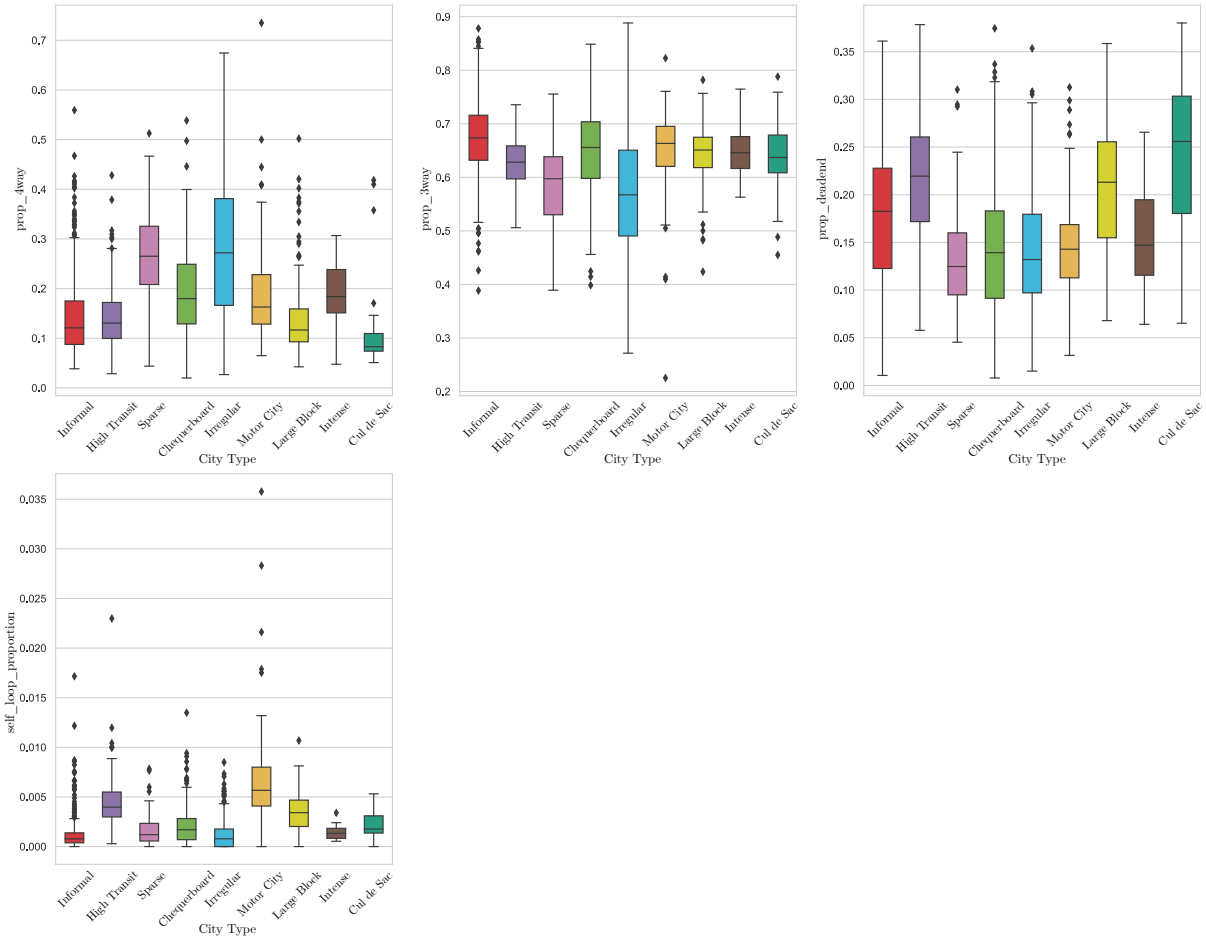


Fig. B.2 Street network indicators across city types (10-13).

Curriculum Vitae

Name: Gian-Luca Savino
ORCID: 0000-0002-1233-234X
E-Mail: gian-luca.savino@unisg.ch
Website: https://gianlucasavino.com/
Citizenship: German, Italian

Education

- 2021-2022: University of St.Gallen – PhD student in Computer Science, Advisor: Prof. Dr. Johannes Schöning
- 2018-2021: University of Bremen – PhD student in Computer Science, Advisor: Prof. Dr. Johannes Schöning
- 2016-2018: University of Bremen – M.Sc. in Computer Science, Thesis title: Analyzing and Understanding Mobile Map Usage Behavior, Advisor: Prof. Dr. Johannes Schöning
- 2012-2016: University of Bremen – B.Sc. in Digital Media, Thesis title: Inkrementelle Grammatik Erweiterung (Incremental Grammar Extension), Advisor: Dr. Robert Porzel

Current and Past Positions

- 2021-2022: University of St.Gallen – Research Assistant at the University of St.Gallen, Switzerland in the Human-Computer Interaction group lead by Prof. Dr. Johannes Schöning
- 2018-2021: University of Bremen – Research Assistant at the University Bremen, Germany in the Human-Computer Interaction group lead by Prof. Dr. Johannes Schöning
- 2017-2018: University of Bremen – Student Assistant at the University Bremen, Germany in the Human-Computer Interaction group lead by Prof. Dr. Johannes Schöning
- 2016-2017: University of Bremen – Student Assistant at the University Bremen, Germany in the Digital Media group lead by Prof. Dr. Rainer Malaka

Supervision of students

I successfully supervised 6 bachelor theses and 2 master theses.

Teaching activities

University of St.Gallen

- TA for the lecture Human-Computer Interaction (2021)
- Lecturer for the lecture Human Computer Interaction: Exercises (2022)

University of Bremen

- TA for the lecture Mediainformatics I (2018-2020)
- TA for the lecture Mediainformatics II (2018-2020)

Active memberships in scientific societies, fellowships in renowned academies

I am an active member of the Association of Computing Machinery (ACM) contributing to conferences associated with ACM and serving as an active reviewer in the ACM community and beyond.

Organization of conferences

I was the student competition chair for the MobileHCI conference in Oldenburg, Germany in 2020. I also served as student volunteer at the following conferences:

- CHI 2022
- ICMI 2019
- MobileHCI 2019
- MobileHCI 2018

Prizes, awards, fellowships

- ACM Honourable Mention Award - MobileHCI 2022 in Vancouver, Canada for my paper Free as a Bird, but at What Cost? The Impact of Street Networks on the User Experience of As-The-Crow-Flies Navigation for Cyclists
- SIGCHI People's Choice Award - Student Competition at MobileHCI 2019 in Taipei, Taiwan with our project entitled: Let You Head Do the Talking

Major scientific achievements

I have contributed to and presented my research at many relevant conferences in the domain of HCI, Mobile HCI and GeoHCI. I have published peer-reviewed full articles as a first author and have contributed to and organized workshops at high-ranking conferences in the field. Furthermore, I have contributed to multiple poster sessions:

1. Gian-Luca Savino, Ankit Kariryaa, and Johannes Schöning. 2022. Free as a Bird, but at What Cost? The Impact of Street Networks on the User Experience of As-The-Crow-Flies Navigation for Cyclists. Proceedings of the ACM on Human-Computer Interaction, (2022)

2. Gian-Luca Savino. Improving Agent-Based Route Predictions for As-The-Crow-Flies Navigation. CHI 2022: Conference on Human Factors in Computing Systems Extended Abstracts, (2022)

3. Gian-Luca Savino, Jessé Moraes Braga, and Johannes Schöning: VeloCity: Using Voice Assistants for Cyclists to Provide Traffic Reports. ACMMM 2021: Proceedings of the 29th ACM International Conference on Multimedia, (2021)

4. Gian-Luca Savino, Tamara von Sawitzky, Andrii Matviienko, Miriam Sturdee, Paweł W. Woźniak, Markus Löchtefeld, Andrew L. Kun, Andreas Riener, and Jonna Häkkilä: Cycling@CHI: Towards a Research Agenda for HCI in the Bike Lane. CHI 2021: Conference on Human Factors in Computing Systems Extended Abstracts, (2021)

5. Gian-Luca Savino, Laura Meyer, Eve Emily Sophie Schade, Thora Tenbrink, and Johannes Schöning: Point Me In the Right Direction: Understanding User Behaviour with As-The-Crow-Flies Navigation. MobileHCI 2020: Proceedings of the International Conference on Human-Computer Interaction with Mobile Devices and Service, (2020)

6. Gian-Luca Savino: Virtual Smartphone: High Fidelity Interaction with Proxy Objects in Virtual Reality. EPO4VR - 1st Workshop on Everyday Proxy Objects for Virtual Reality at CHI, (2020)

7. Gian-Luca Savino, Miriam Sturdee, Simon Rundé, Christine Lohmeier, Brent Hecht, Catia Prandi, Nuno Jardim Nunes, and Johannes Schöning: MapRecorder: analysing real-world usage of mobile map applications. Behaviour & Information Technology, (2020)

8. Gian-Luca Savino, Ankit Kariryaa, Matthis Laudan, and Matthis Würdemann: Let Your Head Do the Talking. MobileHCI 2019 Student Competition - Human Augmentation. MobileHCI 2019, (2019)

9. Gian-Luca Savino, Niklas Emanuel, Steven Kowalzik, Felix A. Kroll, Marvin C. Lange, Matthis Laudan, Rieke Leder, Zhanhua Liang, Dayana Markhabayeva, Martin Schmeißer, Nicolai Schütz, Carolin Stellmacher, Zihe Xu, Kerstin Bub, Thorsten Kluss, Jaime Maldonado, Ernst Kruijff, and Johannes Schöning: Comparing Pedestrian Navigation Methods in Virtual Reality and Real Life. ICMI 2019: Proceedings of the International Conference on Multimodal Interaction 2019, (2019)

10. Gian-Luca Savino, Miriam Sturdee, Simon Runde, Christine Lohmeier, Brent Hecht, and Johannes Schöning: MapRecorder: Analyzing Real World Usage of Mobile Map Applications. Spatial Cognition 2018: Adjunct Proceedings of the International Conference on Spatial Cognition, Honorable Mention Poster Award, and Abstract presented at IC2S2 2018: Adjunct Proceedings of the International Conference on Computational Social Science, (2018)