JYVÄSKYLÄ STUDIES IN COMPUTING

246

Liisa Kuparinen

Lost or Not? Designing and Evaluating User Interfaces of Mobile Map Services

The Viewpoint of Supporting Users' Location Awareness

JYVÄSKYLÄN YLIOPISTO

JYVÄSKYLÄ STUDIES IN COMPUTING 246

Liisa Kuparinen

Lost or Not? Designing and Evaluating User Interfaces of Mobile Map Services

The Viewpoint of Supporting Users' Location Awareness

Esitetään Jyväskylän yliopiston informaatioteknologian tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston Agora-rakennuksen Lea Pulkkisen salissa
marraskuun 21. päivänä 2016 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Information Technology of the University of Jyväskylä,
in building Agora, Lea Pulkkinen hall, on November 21, 2016 at 12 o'clock noon.

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2016

Lost or Not?
Designing and Evaluating User Interfaces of Mobile Map Services

The Viewpoint of Supporting Users' Location Awareness

JYVÄSKYLÄ STUDIES IN COMPUTING 246

Liisa Kuparinen

Lost or Not? Designing and Evaluating User Interfaces of Mobile Map Services

The Viewpoint of Supporting Users' Location Awareness

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2016

Editors
Marja-Leena Rantalainen
Department of Mathematical Information Technology, University of Jyväskylä
Pekka Olsbo, Ville Korkiakangas
Publishing Unit, University Library of Jyväskylä

URN:ISBN:978-951-39-6830-4
ISBN 978-951-39-6830-4 (PDF)

ISBN 978-951-39-6829-8 (nid.)
ISSN 1456-5390

Jyväskylä University Printing House, Jyväskylä 2016

ABSTRACT

Kuparinen, Liisa
Lost or Not? Designing and Evaluating User Interfaces of Mobile Map Services: The Viewpoint of Supporting Users’ Location Awareness
Jyväskylä: University of Jyväskylä, 2016, 96 p. (+ included articles)
(Jyväskylä Studies in Computing
ISSN 1456-5390; 246)
ISBN 978-951-39-6829-8 (nid.)
ISBN 978-951-39-6830-4 (PDF)

The motivation for this thesis arose from the problem of people getting lost, both with and without mobile maps. I will answer a primary research question: 1) How can we support users’ location awareness with mobile map applications? As an ad-dition to this, I have the following sub-questions: a) Why do people get lost even when using a mobile map application? b) What are the best practices to support navigation? c) How can we research what the important objects in the natural environment are that should be emphasized in mobile maps? d) How do we prevent the user from focusing on the map service at the expense of perceiving the location in the real environment? e) What would a good mobile map application be like concerning the usability and user experience?

This thesis has four parts. In the introduction, I discuss the topic based on previous research. Second, I present the article where I studied one method of user-centric design, the eye-tracking method, and discussed its suitability for mobile map research in the wild. Third, I present articles where I compared augmented reality towards the real world in the sense of perceiving distances. Fourth, I present articles where I formulated and validated usability heuristics for evaluating mobile map applications.

As result, I state that users’ location awareness may be supported by many technical and design-based solutions as well as taking user-centred design approach as part of the development process. One good method to be used in this approach is eye-tracking, which is valuable for studying users’ areas of interest while navigating and self-locating. Augmented reality is one possibility to keep users paying attention to the real world and through that, to stay aware of their location. Still, as it seems to be more difficult for the users to perceive distances when using augmented reality versus real world, special focus needs to be put on the design of presenting location information in augmented reality based maps. Other solutions to support user’s location awareness are, e.g., using multimodal interaction techniques and making use of user-generated content to make the user experience of application more personal and locations memorable. There are also numerous design recommendations presented in the previous research and in the usability heuristics I introduce in this thesis, and following these is needed to support users’ location awareness. This thesis is supposed to be usable in the development of mobile map services to better support users’ needs.

Keywords: mobile maps, map service design, location awareness, usability, user experience, spatial perception, usability heuristics, augmented reality

Author Liisa Kuparinen
Department of Computer Science and Information Systems
University of Jyväskylä
Finland
liisa.kuparinen@iki.fi

Supervisors University Lecturer Antti Pirhonen, PhD
Department of Teacher Education
University of Jyväskylä
Finland

Professor Mikko Siponen, PhD
Department of Computer Science and Information Systems
University of Jyväskylä
Finland

Reviewers Assistant Professor Corné van Elzakker, PhD
Department of Geo-Information Processing
University of Twente
Netherlands

Teaching Fellow Artemis Skarlatidou, PhD
Dept. of Civil, Environmental and Geomatic Engineering
University College London
United Kingdom

Opponent Professor Kaisa Väänänen, PhD
Department of Pervasive Computing
Tampere University of Technology
Finland

PREFACE

It has been interesting to travel on this PhD journey. I have had the privilege to get to know a lot of insightful people from different research areas and cultures, to travel to many interesting locations as well as to learn from, undertake, and present research. Above all, I have had the privilege to dive into the inspiring world of mobile maps and the use, user and user experience issues related to them.

Still, there have been times when I have been lost – not just geographically – but, also with this thesis. It is not easy to finish a PhD thesis. Sometimes the goals are too high and the future after finishing it is too unclear. The uncertainty and discontinuities in funding do not help either. Another big issue is the culture in the academic world; it is not the most encouraging one. Especially in the reviewing processes of scientific work, the focus is typically in the deficiencies of work and the positive aspects get ignored. Pointing out the deficiencies is needed to correct them, but the research world has a lot to learn about criticizing constructively. Besides presenting some statements about my research topic in the other parts of this thesis, in the preface I state that our academic world – as well as the whole world – would be better and do better if we would focus more on giving positive feedback to others. We should admit and understand that what keeps people going and makes them do better, is the positive feedback, trusting them and appreciation towards their work. How about we all try to focus on giving more positive feedback to others, and to ourselves too? That is not easy either, and this I can ground on citing my own experiences.

But I did finalize this thesis, as I desperately wanted, and now it is time for some acknowledgements. I am grateful for the many sources that have been supporting my research work financially. My longest funding period came from Academy of Finland -funded national doctoral school Doctoral Program in User-Centred Information Technology (UCIT). Thank you also to Department of Computer Science and Information Systems, University of Jyväskylä's Vice-Rector's mobility grant, Nokia Foundation, Emil Aaltonen Foundation and Varma. Thank you for believing in me.

Thank you to my supervisors: in the very beginning: Pertti Saariluoma for the connections to start doing usability and user experience studies in industry and Antti Oulasvirta for setting the goals high; for a short period in the middle: Hannakaisa Isomäki for the practical approach; in the finalizing phase: Mikko Siponen for making things concrete enough to achieve the goal; and during almost the whole journey: Antti Pirhonen for challenging me to think the fundamental basis of science. Naturally, thanks need to go to the reviewers, editors and opponent of this thesis.

It has been good to have a research community around when I have been doing this research work. It was inspiring to meet with other doctoral students of UCIT, as there was not a community for my research area at the University of Jyväskylä. Also, the discussions with colleagues from my home department and faculty and from other professional areas I have had a chance to be part of

(SIGCHI Finland, HCI and cartographic communities, among others) along the way have been needed. Thank you.

Thank you also to other communities and activities outside science in which I have been part of; the dog-centred groups, the Greens, the “körts” and many others. Thank you friends in and outside these communities for balancing my life.

Thank you to my family: sisters, brothers, nieces, nephews and other relatives. A chance to play with kids or have a chat with the older ones has balanced my sometimes too research-centred and target-oriented life. Thank you also to my mother and father. Riitta, one from the next generation might also soon have a PhD.

Actually, I should have started with this chapter, as this is anyway the most important. Thank you Miia. When this PhD thesis has been too much for me to handle, Miia has reminded me that this is not the world and not the meaning of life. I do not know where I would be without Miia’s ability to see and make me also understand what the actual, broader spectrum of life is about. I am sorry too, for too long there has been this PhD’s finalization phase -based stress and pressure around our home.

Some final words, or cuddles, need to go to my four-pawed kids: the already passed away one, Joona, and the two still barking ones, Turca and Carlos. Thanks. How about we go for a long walk in forest – without any mobile devices – after this? It’s even OK to get lost. I will trust that you will eventually guide us back home, to our HauHaus – or if not there, to some great adventure.

Jyväskylä 6.11.2016
Liisa Kuparinen

FIGURES AND TABLES

CONTENTS

ORIGINAL ARTICLES

LIST OF INCLUDED ARTICLES

I Kuparinen, L. & Irvankoski, K. 2011. Experiences from the Use of an Eye-Tracking System in the Wild. Wi: Journal of Mobile Media, vol 6. Published also in B. Poppinga (Ed.), Observing the mobile user experience (OMUE), proceedings of the 1st international workshop, held in conjunction with NordiCHI 2010.

II Kuparinen, L., Swan, J.E. II, Rapson, S. & Sandor, C. 2013. Depth Perception in Tablet-Based Augmented Reality at Medium- and Far-Field Distances. Proceedings of the ACM Symposium on Applied Perception (ACM SAP 2013).

III Swan, J.E. II, Kuparinen, L., Rapson, S. & Sandor, C. 2016. Visually Perceived Distance Judgments: Tablet-Based Augmented Reality versus the Real World. Provisionally accepted (pending minor revisions) for publication: International Journal of Human-Computer Interaction (IJHCI) 17.10.2016.

IV Kuparinen, L., Silvennoinen, J. & Isomäki, H. 2013. Introducing Usability Heuristics for Mobile Map Applications. Proceedings of the 26th International Cartographic Conference (ICC 2013).

V Kuparinen, L. 2016 Validation and Extension of the Usability Heuristics for Mobile Map Applications. Proceedings of the 6th International Conference on Cartography and GIS (ICC&GIS 2016).

1 INTRODUCTION

This doctoral thesis discusses the topic of designing and evaluating user interfaces (UIs) for mobile map applications, with special attention paid to supporting users in locating and orienting themselves. By *mobile map applications*, I refer to maps that are used by a mobile device, typically a mobile phone or tablet.

The thesis has four parts considering the subject matter. First, in the introduction part of the thesis, the topic is oriented on the basis of previous research. The following three parts, described next, are presented in the included articles and briefly in the chapter summarising the articles.

The second part is about examining a research method that is quite novel in the context of map research, eye tracking. This part, concentrating on using eye-tracking as a method to use in mobile map application development, is located in the first included article of the thesis.

The third part of the thesis is present in articles two and three. When it concerns the human spatial and depth perception in augmented reality, from a more practically oriented point of view, it offers indications for designing and locating points of interest in a possible future field: mobile maps with augmented reality.

The fourth part of the thesis is articles four and five, introducing, validating, and further developing usability heuristics for mobile map applications. This fourth part is probably the part that is most usable as-is in the concrete hands-on development of mobile map applications, as it offers the most easily applicable and widest recommendations for the development and evaluation of mobile map applications.

Next, I will proceed with the Introduction, starting with presenting the overall motivation for the research, introducing the research questions, going through the related disciplines, presenting the definitions for the main terminology, and then describing the research field.

After that, in Chapter 2, I will discuss the solutions supporting users' location awareness with mobile maps. In Chapter 3, I will present the research methodology, and in Chapter 4, I will introduce the included articles and the overall results. Chapter 5 is for discussion.

1.1 Research Problem and Motivation for the Research

When I have discussed my research topic with other people, very often I have heard stories about how a mobile map helped with finding a way somewhere. But then again, I have also heard stories where the map application had taken the person to a wrong destination or on unreasonable routes, or stories about the device battery running empty in a critical moment and the person ending up being lost, as he or she had not paid attention to his or her physical surroundings because trusting the map application to take care of navigation.

As the use cases of mobile map applications are typically critical concerning things like safety and timetables, it is also important that the usability of mobile map applications be at a good level (Kuparinen, 2016). In the field of mobile map applications, there are problems in supporting the interactions between users and map applications (Looije, te Brake, & Neerincx, 2007). Nivala and colleagues (Nivala, Brewster, & Sarjakoski, 2008; Nivala, Sarjakoski, Jakobsson, & Kaasinen, 2003) examined the usability of different kinds of digital maps before and after they became commonly used in mobile phones. They found the usability problems to be, for example, related to search operations, user interfaces, map visualization (e.g., size and placement of map symbols in mobile device use), and map tools.

When designing mobile map services, a special focus should be on the clarity of the user interface (UI), as problems understanding the map UI may have serious consequences; e.g., getting lost.

One main motivation for my research topic is the problem of people getting lost (e.g., (Carlson, Holscher, Shipley, & Dalton, 2010). It is common to get lost in unfamiliar environments, even with a map along, irrespective of it being physical paper map or digital map used by a mobile device and including automatic positioning. The problem of getting lost and losing location awareness motivated the overall research. Modern mobile map services decrease the problem of getting lost even while they are able to define locations automatically through positioning systems. Although the mobile device may technically define the location, the user often has problems understanding the location and the direction he or she is supposed to go. Besides causing confusion and disorientation, this may lead to anxiety (Montello, 2010).

Darken and Sibert (1993) have researched navigation in virtual environments and state that the major problem there is the user maintaining knowledge of his or her location and orientation while he or she moves through the space. Carlson et al. (2010) discussed the problem of getting lost indoors from the perspective of cognitive science and especially cognitive maps. They found three factors predicting navigation in buildings: 1) correspondence between the building and the cognitive map, 2) compatibility between strategies/individual differences and building, and 3) the completeness of the cognitive map as a function of strategies/individual differences.

Willis and colleagues (Willis, Hölscher, & Wilbertz, 2009; Willis, Hölscher, Wilbertz, & Li, 2009) studied the performance between paper map users and mobile map users and found out that, in their experimental setting, mobile map users performed even worse in distance estimation tasks than did paper map users. They assumed that this happened because of the insufficient format and presentation of the spatial information on a mobile map. They state that mobile maps require attention, as the information or view on the mobile map is automatically changing and updating and because the user can interact with the information. This challenges the user's spatial abilities, memory, and performance in their map-related tasks (Willis, Hölscher, & Wilbertz, 2009).

I state that getting lost in an unfamiliar environment usually happens for three reasons (even with a paper map): 1) poor interaction design, i.e., design solutions that result in poor user experience (UX); 2) insufficient addressing of human perception and UX; and 3) the user ignoring the environment.

The Cause 1: Design Solutions

It is not always obvious to the user how the map on the screen and the user's physical environment correlate with each other. That is often because of usability-related problems, like a mixed design of the map service's UI (e.g., the use of weird symbols or missing data) or poor (fuzzy, inaccurate) maps.

The Cause 2: Human Perception and User Experience

Sometimes the user interface or map is deficient, but sometimes there are other reasons the user may interpret the map differently than intended. People perceive their environment in different ways concerning, e.g., the orienteering experience, knowledge or cultural background and characteristics, the current time schedule, the current task or target, or possible distractions. Does the mobile map service take these into account?

The Cause 3: Ignoring the Environment

Another possibility of getting lost is that the user relies too much on the map service's guidance and fails to pay attention to the environment and the route. This phenomenon is called *inattentional blindness* (Mack & Rock, 1998). Ignoring the environment is an issue where the automatic positioning system turns against itself. It is important that the user does not forget to keep on eye on the physical environment while using a virtual map service.

Technology-driven development is typical in ICT development, and so is the case with the development of mobile map applications (Nivala, Sarjakoski, & Sarjakoski, 2007). Neither does the result differ from other fields: not paying enough attention to the UX and usability leads to problems in use. Veryzer and Borja de Mozota (2005) discussed the positive consequences of following user-oriented design from the corporate view. They stated the benefits to be, for example, a heightened sense of the range of possibilities for a product, better understanding of the customer needs and the realities of the market, cost savings due the non-existent need for redesign and heightened design for manufacturability, and better achievement of the company's strategic goals.

Nivala et al. (2007) researched the benefits of including usability aspects in the map application development process and presented five benefits: 1) for map applications, user requirements are especially demanding; 2) usage situations are especially demanding (e.g., driving a car 100 km/h); 3) user tasks are unfamiliar to the designers; 4) usage situations are unfamiliar to the designers (e.g., use in special professions); and 5) applications are targeted for a large number of users.

To sum up, the main motivation for this thesis comes from the fact that there are problems in the usability and UX of mobile map applications, especially when it comes to supporting the user's location awareness. Besides that, I will next go briefly through the motivation for the sub-studies of this research.

Studying the eye-tracking method, where the person's eye movements are tracked with technical equipment, was motivated by the problem of not having a comprehensive method to collect information of mobile map users' problem-solving strategies and information about use of different landmarks in the wild and not having, at least not many, published results of using eye-tracking systems in forests for supporting the development of map applications for forest and other unbuilt areas.

Augmented reality combined with mobile maps has the potential to support users' location awareness. Although an increasing amount of experiments with users have been conducted in the AR field (Dünser, Grasset, & Billinghurst, 2008; Swan & Gabbard, 2005) , UX research is still noted to be in its infancy when considering the recent AR applications and AR-related technologies (Olsson & Salo, 2012). The current AR applications have problems concerning navigation, finding points of interest (POIs), and other user perception-related tasks (Olsson & Salo, 2012). This has also been the case with mobile augmented reality navigation applications (Rehrl, Häusler, Leitinger, & Bell, 2014). Olsson and Salo (2012) predict that UX will become a central goal and design strategy in AR research. This motivated my need to study one piece of augmented reality for supporting the user's depth perception and distance estimations better with use of AR (Kuparinen, Swan, Rapson, & Sandor, 2013; Swan, Kuparinen, Sandor, & Rapson, 2016).

The development of usability heuristics for mobile map applications (Kuparinen, 2016; Kuparinen, Silvennoinen, & Isomäki, 2013) was motivated by the lack of previous overall design guidelines and usability heuristics for mobile map applications. Nivala (2007) presented design guidelines for web mapping sites—though these were not for mobile use—and the technology has taken huge steps forward since then.

Although, for example, many case studies of user-centric design of mobile map applications have been presented, there was still a gap in supporting the user-centric design of mobile map applications. As a whole, this thesis aims to fill that gap by presenting usability heuristics for mobile map applications.

1.2 Research Questions

I approach the problem of users' weakened location awareness from two perspectives: the one concerning the design of UIs and the reasons for getting lost.

The goal of my doctoral thesis is to find answers to my main research question: "**How can we support users' location awareness with mobile map applications?**" or with a longer version: "How can we implement a map service on mobile device so that the service will support the user as well as possibly perceive locations and directions?" As an addition to this, I have the following sub-questions:

A. Why do people get lost even when having a mobile map application along?

   This sub-question will be answered in the literature review of the thesis.

B. What are the best practices to support navigation?

   This sub-question will also be answered in the literature review.

C. How can we research what the important objects in the natural environment are that should be emphasized in mobile maps?

   This sub-question will be answered in Article 1, on eye-tracking in the wild.

D. How can we prevent the user from focusing on the map service at the expense of perceiving their location in the real environment?

   This sub-question will be answered in Chapter 2 and in Articles 2 and 3, on augmented reality.

E. What would a good mobile map application be like concerning the usability and UX?

   This sub-question will be answered in the Introduction, Chapter 2, and Articles 4 and 5, on usability heuristics.

1.3 Disciplines

My personal background is in **information systems science** and user-friendly information technology, which areas are also in the background of my thesis.

Besides these, the thesis is settled in the field of **Human-Technology Interaction (HTI)**, or more precisely, Mobile Human–Computer Interaction (MobileHCI/MobileHTI). Typical topics in that area are related to UX, usability and UI design, which all need to be approached from the viewpoint of **user psychology**. I partly approach the topic from the theory of cognitive science, especially from spatial perception, and merge the understanding gotten from there to the UI design. Although the research basis of spatial perception is strong, there are deficiencies in applying the knowledge to the UI design of navigational applications.

Yet another related field is **cartography**. Cybercartography is a subcategory of cartography and is seen to mean the current technology-based solutions to create multimedia and interactive maps (Zentai, 2016). Map design, especially the visualization of, for example, map objects and overall graphical user interfaces (GUI), is also related to my thesis topic.

As information systems science is seen as an **economic** science, there is a point of stating something also of pure economic issues related to mobile map services. Probably the majority of mobile map applications is developed at least partly for making financial profit. It has been noted that especially the experienced good usability (in terms of, for example, an efficient, error-free, satisfactory product) of the product typically leads the product to be chosen for permanent use (Kuparinen, 2008). This leads to a conclusion that it should be in the manufacturers' interests to design products with good usability. The impact of usability in the choosing process of products is also a reason why companies developing products should pay high attention to the overall usability and UX. The better the app, the more users and the more profit.

Mobile phones have been widely proposed as the basis of marketing applications (Tiru, Kuusik, Lamp, & Ahas, 2010), and tourism is often the reasoning for mobile map application development from the perspective of economics. Based on Genovese, Cotteret, Roche, Caron and Feick's (2009) work, at least the use of geographic information is lacking research on business cases, cost benefit analysis (CBA), and return on investment (ROI) studies. A similar argument was expressed by Raper, Gartner, Krimi, and Rizos (2007) concerning location-based services; there are very few studies on such business models.

Being present in mobile map services may be a competitive advantage for a company. For example, adding a company or office location on a public mobile map service that is used for navigation may raise the visibility of the company. Personally, I noticed this after building my home in a new housing area for which there were no up-to-date maps. After using the map provider's tool to suggest they add the new roads on their map data, and after adding my ICT company's home office as a POI on the map, visitors using the map service for navigating were always shown my company on an otherwise still empty map area.

The combination of disciplines of this multidisciplinary research is presented in FIGURE 1.

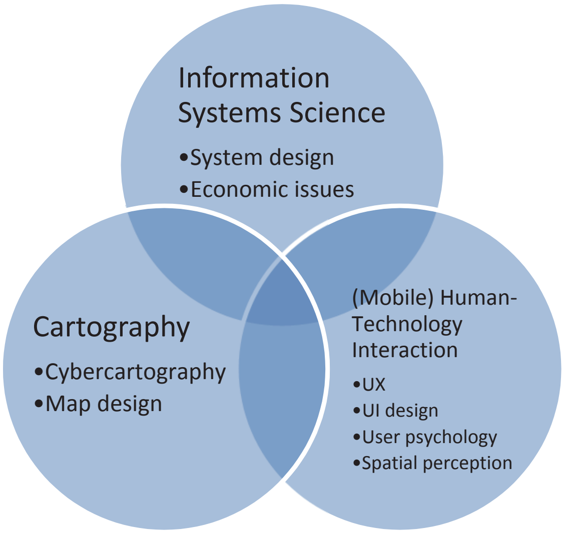


FIGURE 1 The disciplines of the thesis

1.4 Terminology

At first, I will present definitions for the terminology in the title of my thesis. After that, I will go through the other substantive terminology that is used in this thesis.

By **mobile maps**, I do not mean paper printed maps that may be taken with a person. Instead, I mean maps that are used by a mobile device, typically by a mobile phone.

By **mobile services**, I do not mean, for example, public services such as libraries or ambulances or dental clinics that may be brought to the citizen on wheels—although, in a literal sense, they are also mobile services. Besides using the term *mobile map services*, the term *mobile map applications* could also be used. By choosing to use services instead of applications, I want to refer to that the user is someone to be served, the user is important, and often there is a service provider who should take care of the servicing. At the same time, I would like to use the term *application* to refer to the scientific field and the background of mine: information systems science, developing applications. From these two perspectives, I still chose to use the one emphasizing the user.

By **User Interface (UI)**, I mean the visible and touchable area of a mobile device, typically the screen, which a person uses to control and use the mobile map service.

Users' location awareness is the last special term in a need of a definition in the title of my thesis. Location awareness has initially been understood to describe the technical device's awareness of a current location. Today, and in this context, I refer to location awareness meaning the map user's understanding of his or her location and direction. Instead of using *location awareness*, I might use also *spatial perception*, but I chose *location awareness* from the reader-centred perspective; I believe *location awareness* is an understandable term for readers who may or may not be from disciplines in which the term *spatial perception* is obvious.

1.4.1 Related to Mobile Maps and Cartography

Let us then go forward to introduce the other related terminology.

Cartography is "the art and science of expressing graphically, usually through maps, the natural and social features of the earth" (ESRI, 2016). MacEachren (1995) fulfilled the definition by explaining cartography to be about representation and stating that the research of cartography should not be targeted only to maps, but also to the research of maps as spatial representation. MacEachren also emphasized cartography's role in communication. The type of cartography that combines modern technology to create interactive maps is called *cybercartography* (Zentai, 2016). *Neocartography* is another related term referring "to mapping on the web commonly by nonprofessional cartographers using open-source software and data" (Zentai, 2016, p. 22).

Location-Based Services (LBSs) is an oft-used term in the field, and which term he or she uses seems to depend partly on the author's discipline. There seems to be no common definition for LBSs; the reason for this has been thought to be in the different communities discussing the topic (Küpper, 2005). I see LBSs as types of services that automatically use location data but not necessarily maps to represent it. When a LBS uses maps, it may be called a *map-based LBS* (Raper et al., 2007), but if the map is in an essential role, then I would speak about mobile map services instead of LBSs.

Küpper (2005) stated that LBSs are always context-aware services (which is a nearby term to location awareness), meaning they are always interacting with a type of context: the location. **Context awareness** was first introduced by Schilit, Adams, and Want (1994, p. 85). They stated that context-aware software "adapts according to the location of use, the collection of nearby people, hosts, and accessible devices". Dey (2001, p. 5) had an updated definition for context-aware applications: "A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task". To make the difference to the classic definition of a device's location awareness, it may be stated that context awareness is seen as a wider issue, considering factors other than just location.

Augmented Reality (AR) is not initially related to mobile maps or cartography, but as the context of it is mobile maps in this thesis, let us discuss it in this point. AR is defined as a system that has the following three characteristics: 1) it combines real and virtual, 2) it is interactive in real time, and 3) it is registered in three dimensions (Azuma, 1997). To concretize this, I will give some examples of the traditional AR systems. One important use context of AR is medical. Besides having virtual reality (VR) simulators for surgical training

(Silvennoinen & Kuparinen, 2009), some AR systems, typically used as head-mounted displays (HMDs), are used for visualizing medical data and the patient within the same physical space (Sielhorst, Feuerstein, & Navab, 2008). AR has also been used in the design and manufacturing industry to simulate, assist, and improve manufacturing processes (Nee, Ong, Chryssolouris, & Mourtzis, 2012). A third use example is from the military field, where AR has been used for presenting military information on top of the real-world view, especially in military training (Livingston et al., 2011). In the field of mobile map applications, AR may be used for showing map objects, POIs, or navigation instructions on top of the real-world view seen through the mobile device.

The terminology related to tasks concerning map use is still being used in a mixed manner, depending, for example, on the researcher's background.

Darken and Sibert (1993, p. 157) defined **navigation** as "the process by which people control their movement using environmental cues and artificial aids such as maps so that they can achieve their goals without getting lost". From the field of spatial cognition, the equivalency for navigation is route following, used by, for example, Mallot and Basten (2009). **Wayfinding** is also commonly used as a synonym for *navigation*. Wayfinding was defined by Roger, Bonnardel, and Le Bigot (2007, p. 238) to be "a movement which aims at reaching a precise destination". Roger et al. (2007) called wayfinding a task that relies on many cognitive abilities, which include spatial and working memory abilities.

Landmarks are a fundamental element of a place (Lynch, 1960), and they have been seen as the most critical wayfinding cue (Elvins, 1997). Elvins defined landmarks as specific memorable objects in an environment, and stated that, to be a landmark, an object must be distinctive from other objects in the environment.

POI is close to *landmarks*, but it is also more than landmarks and sometimes not about landmarks at all. I would say that the user's role in typing an object as a POI is categorical. Whereas a landmark can be a big church tower that is seen from far away, that same church tower may not be in the interest of the user and is thus not a POI for the user. In the previous literature, POI is seen as a "location or point that has a particular priority during the navigation and orientation tasks" (Trapp, Schneider, Lehmann, Holz, & Döllner, 2011, p. 80). In 2D maps, a typical visualization of POIs is a small icon overlaying a map, but in 3D, there are various, not settled solutions for POI visualizations (Trapp et al., 2011).

1.4.2 Related to the UX

Usability is at the core of my thesis topic. There are two typically cited definitions for usability. Nielsen (1993) defined usability as having five attributes: 1) learnability (the system is easy to learn so that the user can rapidly start getting work done), 2) efficiency (the system is efficient to use, so that a high level of productivity is possible), 3) memorability (the system is easy to remember, so that a casual user is able to remember how to use the system after a period of not using it), 4) errors (the system should have a low error rate, so that users make few errors and it is easy to recover from them), and 5) satisfaction (the system is pleasant to use, so that users like it). The second highly used definition is from the ISO standardization organization (1998): "The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use".

UX, which has no widely accepted definition (Kuniavsky, 2010), is another core concept. Roto and colleagues produced a review of UX in their white paper (Roto, Law, Vermeeren, & Hoonhout, 2011). They describe the definitions of UX as varying depending on the perspective: from psychological to business and from quality-centric to value-centric. Roto et al. refer to a total of 27 different UX definitions or steps towards them, though many others still exist. I find one of the sufficient definitions to be the one from Kuniavsky (2010, p. 14): "The user experience is the totality of end-users' perceptions as they interact with a product or service. These perceptions include effectiveness (how good is the result?), efficiency (how fast or cheap is it?), emotional satisfaction (how good does it feel?), and the quality of the relationship with the entity that created the product or service (what expectations does it create for subsequent interactions?)".

Roto et al. (2011) simplified three factors affecting UX: 1) context, referring to social, physical task, and technical and information context; 2) user, including a person's motivation to use the product, their mood, and current mental and physical resources and expectations; and 3) system, including, for example, functionality, aesthetics, designed interactive behaviour, responsiveness, and the brand or manufacturer image. Earlier, Morville (2004, 2005) took a wider view of the factors of UX, stating the qualities of UX be useful, usable, desirable, findable, accessible, credible, and valuable.

A close term to UX is **product experience** (PX) (Schifferstein & Hekkert, 2008), where a sight to products or systems is taken from more commercial, but still very user-centred—or to put it better, consumer-centred—side.

User-centred design (UCD) is also at the core of this thesis topic. As the focus is on developing mobile map applications that better serve the user, the design paradigm has to be UCD. UCD is an umbrella with a wide variety of design and research methods under it, e.g., user experiments, UX and usability studies. Nielsen is the big name when it comes to UCD, as he published the highly used and cited book of UCD methods (Nielsen, 1993). There is also an ISO standard for UCD, or to "human-centred design for interactive systems" as the literal definition goes. ISO definition states human-centred design to be an "approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques" (ISO, 2010).

1.4.3 Related to Spatial Perception

In the multidisciplinary field of cognitive science, which my thesis partly belongs to, the conception of perception is understood in different ways depending on the context and the backgrounds of people. That is why it is not always unambiguous to see what the term stands out for.

Golledge and Stimson (1997) noted that the perceptions of individuals vary as a function of differences in the content of the presented information and the differences in ability of individuals to pick up the information messages. That is why user tests with various people are needed to test how users perceive the use of mobile maps and the connection of maps and the environment.

Roughly, the term **spatial cognition** means knowledge of space. The field of spatial cognition is not a simple one. It includes multiple distinctions like spatial perception, spatial orientation, cognitive representation, spatial representation, cognitive mapping, and cognitive or mental maps. Hart and Moore (1973) combined a summary of different views towards these terms, and although it is from the 1970s, it seems to be still quite an extensive and widely cited ground for researchers, and it has also been taken into new editions in recent years. Hart and Moore (1973) drew a conclusion based on those different sights of the field of spatial cognition; they summarized that spatial cognition is the knowledge and cognitive representation of the structure, entities, and relations of space, or in other words, the internalized reflection and reconstruction of space in thought.

Marshall and Fink (2001) listed three relevant questions when moving in a 3D environment that are answered by the spatial cognition of a human: 1) Where am I, and how are my body parts currently oriented? 2) Where are important environmental objects in relation to me, and where are these objects in relation to each other? 3) What do I need to do about these objects, and how should I go about doing what should be done?

Golledge and Stimson (1997) stated that, together, **perception** and cognition are one of the key psychological variables intervening between environment and human behaviour. The others are cognitive and affective attitudes, values, emotions or other affective responses, and learning. Werner (1948) and his many followers have presented perception as a subsystem of cognition. In that view, knowledge about the world may be constructed by many means, of which perceptual judgments is only one, and as development proceeds, perception is subordinated to higher mental processes.

The term *perception* has been used in many different contexts. Among geographers, it has been used differently than in psychology. Golledge and Stimson (1997, p. 189) noted that geographers have tended to use the term in the sense of how things, like hazards, are remembered by people; architects to describe the mutuality of interests among groups of actors in the design process; and psychologists have treated perception as a subset of function of cognition. Golledge and Stimson continued to explain probably the most common understanding of perception so that a person receives signals of the environment through his or her senses—by sight, hearing, smell, taste, and touch. Because the real world is complex and sends millions of information signals continuously, we can only be aware of a small amount of them.

As there are different senses, there are different types of perception, like haptic perception, olfactory perception, auditory perception, and visual perception.

Spatial perception is the type of perception that is the most essential to my thesis topic. Although spatial perception may often be used as a synonym to spatial cognition, it is important to make a distinction between these two terms, as Hart and Moore (1973, p. 249) reminded us. While cognition includes all the modes of learning and knowing (perceiving, thinking, imaging, reasoning, judging, and remembering), it also seems to include perception, according to Hart and Moore.

The simple definition for spatial perception is that it means perceiving distance, depth, size, and shape with the aid of interpretable "signs" or "cues" that have a meaningful connection between the sign and the thing signified. The question of how distance is perceived was addressed by psychological theories of vision and led to speculation about mental processes related to perception of a 3D visual world on the basis of a 2D image (Hatfield, 1990).

Cognitive maps are one part of spatial cognition and spatial perception. Essentially, a cognitive map is a network of representations coding both places and the sequential relations among them—or to put it simply, a mental image of a place (Moore & Golledge, 1976). At its most general, a cognitive map is a mental construct that we use to understand and know the environment (Kaplan, 1973). Downs and Stea (1973) noted that cognitive maps are used by people to orient themselves in environments, execute judgmental preferences concerning distance, and other metric characteristics of spatial environments. Cognitive maps and cognitive mapping are used specifically to form map-like representations of geographic environments (Hart & Moore, 1973). Kitchin (1994, p. 13) stated that cognitive maps in the context of geographic information systems could be of importance in three main ways: 1) Cognitive map information could be used to supply designers with knowledge that could improve system's interface, and thus make them easier to use; 2) cognitive map information concerning how we store and think about geographical data could be useful in improving database design and efficiency; and 3) cognitive map information could be used to improve education, specifically to increase understanding of the images displayed.

1.5 Research Field

In new fields, development is typically technology-driven, and the human-centred perspective is lagging behind (Veryzer & Borja de Mozota, 2005). That is also the case in the field of mobile map services, which is in a constant development regarding the **technology** (e.g., positioning technologies and mobile devices), features of the **application** (e.g., input/output modalities used and connections to social networks), their intended **use environments** (e.g., navigation in cars or pedestrian navigation in forests), and the **use cases** (e.g., navigation, self-locating, recording sports, or creating a travel diary). The spectrum is wide, and so are the implementations.

In FIGURE 2 *The properties of mobile maps vs. traditional paper maps*, I present properties between traditional paper-printed maps and mobile maps.

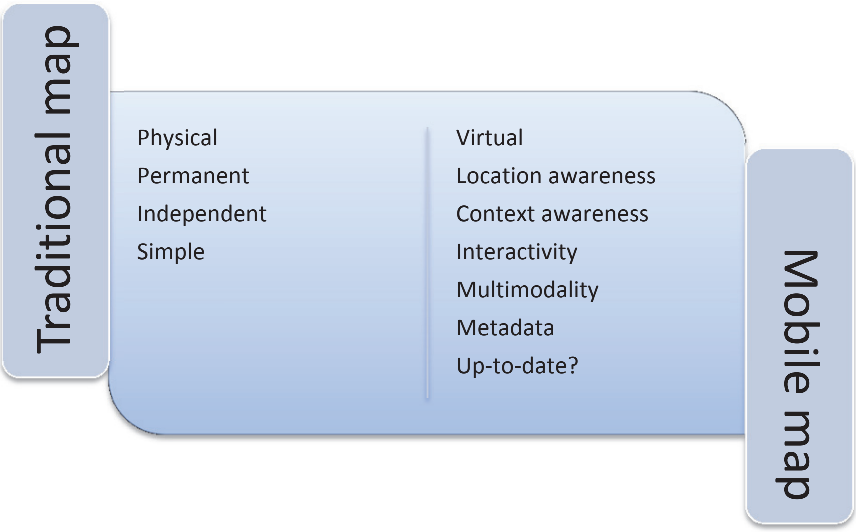


FIGURE 2 The properties of mobile maps vs. traditional paper maps

We can see that where the traditional map is physical, the mobile map is virtual. Traditional maps are also permanent; the map data are not updated on the specific map once it is printed out. The user, though, can make additions on both map types: they can write or draw on a paper map and, depending on the mobile map, also add markings (e.g., POIs, pictures, or notes) on the mobile map. The mobile map is still the only map type where the actual map data may be updated.

Mobile maps may also offer metadata, such as information about opening hours of attractions, speed limits on roads, or tips that other users have left or pictures they have taken.

The permanency of traditional map also has profits; once the map user learns how to read the map, there will not be irritating changes in the UI of the traditional map. Another benefit is that the traditional map does not suffer from running out of battery power, as does the mobile map's mobile device.

Traditional maps are independent; their data are not affected by the surrounding environment, whereas mobile maps often vary depending on the location (e.g., directions) or context (e.g., moving by car or foot). Mobile maps are also interactive; the user may give orders to it (e.g., to get directions), and the map application responds.

While the traditional map is simple in terms of use of different media channels and users' senses, mobile maps may use multimedia and offer feedback and functionalities through many senses; e.g., from visible maps to haptic feedback and voice guidance.

In FIGURE 3, I present the main aspects of mobile map application use that are considered in this thesis: user, use context, tasks, and maps. Previously many taxonomies and categorizations about different aspects related to mobile map use have been presented (Mallot & Basten, 2009; Meng, 2008; Nivala & Sarjakoski, 2003; Wiener, Büchner, & Hölscher, 2009). The figure 3 presents the aspects that I have seen the most relevant on the basis of previously presented research. I discuss each of the aspects in detail with their scientific justification in the following chapters.

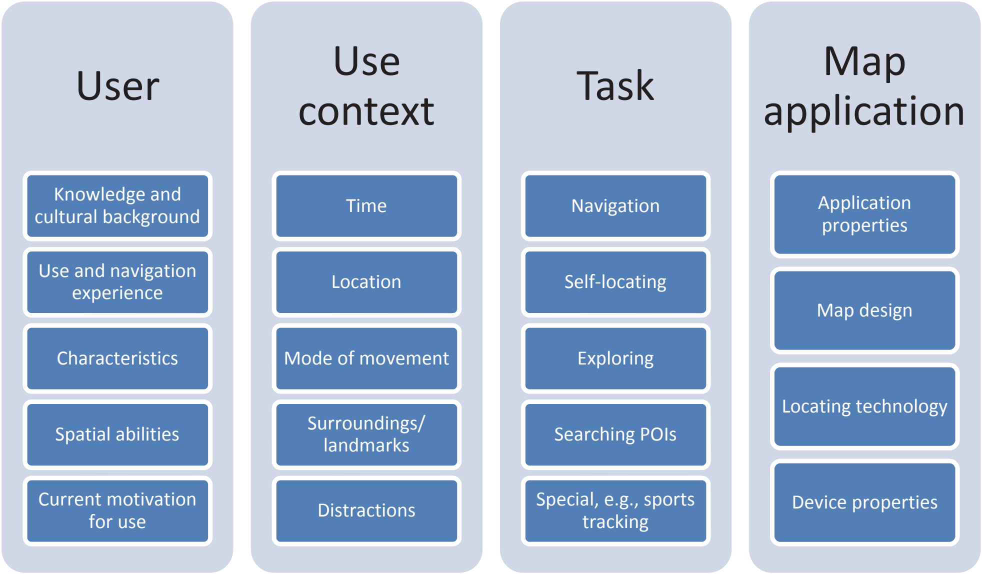


FIGURE 3 The elements that influence human-map interaction and that are needed to take into account when designing mobile map applications

1.5.1 The User

First of all, there is the user. The user, in this case a human, is complex and is impossible to be explained throughout. Roto, Law, Vermeeren and Hoonhout (2011) discussed the user's role from the point of general user experience and referred to the user as a dynamic experiencer with the changing state of the user's motivation to use the product and the user's mood, current mental and physical resources, and expectations.

The properties of the user that need to be taken into account in the design of mobile map applications, and that are discussed here, include the user's **knowledge background** (e.g., map reading skills, understanding of map symbols) and **cultural background** (e.g., the meanings of colours vary). It is known that, between cultures, colours, icons, symbols, pictures, character sets, time formats, jargon, and abbreviations may have different meanings (Bourges-Waldegg & Scrivener, 1998). For example, Nivala and Sarjakoski (2005) found differences in the understanding of specific map symbols between nationalities. In their research, it was not obvious that map symbols meaning a cottage or camp fire site, that are very well known by Finnish people, would have been understood by non-Finnish people. Thus, Nivala and Sarjakoski suggested adapting map symbols for different users. Rousi (2010) studied the user perceptions of attractiveness in smartphone icons and found out some significant differences in people's preferences of icons between Finnish and Australian people.

Ooms et al. (2016) conducted a recent study on young—from 11 to over 18 years—people's map reading skills and found that the higher performance and the higher age of the participant correlated together, and that was assumed to happen due to the received education in cartography at school. Albert, Virág, Dávid, Csaba, and Dávid (2016) studied the map reading skills of university students from six European countries. They also found higher age correlating with better performance, at least in certain tasks, such as distance and travel-time estimations, as well as frequent map usage correlating with better performance. There was also a clear difference in performance between nationalities in different map reading tasks.

The user's **use experience** with mobile devices, mobile map applications, and their **navigation experience** are also important factors. Darken and Goerger (1999) conducted in-depth research on navigation strategies and noticed many differences between experienced map users and beginners. For example, while experienced users begin by getting a holistic view of the environment, less experienced users start by planning their route without spending much time familiarizing themselves with the environment. To more recent assumptions and findings, those users that are good on spatial tasks, perhaps having experience in playing computer games, are supposed to be better in the use of 3D maps (Oulasvirta, Estlander, & Nurminen, 2008). Quite naturally, geography students have been shown to be better in tasks that require map reading skills (Ooms et al., 2016). Prior knowledge of geography also led to better performance on landmark search performance tasks when using Google Earth (Lei, Kao, Lin, & Sun, 2009).

The user's **characteristics**, such as age, gender, and ability to see, hear, and move also need to be considered. For example, users with problems with sight need more auditory or tactile cues in their map-related tasks (Abd Hamid & Edwards, 2013; Heuten, Henze, Boll, & Pielot, 2008). Considering gender differences, there is an indication of men performing better in tasks concerning orientation skills and mental rotation and the interpretation of map symbols (Albert et al., 2016). This is similar to the finding that males perform better in navigational tasks in virtual environments (Tlauka, Brolese, Pomeroy, & Hobbs, 2005). Tlauka et al. assume this to be, e.g., because of the differential use of spatial strategies. Ooms et al. (2016) explain females' lower performance on tasks with time limits as being partly females' tendency to pay more attention to details and being more affected by time pressures. These results emphasize the need for some training time prior to performing complex navigational tasks with mobile map applications. Also, the experts in the area suggest that training improves performance (Darken & Cevik, 1999). Besides freeform training, there is a specific spatial learning method that uses the cognitive mapping to teach relationships in spatial virtual environments, although the method has some major challenges (Johns, 2003).

The insufficient **spatial abilities** of users have been stated to be one of the main reasons for people getting lost (Carlson et al., 2010). So, this aspect needs to be taken into account as well. There is much previous research concerning human spatial abilities related to map use and, e.g., wayfinding. When discussing users' spatial perception in practice, we need to understand what kinds of categories spatial abilities can be divided into. Based on Golledge and Stimson (1997), the psychological definition for spatial abilities includes three dominant dimensions: spatial visualization, spatial orientation, and spatial relations. Self and Golledge (1994) suggested a detailed list of spatial abilities. Those relevant to my research include the ability to think geometrically; image complex spatial relations; recognize spatial patterns of phenomena at a variety of different scales; perceive three-dimensional structures in two dimensions and the related ability to expand two-dimensional representations into three-dimensional structures; give and comprehend directional and distance estimates as required in navigation and path integration activities used in wayfinding; perform transformations of space and time; image spatial arrangements from verbal reports or writing; image and organize spatial material hierarchically; orient oneself with respect to local, relational, or global frames of reference; perform rotation or other transformational tasks; recreate accurately a representation of scenes viewed from different perspectives or point of view; and compose, overlay, or decompose distributions, patterns, and arrangements of phenomena at different scales, densities, and dispersions.

Montello (2010) studied You-Are-Here (YAH) maps, which automatically inform the user of his or her current location, from the cartographic and psychological perspectives. He pointed out the problems of orientation with misaligned YAH maps and also noted that even automatically updated, correctly aligned maps place challenges for the user as the map alignment happens without the intent or possibly attention of the user. To simplify, Montello seems to mean that those maps that are not automatically aligned might be better for the user to maintain a better understanding of their location and directions.

Although even a very simple schematized map is enough for a good navigation performance (Meilinger, Hölscher, Büchner, & Brösamle, 2007), there are often also many other aspects than the rough performance of efficiency to take into account when designing a map service. This is why map application developers should not pay too much attention to the spatial abilities of users at the expense of the other factors.

The last aspect in this category is the **motivation for use**. Naturally, it has a major influence on the use and the user experience. Sometimes a little gamification might help in motivating the user, although it should not be conducted at the expense of the actual task. An excellent example of gamification in the context of mobile map applications is the *Pókemon GO* game (Niantic, 2016) that was released and became a highly popular worldwide phenomenon in the summer of 2016. The game combines four interesting aspects to a location-based game: mobile maps, augmented reality, and encouraging users to explore their surroundings and do sports. It is obvious that this kind of gamification is not suitable to all mobile map services, as the choice has to be made on the basis of the main task of the application, among other aspects, such as the users as discussed earlier.

1.5.2 Use Context

Second, there is the use context. Dey (2001) stated that context is a poorly used source of information in computing environments, but as mobile map applications are especially strictly linked to the use context, context is essential to take into account in the design and development of mobile map applications. Oulasvirta (2004) discussed the variety of use cases for context-aware technologies overall. He noted the differences in context-aware technologies towards the traditional desktop contexts to lay in internal factors, such as task goals, and in external factors, such as social resources and physical surroundings that are more dynamic and less predictable. Nivala and Sarjakoski (2003) included in their categorization of contexts for mobile map services the following: system (size and type of display, input method, network connectivity, communication costs and bandwidth, and nearby resources); purpose of use, user, and social and cultural factors (UX, disabilities, people nearby, and social situations); location, physical surroundings, and orientation (lightning, temperature, surrounding landscape, weather conditions, and noise levels); time (time of day, week, month, and season of the year); and navigation history (previous locations, former requirements, and POIs). This categorization is important, but the details of it have become a bit outdated by some parts as the technology has taken big leaps in the last 13 years and also the interaction between human and technology has changed (e.g. today black-and-white screens and pen-based interaction are not typical; audible navigation aids, acting on audio commands and automatic orientation of maps are).

In this thesis, I count the use contexts to consist of the following. Use contexts of mobile map applications are often time-critical (Meng, 2008); for example, the user needs to arrive at his or her target location at a certain time. Naturally, the location or target is an essential part of the use context of mobile map applications. Nivala and Sarjakoski (2003) stated that the user's current location is the most important advantage of digital mobile maps in the sense of context.

Hampe and Elias (2004) presented components of mobile navigation depending on moving mode: car, bicycle, or foot. They clarified the degree of freedom in routing to be by car tied to road networks; by bicycle to roads and cycle paths, but additionally forest and farm tracks; and by foot to be free in all directions. I would add the restriction of walking on motorways. Hampe and

Elias also classified the presentation components for different moving modes. When moving by car, they note map attention to be very poor and recommend voice output and simple graphics for maps, and restricting additional information to essentials, so there is no need for interaction while driving. When moving by bicycle, they note that eye contact with a map is possible and recommend using voice output or maps, avoiding the need for interaction; however, the need for additional information would increase. When moving as a pedestrian, they see attention to the map being absolute and eye contact and interaction being possible, and they recommend using only the map (without voice output) for output presentation, allowing for hand operation; they also state the need for additional information and features. Twelve years later, in 2016, the needs have changed and definitely gotten more specific; for example, voice output and tactile feedback are justified for pedestrian navigation (Schnitzler, Giannopoulos, Hölscher, & Barisic, 2016).

The physical surroundings are an important part of the use context and should be taken into account in map service design when choosing landmarks to show on a map application. There is a consensus in that pedestrians prefer navigation instructions based on landmarks, but the discussion is ongoing concerning the need for landmark-based instructions in car navigation systems (Ohm, Müller, & Ludwig, 2015). Suitable landmarks are different, whether the mobile map use happens outdoors or indoors. Duckham, Winter, and Robinson (2010, p. 41) presented factors for scoring landmark suitability for POI categories in outdoor routing instructions. These factors are divided into three characters: visual, semantic, and structural. Under visual characteristics there are physical size (larger POIs are easier to see), prominence (e.g., visible signs), difference from surroundings, night-time vs. daytime salience, and proximity to roads. Semantic characteristics include ubiquity, familiarity, and length of description. Structural characteristics consist of spatial extents (point-based POIs are less ambiguous than landmarks with spatial extent, they explain) and the permanence of POIs. Ohm et al. (2015) stated that suitable landmarks in pedestrian indoor navigation are, for example, stairs and doors.

A typical use context of mobile map applications is a situation with distractions. This poses challenges to the design of mobile map applications, as the navigation situation itself requires paying attention to surroundings, and attentional human resources available for interaction with a mobile device are limited (Tamminen, Oulasvirta, Toiskallio, & Kankainen, 2004). Typical distractions in mobile map use are, for example, traffic (queues, traffic lights, etc.), conversations, phone calls, SMSs, emails, notifications from social media, and other applications.

1.5.3 Tasks in Mobile Map Application Use

Mobile map applications are used for different tasks. Meng (2008) stated that users have two fundamental actions in a mobile environment: 1) move from one place to another and 2) stay where he or she is and look around. Meng also described map-based services typically supporting the following mobile tasks:

finding the location(s) of the user (addition from me: i.e., self-locating), objects, or people; planning routes; guiding a city tour; navigating and orientating for different movement modes; retrieving information on landmarks; simulating traffic noise; emergency and disasters; and supporting fleet management.

Navigating or wayfinding tasks have been classified into three primary categories: 1) a naïve search, where the navigator has no prior knowledge of the whereabouts of the target; 2) a primed search, where the navigator knows the location of the target; and 3) exploration, where there is no target (Darken & Sibert, 1996).

Also, some taxonomies are presented concerning the different tasks of mobile map use. For example, Wiener, Büchner, and Hölscher (2009) presented a taxonomy of wayfinding, including exploration, searching, undirected and directed wayfinding, target approximation, and path planning.

Mallot and Basten (2009) discussed the topic from the point of view of spatial cognition and navigational behaviour. They presented a task hierarchy in spatial cognition and stated it to consist of the following tasks and with the following required representations and information processing abilities: recognizing places (memory of local position information characteristic of places), finding home after an excursion (landmark guidance and/or path integration), following a route (associate places with motor actions, stimulus-response, or stimulus-response-stimulus), recombining known route segments (graphs of stimulus-response-stimulus associations), route selection and planning (working memory), cross-country shortcuts (metric embedding of places), and communication about space (naming places and actions).

I consider the most common tasks in the use of mobile map services, and the most essential tasks in the context of my thesis, to be navigation, self-locating, exploring, searching POIs, and searching (Kuparinen, 2016).

The term *self-locating* that is used in the field of information systems science and in other most common fields of IT is similar to the terms *place recognition* and *homing*, which have been used more in the area of spatial cognition and more psychology-oriented fields (for example, by Mallot and Basten (2009)).

Today, the variety of tasks that mobile map applications are used for—their use cases—has widened. Examples of these new use cases that have new mobile map applications are, for example, tracking sports (Reddy et al., 2010; Sports Tracking Technologies, 2016; Vaittinen, Laakso, & Itäranta, 2008), tracking dog walking (MapMyFitness, Inc., 2016), playing location-based games like the highly popular geocaching (Groundspeak, Inc., 2016; O'Hara, 2008) or *Pokémon GO* (Niantic, 2016), saving mushroom spots (Ubyca, 2016), locating pets (Tractive, 2016), and locating lost or stolen phones (Life360, 2016). The use of mobile maps is also included in many applications that are mainly designed for non-map-focused tasks, such as locating the initiators of incoming calls (iPlay Games Store, 2016), locating Wi-Fi hotspots (Koo & Cha, 2012; WiFi Map, 2014) or charging stations (Recargo Inc., 2016), and checking if trains are on schedule (VR Group, 2013).

1.5.4 Map Application and Technology

Next, I will discuss the elements to take into account when designing the UI for mobile map applications.

First, there are the application properties. For what purpose and for what kind of tasks the application is made for determine what kind of functionalities it should have.

In 2008, Meng stated that current map-based services were mainly developer-oriented and action-driven, and divided them into three categories. First is *mobility support*, including “you-will-go” services where routes between given points are calculated and visually highlighted; “you-are-here” services where the user’s location is always visible; “find next” services where the actual location and the next destination are visible; “wayfinding” services where the route with starting, intermediate, and terminating stations and landmarks is visualized; and “city guide” services where scenic spots are visualized. Meng’s second category for map-based services is information acquisition consisting of *event calendar* services where location- and time-relevant events are classified and visualized, “tour suggestion” services where tours considering personal preferences are displayed along with routing instructions, and “landmark” services where the semantic information specifying landmarks is displayed at the user’s request. The third category is information communication, including “group diary” services where members of a mobile group inform each other of their locations and “group activity” services where the map graphics are dynamically adapted to keep locations of group members visible (Meng, 2008).

Besides Meng’s categorizations, there are also other possibilities to categorize mobile map services, such as by the technology used or the visual layout, e.g. 3D versus 2D maps. I am inclined to categorize by the use environment (presented in FIGURE 4) and by the use purpose, as these are the most important aspects concerning my research topic and answering my research questions.

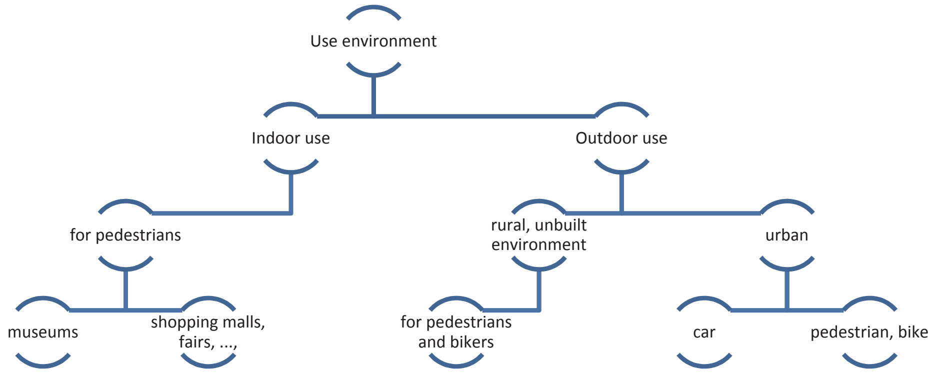


FIGURE 4 Rough categorization of the intended use environments affecting the application properties

The first categorization under use environment is the categorization of indoor and outdoor use. In indoor use, one typical example of mobile maps is museum guides, presented by several authors in several publications (e.g., (Abowd et al., 1997; Ghiani, Paternò, Santoro, & Spano, 2009; Lanir, Kuflik, Wecker, Stock, & Zancanaro, 2011). Some others are mobile map applications for a fair (Bouwer, Nack, & El Ali, 2012), for a shopping mall (Puikkonen, Sarjanoja, Haveri, Huhtala, & Häkkilä, 2009), for cultural tours (Suh, Shin, Woo, Dow, & MacIntyre, 2010), or for a library (Sciacchitano et al., 2006).

The spectrum of mobile map applications is much wider in outdoor use. Karimi (2011) wrote a comprehensive book on navigation with smartphones. He discussed outdoor and indoor, universal, anywhere, anytime, and any user navigation, as well as social navigation networks. However, he missed rural navigation, especially in unbuilt areas. Typical cases of mobile map applications for unbuilt environments are applications for hikers (e.g. (Vaittinen et al., 2008)) and for various other leisure activities (e.g. (Kettunen, Sarjakoski, Ylirisku, & Sarjakoski, 2012). Other kinds of applications have been introduced, such as a map-based service for searching for wildlife species information in a recreation area (Edwardes, Burghardt, & Weibel, 2003).

The category or purpose of a mobile map application affects the needed functionalities, such as navigation and searching for and saving POIs, as well as needed support for mode of movement and the implementation of feedback (e.g., auditory or haptic) from the application concerning navigation guidance or other interactions. As an example, Pielot, Krull, and Boll (2010) suggested using tactile—or haptic—feedback in situations where external factors, such as darkness or noise, interferes with the ability to receive visual or auditory feedback about locations. As a small example from map applications developed for rural areas, Schöning, Hecht, and Kuhn (2014) suggested displaying usage rules for the depicted space (e.g., "no smoking" or "no campfires") on the map.

Harrower and Sheesley (2005) stated the functionalities of the map application imposing map application design solutions, in their case indicating the applicable pan and zooming methods. They presented a framework for evaluating the functionality and efficiency of panning and zooming methods. They included the following functionality criteria: 1) sequential or non-sequential map browsing, 2) user-defined or pre-defined browsing precision, 3) presence or absence of local–global orientation cues, and 4) direct or indirect manipulation of interface controls, and the following efficiency criteria: 1) interface workload and 2) information-to-interface ratio.

A common choice to make is between the use of 3D and 2D maps. Darken and Durost (2005) emphasized the need to match the choice to the corresponding interaction tasks to reach the best performance and usability. The differences and effects to user experience and performance between 3D and 2D representations on maps have been researched heavily. For example, in the experiments of Davies and Peebles (2010), reaction times were much longer when using 3D cues on the map. A similar finding came from the experiments of Nurminen (2008): using graphically rich 3D visualizations did not imply intuitive navigation or good navigation performance. Still, Davies and Peebles (2010) suggested not turning 3D down, as it contains stronger cues for locating and it still demands less map reading skill from the person to be able to understand it. In contrast, Oulasvirta, Estlander, and Nurminen (2008) suggest 3D performance being more dependent on users' spatial skills than 2D. Later, Lorenz, Thierbach, Baur, and Kolbe (2013) found performance with 3D maps to be better than with 2D maps, and they stated this to be because 3D maps enhance spatial understanding. Probably the difference between results of different studies and researchers comes from the different representations of 3D maps.

Oulasvirta et al. (2008) studied the differences and user performance between 3D and 2D mobile maps in more detail. They found that 2D maps direct using cues like street names and street topology, and 2D maps afford the use of pre-knowledge and bodily action to reduce the user's cognitive workload. They pointed out problems of 3D: street-level perspective was uninformative, and photorealistic cues on a mobile device's small display were ambiguous. The use of 3D relied on different cues than the use of 2D. 3D users relied on known landmarks and used building shapes, façades, and relative directions, while 2D users relied on street names and street crossings more often.

3D representation has been used frequently and found to be useful, especially in small areas, to present city information, typically for tourists, such as mobile guides (e.g., (Chittaro & Burigat, 2004; Vainio & Kotala, 2002). Common 3D map attributes were recognized by Nurminen and Oulasvirta (2008), who stated that 3D maps were ideal (data set and visualization matching the real world), realistic, real-time rendered, navigable, interactive, dynamic, electronic, urban/outdoor/indoor, mobile, and immersive.

Then there is the choice of which map data to use as a basis for the map application. Common choices are Google Maps, Here Maps, Bing Maps, and open-source-based OpenStreetMaps (OSM), which also has pedestrian paths from forests included, but naturally the variety is not locked to these—it is possible to use any map basis, as well as maps that are drawn just for the application being developed. One solution outside the most common ones is OpenScienceMap, which is stated to consume less bandwidth than the alternative services (Schmid, Janetzek, Wladysiak, & Hu, 2013). There are also differences between the maps in terms of being up-to-date with the map data and visualizations. Especially if the map application is designed to be used in a predefined area, it is best to check the applicability of different map data to the purpose in mind. Interoperability between the map data and the resources needed to be connected on the map also has an effect on choosing the map basis, and from that perspective, open-source map data are often the best to use (Steiniger & Hunter, 2012).

Locating Technologies

The use environment also has an effect on choosing the locating technology. Hightower and Borriello (2001) presented a taxonomy of the then-current location-sensing technologies, explaining them to include, for example, satellite-based Global Positioning System (GPS), 802.11 wlan access points, radio frequency identification (RFID) tags, ultrasound, and perhaps a more experimental solution, smart floors embedded with pressure sensors. Tsalgatidou et al. (2003) divided locating technologies into three categories: satellite positioning, network-based positioning and local positioning. Although GPS is the most typical locating technology, it does not function well in indoor settings, as the satellite signal is often unavailable or at least weak when inside buildings (e.g., (Abowd et al., 1997)). Even using Assisted GPS (A-GPS) does not make the situation better (Zandbergen, 2009). Therefore, different locating solutions have been used indoors, such as RFID tags (Chittaro & Nadalutti, 2008), infrared (IR) (Abowd et al., 1997), or a combination of various wireless networking sources, like 802.11 access points, fixed Bluetooth devices, and GSM cell towers (LaMarca et al., 2005).

Also, more recent studies concerning indoor navigation technologies have been presented. Curran et al. (2011) compared the installation, accuracy, and encountered problems of different indoor locating technologies: Wi-Fi-based LA200, UWB radio technology-based Ubisense, Java-based Ekahau, and RFID; based on that, the 802.11 wlan location-tracking system still seems to be a strong option. Furthermore, Link, Smith, Viol, and Wehlre (2013) introduced another technology for indoor navigation, map-based FootPath, which uses an accelerometer and compass for locating. There are also examples of using Near-Field Communication (NFC), which is a combination of RFID and interconnection technologies, for locating in both indoor and outdoor settings (Borrego-Jaraba, Luque Ruiz, & Gómez-Nieto, 2011).

Fallah, Apostolopoulos, Bekris, and Folmer (2013) surveyed locating technologies and grouped them into four categories: 1) dead-reckoning, meaning techniques that estimate location based on previously estimated or known positions (e.g., accelerometers, magnetometers, and compasses); 2) direct sensing, meaning determining location through identifiers or tags that are installed in the environment (e.g., RFID tags, infrared, Bluetooth, and barcodes); 3) triangulation, meaning using multiple identifiers and triangulation to locate (e.g., a combination of RFID, IR, and ultrasound); and 4) pattern recognition, meaning using data from sensors carried by the user and comparing the data with prior collected sensor data in the environment (e.g., computer vision and signal distribution).

Concerning most of the literature I have been going though, there seems to be a consensus that it is best to use a combination of different locating technologies, especially in indoor navigation. This comes from knowing that each locating technology has its disadvantages, and the best coverage can be achieved by using multiple technologies complementing each other. Tsalgatidou et al. (2003) also listed requirements for location infrastructure in their article.

Besides concerning locating technology, device properties also need to be taken into account. Current mobile devices still have major deficiencies in their possible use durations because of the battery capacity lagging behind use needs—and that lag is even more common nowadays than when the use amounts of applications needing high capacity was much rarer. This affects the designing of mobile map applications by emplacing needs for battery-saving options, such as turning the screen off when there is no need for active feedback from the device or need to see the map view. Naturally, studies towards finding solutions to the problems with battery capacity have been published. Suggested solutions from recent years include offloading the workload to the cloud (Mao & Yeung, 2014; Qian & Andresen, 2015), optimization frameworks (Chen, Wang, & Pedram, 2014), smart proxying schemes (Bolla, Giribaldi, Khan, & Repetto, 2013), and informing the user of the remaining battery time for the user to manage power resources (Ferroni et al., 2013).

2 SUPPORTING USERS' LOCATION AWARENESS WITH MOBILE MAPS

There are some obvious yet challenging-to-define solutions to support the user's location awareness: designing better, more accurate, and clearer maps and designing user-friendlier UIs, for example, by emphasizing the important objects in the map. The basis of all this is in the methods of user-centred design (UCD), but besides that, I present some other possible solutions here.

Besides pointing to UCD and the above-mentioned general goals, some other novel solutions could be useful to support the user's location awareness. These are, for example, making sure of the realization of application- and device-based context-awareness, emphasizing landmarks in maps in a supportive way, using AR to keep the user's attention on the physical environment, exploiting multimodal feedback, and using user-generated content (UGC) on the map to make the UX more personal.

Furthermore, there are naturally also design guidelines and research-based recommendations for designing mobile map applications to support location awareness, or at a more general level, the UX of the map services.

Next, I will discuss all these in more detail.

2.1 Context Awareness

As defined in the chapter on terminology, context awareness is about the application adapting to the use context, such as the location, nearby people, accessible signal points and other devices, and the user's tasks. From the definition, we can assume that context awareness helps the user to maintain his or her sense of location. Context awareness is also assumed to be one of the rising trends of mobile technology (Häkkilä et al., 2009). The use of the terms *context awareness* and *location awareness* is partly overlapping, although *location awareness* (of the device) is a narrower term than *context awareness*. Here, I will consider both as a solution to support the user's location awareness.

Many case studies of context-aware systems have been published. Raento, Oulasvirta, Petit, and Toivonen (2005) presented a study of developing a platform for context-aware applications. They had several design goals for the platform that also reflected the properties of context awareness. They wanted the platform to represent the context for the user in such a way that the user could exploit it as a resource in social interaction. They also needed the platform to incorporate with existing applications, such as messaging and calling functions. The third design goal was to offer fast interaction and unobtrusiveness. Next, they wanted the platform to ensure robustness by automatically recovering from interruptions and failures. An understandable need was also the need for letting the user control seams, such as network connectivity gaps. The sixth goal was to emphasize timeliness; i.e., to provide quick access to context information. The last design goal was to enable rapid development of the application. All these are still goals for good context-aware systems.

A year later, Häkkilä and Mäntyjärvi (2006) introduced 10 design guidelines for context-aware mobile applications. The guidelines included 1) considering the uncertainty in decision-making situations, 2) prevention from interruptions, 3) personalization, 4) avoiding information overflow, 5) securing the user's privacy, 6) remembering mobility, 7) securing user control, 8) access to context, 9) visibility of system status, and 10) usefulness.

A good example of thinking of the possibilities of context awareness in the field of mobile map services is Raubal (2015) discussing the chance that a smart mobile map service could recognize that a user does not pay attention to his or her surroundings and involve him or her at the next decision point by requiring manual interaction in order to receive the next wayfinding instruction.

Schöning, Hecht, and Kuhn (2014) suggested integrating a "location-aware cartography" approach into the design of online and mobile map systems. There are some major defects in their research, as they state wrongly that no previous work "has turned to traditional cartography or the collective wisdom of cartographers to provide general design guidelines for online and mobile maps" (Schöning et al., 2014, p. 766). In this statement, Schöning et al. seem to be unaware of the previous work by, for example, Nivala, Brewster, and Sarjakoski (2008); Nivala (2007); and Kuparinen, Silvennoinen, and Isomäki (2013), whose work has been published in the venues of the cartographic community. Despite the deficiencies in being aware of the previous research, Schöning et al.'s paper sufficiently discusses what they call "location-aware cartography." By "location-aware cartography," they mean that different types of locations should use different cartographic approaches in the sense of design dimensions ranging from map orientation to the selection of visible map layers (e.g., hiding a north arrow from the map when viewing an indoor area).

Showing metadata of the interesting objects in the map service is also a good add-on to make the UX more meaningful to the user. Reponen and Keränen (2010) presented an idea and an interaction concept that enables viewing and accessing geospatial data on the mobile device's screen by pointing with a mobile device towards physical locations. Reponen and Keränen reported that the concept made the world feel more intimate to the participants taking part in their UX experiment.

2.2 Landmarks in Maps

Using landmarks in maps helps the user to identify his or her location. The use of landmarks has been shown to support environmental learning and cognitive mapping (G. W. Evans, Marrero, & Butler, 1981), and more recent studies have been published from the field of mobile maps (Kässi, Krause, Kovanen, & Sarjakoski, 2013). Keeping landmarks visible at different stages of zooming the map is supposed to improve the user's understanding of connections between the map, the user's cognitive map, and the real world (Delikostidis, van Elzakker, & Kraak, 2016). The use of landmarks as navigation aids has been shown to be especially useful to support older people in navigation (Goodman, Gray, Khammampad, & Brewster, 2004), but landmarks are important to helping people of all ages.

The use of landmarks is also one of the main factors affecting the map user's satisfaction with maps (Lorenz et al., 2013). In their study of factors influencing user satisfaction with indoor navigation maps, Lorenz et al. found out that landmarks and map perspective together explain about 30% of user satisfaction with maps. They also said that landmarks may not be regarded as very helpful when added to a complex or overloaded map design.

Vinson (1999) introduced design guidelines for landmarks to support navigation in virtual environments. Although the guidelines are meant to be used in the design of virtual environments, most of them are adequate for the design of mobile map services. Vinson emphasized the need to make landmarks distinctive. He suggested choosing as landmarks those buildings that have features that increase the memorability of them: significant height, complex shapes, free standing, surrounded by landscaping or large, visible signs; or features that improve the memory for building location: expensive building materials and good maintenance, bright exteriors, or unique exterior colours or textures. Vinson also suggested using landmarks that are visible at all navigable scales; sometimes even a city can then be a landmark. One of Vinson's guidelines points out the need to make the sides of each landmark different from one another, as these differences may help users determine their orientation. Based on the findings of Evans, Smith, and Pezdek (1982), Vinson suggested placing landmarks on major routes and junctions, as this enhances the memorability of landmarks and their locations. Lastly, Vinson emphasized the need to use both paths and landmarks to support navigation.

Snowdon and Kray (2009) explored the use of landmarks for mobile navigation support in natural environments and found that landmarks shown in mobile devices are important for people, especially while navigating the countryside. They also encouraged using photographs of natural landmarks for navigation in the wild. Sarjakoski et al. (2011) studied the use of landmarks in rural environments, especially hiking paths. They concluded that landmarks have a central role in verbal route descriptions in a hiking environment. They also found that is it harder to identify landmarks in natural environments than in urban environments, as the landscape is dominated by objects that are difficult to differentiate from one another, such as vegetation and landforms. They suggested always using structure landmarks and mentioned the other important landmarks as trees and water.

Sarjakoski et al. (2011) also faced the challenges of different seasons; for example, in the winter, the snow may hide footpaths, while the non-existence of leaves on the trees in the winter improves the visibility of large areas. Consequently, in winter, different landmarks should be used to support navigation in forests and other natural environments. For example, as lakes get frozen into ice in the winter in some parts of the world, as in Finland, lakes, rivers, etc. may not be good landmarks, and the same goes with snow-covered footpaths. Instead, landforms are usable landmarks in winter.

Dearman, Inkpen, and Truong (2008) studied mobile map interactions during a rendezvous exploration, and they suggested that prominent landmarks could be flagged by the system, or users could define landmarks as target locations. Previously, Raubal and Winter (2002) presented a method to automatically extract local landmarks from datasets to be integrated in wayfinding instructions. Winter (2003) continued this work and proposed a measure for selecting salient features to be used in the choosing of landmarks. Another solution, an algorithm for generating navigation instructions that include landmarks, was presented by Duckham, Winter, and Robinson (2010).

2.3 Augmented Reality

In recent years, AR has become more popular as a combination for mobile maps. AR cues combined with in-vehicle navigation systems have been found to be promising for improving driver safety by increasing hazard detection likelihood in a safe manner (Schall et al., 2013) and decreasing the number of driver errors (Karvonen, Kujala, & Saariluoma, 2006). Increased safety comes from the reduced need to take the driver’s gaze away from the road ahead, as the navigation instructions are shown on the top of the actual windshield view. For example, Chittaro and De Marco (2004) stated that the use of navigation systems via mobile devices while driving is one of the most distracting tasks for the driver and therefore a safety risk.

Differing from AR systems is in-vehicle navigation. In AR navigation systems for pedestrians, the user’s freedom of movement is maintained, and the mobile device can be moved in any direction (Narzt et al., 2006).

Besides the possibility of enhancing safety with AR in in-vehicle systems, I assume that using AR could be a solution to help users maintain their location awareness better with AR. I base my statement on the issue that, with AR, the user sees all the instructions or objects on top of the real-world view and is thus forced to pay more attention to the real world when seeing the instructions or object on the AR user interface.

Although it is probable that the use of AR might enhance navigation performance, especially when it comes to users' location awareness, there are still challenges considering AR technology. In 2012, Rehrl et al. studied pedestrians' navigation performance and user experience between GPS-enhanced digital maps, voice-only navigation, and AR UIs (Rehrl et al., 2012). In their experiment, users performed the poorest with the AR UI. Rehrl et al. considered this to happen due people's inexperience in using AR technology. They also conclude that AR technology suffers from technological drawbacks of mobile devices, such as positioning inaccuracies or inaccuracies of the magnetometer. Rehr et al. believed that image-based AR could solve these problems (Rehrl et al., 2012, 2014). Mulloni, Seichter, and Schmalstieg (2011) presented a design of an AR interface for indoor navigation, and in their validation, found it to be effective in supporting indoor navigation.

2.4 Multimodal Feedback

Using multimodal feedback in the interaction between the user and the mobile map service releases the user's attention to be used to complete his or her actual tasks and to maintain his or her attention better on the real world even in multitasking situations. By using multimodal feedback, the user may also maintain his or her location awareness at a better level. It is also suggested that spatial anxiety, which users may feel in unfamiliar environments (Hund & Minarik, 2006) and when lost, may be tackled by using multimodal, predictive cues to support navigation (Vainio, 2011).

Several examples of mobile map services providing the user feedback by exploiting other modalities than the typical visual and auditory communication methods have been introduced. After these two, the most common seems to be the use of tactile/haptic feedback in such situations where the user is supposed to take a turn in navigation or be aware of something. Typically, this is done by using the mobile device's vibration when the phone is in a pocket, but other solutions have been presented. Van Erp and colleagues (Van Erp, Van Veen, Jansen, & Dobbins, 2005), Heuten and colleagues (Heuten et al., 2008), and Pielot and colleagues (Pielot, Henze, & Boll, 2009) presented tactile belts with vibrators that indicate directions in an unobtrusive and hands-free way. In all of these studies, the UX of the tactile belt was considered mainly positive. Heuten et al. stated that the system was appropriate for pedestrians, bicyclists, and blind people. Pielot et al. found that users of tactile belts took shorter routes, spent less time studying the map, and were less often disoriented. Srikulwong and O'Neill (2011) also researched the use of tactile belts for pedestrian navigation. In their study, tactile feedback was given by different types of landmarks and directions towards them. They found tactile feedback to be suitable for landmark and direction-based navigation. I state that this kind of method of implementation for haptic feedback is better than using just a phone's vibration in a way that the user receives, i.e., feels, the feedback more likely than from a phone that may lie in a pocket, not so close to the user's skin. The disadvantage is that the user may not be willing to wear the belt, to have one more object to remember to take with him or her, and perhaps there may be some installation issues as well. The idea, however, is interesting, and implementation may become more popular in the future.

Later, Pielot, Poppinga, Heuten, and Boll (2011) continued their work based on tactile belts and examined the UX of giving tactile feedback by a handheld device, a tactile compass, compared to the feedback given by the tactile belt. Besides giving tactile feedback, visual feedback was available, and the combination of these two was reported as the preferred condition by the users. The results also showed that the presence of the tactile feedback led to slower walking speeds, similar to Van Erp et al.'s (2005) results, and perhaps cognitive overload. As many of the participants reported that they had felt the constant tactile feedback was mentally demanding, perhaps the performance could be better by enhancing the design of giving the tactile feedback, such as the frequency of feedback or the devices used. The overall conclusion of Pielot et al. (2011) is that tactile feedback recused the user's distraction, while the multimodal feedback improved navigational performance.

Tactile feedback is suggested to be used in situations where external factors, such as darkness or noise, interfere with the possibility of receiving visual or auditory feedback about locations (Pielot et al., 2010), as well as the need to focus on traffic on the street, as a hiker on hiking trails where tactile feedback is valuable, and for people with visual impairments (Heuten et al., 2008). There is also evidence that, when users feel spatial anxiety, they prefer tactile guidance (Vainio, 2011). Fröhlich, Oulasvirta, Baldauf, and Nurminen (2011) pointed out the need for traditional interaction techniques along with new ones, such as text-based search functionality being needed to locate street addresses. Today, though, target addresses can be input verbally. In their study on mobile touchscreens, Hoggan and Brewster (2010) emphasized the need to support both audio and tactile feedback, and these are often needed in different environments and locations, for different user preferences and with different tasks.

To conclude, besides utilizing other modalities, tactile feedback has possibilities in supporting users' location awareness. The best option seems to be the use of different feedback channels in a combination, giving the user a chance to choose and supporting the user in different use situations and environments.

2.5 User-Generated Content

Personalization of a service makes it feel closer and more important to the user and also enhances the UX of a mobile map service by making it more personal and the use of it memorable. Personalization may also improve the usability of the service by providing the most essential information and the easiest options available (Kaasinen, 2003). Kaasinen stated that letting users participate in the service could also enhance the use of it. One possibility to achieve the benefits of personalization is making use of UGC.

UGC is data, information, or media that is voluntarily contributed by people and is available for other service users in a useful or entertaining way, such as restaurant ratings, metadata, formerly especially wikis, and videos (Krumm, Davies, & Narayanaswami, 2008). The OpenStreetMap project is an example of major utilization of UGC. There the users of the map service contribute GPS data to produce and enhance the accurate map data that is free for everyone to use.

UGC is stated to be the fastest-growing source of spatially referenced data, as mobile device users are keen to share photos and other media (Cope, 2015). Contributing photos as a form of UGC to mobile map services has become easier, as it is typical to have a proper camera and a data package in mobile phones.

Marmasse and Schmandt (2000) presented a location-aware computing environment that links personal information to locations that are important to the user, making it easier for the user to associate information with certain locations and possibly to maintain his or her perception of the environment. Besides, the activity of exploring content that others have generated leads to reflective thinking (Norman, 2003). FitzGerald (2012) reported on research on UGC for location-based learning and stated that the creation of content for a service supports learning, as the user is engaging in experimental thinking, a learning process relating to personal experiences.

One of the benefits of UGC is that it may encourage communication between people and create a feeling of being part of a community (Cheverst, Smith, Mitchell, Friday, & Davies, 2001). The sense of community has also been seen as important for navigation services using user-generated pictures. Uusitalo, Eskolin, and Belimpasakis (2009) of the Nokia Research Center introduced Image Space, a solution for navigating UGC, the UX of which I was also studying at the end of my master’s studies and in the early years of my PhD research. Image Space was one of the many presented solutions for exploring the world and getting familiarized with nearby surroundings via UGC pictures.

Lei and Coulton (2009) studied user-generated POI photography to help users in pedestrian navigation, especially concerning the perception of location and directions. Users found the photographs that included direction information useful in finding POIs. Besides using just photos as a media of UGC, Lin (2015) pointed out the possibility of using user-generated sounds combined with maps. From the perspective of spatial perception and the user’s understanding of his or her surroundings and location, there is a wide area in need of more research.

To summarize, using UGC has many profits: enhancing the UX, increasing the use, making the service feel more personal, reinforcing interaction with other people, adding a feel of being part of a community, and supporting the memorability of locations and perceptions of the environment, locations, and directions.

2.6 Design Guidelines

Following the presented design guidelines for the development of map services or the more specific parts of them are naturally good tools for designing mobile map services that support the user's location awareness, as well as other user needs.

As mentioned earlier, Nivala and colleagues (Nivala, 2007; Nivala et al., 2008) presented design guidelines for web mapping sites. In their contribution, several aspects of web mapping sites were taken into consideration. The guidelines concern the layout and functionality of mapping sites' UIs; the visualization, tools, and level of detail of the map; the functionality and visualization of the search operations; and help and guidance. The design and properties of the web mapping sites and especially the use cases and use environment though differ a lot of the map applications used in mobile settings with mobile devices.

To fill the gap of not having compiled a package of what is a good, usable mobile map application, or not having design guidelines for mobile map applications, I wanted to contribute to that. As part of this thesis, and in the included articles, I have presented usability heuristics, described later in this thesis, partly with my colleagues (Kuparinen, 2016; Kuparinen, Silvennoinen, & Isomäki, 2013), designed specifically for mobile map applications. Although they are supposed to be used as a usability evaluation tool in the method of heuristic usability evaluation, they are also suitable to be used as design guidelines.

Of course, there are also many others who have taken part in the discussion. Vinson (1999) presented design guidelines for landmarks to support navigation in virtual environments (discussed in more detail in the chapter "Landmarks in Maps". Herman and Heidmann (2002) presented user requirements for an example of a mobile map fair guide. Vainio and Kulju (2007) presented a few design guidelines at a high level for navigation aids on the basis of a study with taxi drivers. Furthermore, Skarlatidou, Cheng, and Haklay (2013) presented guidelines for geographic information systems from the point of view of supporting the user's trust.

Besides these, many more detailed recommendations concerning the design of mobile map services have been presented in publications that have focused on certain aspects of UIs. About visualizing geographic data, Burigat and Chittaro (2007) conducted a throughout survey of the previous research and recommendations in the field. The most evident conclusion of that survey is that, nine years ago, many—partly overlapping and partly contradictory—suggestions were made. More recently, Sluter and colleagues (Sluter, Brandalize, van Elzakker, & Ivanova, 2013) aimed at defining a standard set of symbols for urban regions.

On other detailed design-oriented recommendations, such as panning and zooming, Johnson (1995) studied options for panning on touch screens and recommends the solution "panning by pushing the background," where the image moves to the direction of the finger movement, as that was the expected, preferred, and best-performed solution by users. Ten years later, Harrower and Sheesley (2005) conducted a comparison of nine panning and zooming methods. They stated that no single method is both highly capable and efficient in all use cases, but the best solution is to choose a matching method to particular users and map-browsing tasks. They presented a good mix of methods to look for when in a need to choose the best one for a particular use case.

Another example of detailed suggestions is studies on preferred object sizes. Parhi, Karlson, and Bederson (2006) studied the optimal target sizes for one-handed thumb use of mobile handheld devices and recommended that the target size to be 9.2 mm for discrete tasks and 9.6 mm for serial tasks. In 2002, Brewster studied the optimal size for buttons in PDA stylus use and stated that, if sounds are added to pushing buttons, the best button size is 8×8 pixels (Brewster, 2002). Mizobuchi, Chignell, and Newton (2005) examined the adequate key size for text entry on mobile devices while walking and standing, and suggested having a minimum text input box width of 3 mm.

To conclude, there are design suggestions, guidelines, and evaluation tools for the overall design of mobile map applications, such as the new usability heuristics introduced later in this thesis, but there are also many detailed suggestions concerning the different parts of the UIs of mobile map services. When designing a mobile map service from the user-centred perspective, it is highly recommended to be familiar with these and to follow their suggestions.

3 RESEARCH METHODOLOGY

In this chapter, I first discuss the research methods that have been typically used in the research area of supporting the design of UIs for mobile map applications. After that, I present and discuss the research methods that I have been using.

3.1 Previous Research

The need for mixed methods has been emphasized in the UCD or Human-Technology / Human-Computer Interaction (HTI/HCI) research of mobile map applications. When it comes to usability, Meng (2008) divided these methods into three categories based on their time of use in the mobile map service design process: pre-design usability studies, participatory design, and post-design usability tests. Meng (2008) suggested pre-design tests to get a neutral insight into the possibilities and user's wishes or imagination. Meng listed the pre-design method to consist of questionnaires, interviews, scenarios, and controlled experiments. As an example of pre-design study with mixed methods, van Elzakker (2004) used thinking aloud, video recordings, questionnaires, and retrospective interviews to gain knowledge of exploratory cartography.

To go forward, usability tests are used during the mobile map service design process, and their purpose is to help discover usability challenges of current products (Meng, 2008; Rosson & Carroll, 2002). Examples of methods of participatory design are design workshops, conversations, prototyping, and crowdsourcing. A post-design usability test comes into the picture after a prototype or similar aspect of a mobile map service has been completed (Meng, 2008). According to Meng, observation, thinking aloud, and controlled experiments are typical of this state. Meng continued by saying that user observation is mainly non-intrusive, with an emphasis on video recording, registration of clicks, and eye tracking. Besides the above-mentioned, in their review of MobileHCI research methods, Kjeldskov and Graham (2003) added the methods to consist of case studies, field studies (discussed in the next chapter), action research, laboratory experiments, surveys, applied research, basic research, and normative writings. Many of these are more like upper categories for different research methods and typically include mixed methods. One more addition to the list of methods of the map use research comes from Schobesberger (2009): remote evaluation, which may simply mean the logging of use statistics.

One interesting division to different data collection methods of the mobileHTI field is by Hagen, Robertson, Kan, and Sandler (2005). They divided the mediated data collection methods of the UX into three categories: 1) do it, where the participants do the data collection by mobile devices; 2) use it, where the participants use the technology and data about use, content, and metadata are logged automatically; and 3) wear it, where the participants wear mobile recording devices, e.g., sensors or cameras.

Nivala, Sarjakoski, and Sarjakoski (2005) presented the process of using the UCD approach in the development of mobile map services. When developing mobile map services, the UCD approach is supposed to be included iteratively in the development processes of applications, not just in some specific testing phase. The UCD process begins by identifying users and collecting user requirements by suitable methods, e.g., surveys or user observation. After that, the first mock-ups may be formulated. Design is the next step, typically in an iterative manner. Feedback of the design ideas and implementations should be collected from users in this phase. The last phase of the process is evaluation, which is also often concurring with the design phase. In this phase, the target is to find usability problems and other issues in need of correction. One possible method here is the heuristic usability evaluation. Besides finding usability problems, other valuable information for further development may also be gained. If it is found that user requirements are not fulfilled and—as is typical—usability issues occur, then the cycle of design, implementation, and evaluation goes on iteratively until the goals are reached (Nivala et al., 2005).

It is important that Nivala et al.'s (2005) paper about the UCD approach in the development of mobile map services was published in the cartographic community, as in their other paper (Nivala et al., 2007), they found out that UCD and usability engineering (UE) methods were not well-known among map application developers, although it is shown that using such methods in development leads to product that have a higher quality of use. The result of almost non-existent knowledge of using UE and UCD methods is nothing new, however. The emphasis on more technology-oriented (rather than user-oriented) methods is typical, irrespective of the domain field.

Meng (2008) stated that the advantage of usability tests is the support to service designers to infer user requirements and determine suitable design rules. When planning to conduct research focused on the usability of a mobile application, the generic framework of Zhang and Adipat (2005, p. 9) may be worth looking into. They presented a simple graph of making the rough choices of testing method, tools to use, selecting what to measure, and data collection approaches.

Harrison, Flood, and Duce (2013) reviewed mobile usability models and found that usability has usually been measured in terms of only three usability attributes: effectiveness, efficiency, and satisfaction, and that other attributes, such as cognitive load, have been overlooked. This is a similar finding to Meng’s (2008), who listed only these three aspects to be used in the measurement of the usability of mobile maps.

Case studies are very typical in the field of mobile map application research, as well as the overall field of HCI research. Besides the use of mixed methods, another interesting aspect of doing research in the multidisciplinary field of UCD of mobile map services is the use of novel, innovative, and experimental methods, as well as novel use cases and environments. One example of this is a study by Naukkarinen, Sutela, Botero, and Kommonen (2009). They presented their experiences of designing locative media through urban intervention. They had two groups they observed and took as a part of the design process; parkour & rock climbing enthusiasts and urban artists (e.g., graffiti makers). Naukkarinen et al. identified a high amount of possible use cases by executing research with the sports enthusiasts and identifying radically new possibilities by executing research with the urban artists. This was called appropriation. The core idea in Naukkarinen et al.’s research was to examine the possibilities of designing locative media for creative misuse by learning from non-conventional and interventive urban practices. The authors stated that creative misusers should be included in the design process because they play an increasingly important role in the lives of artefacts.

3.1.1 Conducting Research outside Laboratories

Should research be conducted in the wild? In the area of human-technology interaction, research experiments have traditionally been driven in laboratories. That is the case also when the research focus is on the mobile UX (Kjeldskov & Graham, 2003). Recently, the research community awoke to the need for utilizing more applicable methods to be used in the research on the mobile UX. Workshops have been organized (e.g., the first workshop on Observing the Mobile User Experience in 2010), and special issues of journals have been published (e.g., ACM Transactions on Computer Human Interaction Special Issue: The Turn to the Wild in 2013 (Crabtree et al., 2013)).

Kaikkonen, Kekäläinen, Cankar, Kallio, and Kankainen (2005) compared the results of laboratory and field methods when testing the usability of mobile applications. They found that it is not worthwhile to conduct a field test when searching usability problems, but it is possible that field testing is worthwhile when combining usability tests with a field pilot or contextual study where user behaviour is investigated in a natural context. A year later, Nielsen, Overgaard, Pedersen, Stage, and Stenild (2006) got results from their comparison of usability evaluations in the laboratory and in the wild that stated that significantly more usability problems were identified in the field than in the laboratory, and problems with interaction style and cognitive load that were not found in the laboratory were found in the field. They ended up recommending conducting usability evaluations in the field.

It is important to see the difference between studying and evaluating only usability and studying and evaluating also all the other user, use, interaction, and, for example, perception issues. When the scope of the study is wide, the need for conducting research in the field is even more important. Among many others, Looije, te Braxe, and Neerincx (2007) discussed UCD-related research methods for mobile maps. They emphasized the need for proper usability engineering (UE) methods and testing while the user is mobile.

Research on the use of mobile map services and of their design needs is delightfully often conducted in the field. Also, studies about mobile map use in rural areas have begun using field experiments, even in forests. For example, Kettunen and colleagues (Kettunen, Putto, Gyselinck, Krause, & Sarjakoski, 2015) took participants to a nature trail to investigate perception and recall of landmarks between day and night. A study targeting this kind of knowledge would have been very difficult to gain by other methods than taking the participants to nature.

3.2 Research Methods of This Thesis

Besides applying background theory to search answers to my research questions, I have used several other research methods, partly in a mixed methods approach. The summary of the methods is presented in TABLE 1. Next, I will describe the methods used in more detail.

TABLE 1 Summary of the research methods used

	Thesis introduction	**Article I**	**Article II**	**Article III**	**Article IV**	**Article V**
Literature review	X	X	X	X	X	X
User experiments		X	X	X		
Eye tracking		X				
Picture recognition test		X				
Heuristic evaluation					X	X
Survey			X	X	X	X
Interview		X				

3.2.1 Literature Review

Literature reviews, or surveys of previous research, are an essential part of every academic thesis and every research article. As seen from the previous chapters, a literature review is naturally present in this thesis, as well as part of every research article included in this thesis. This was especially important in the study of article IV, development of usability heuristics for mobile map applications, as the development was largely based on the findings of the previous research.

Webster and Watson (2002) discussed in detail the nature of writing a literature review in the field of information systems (IS). They presented reasons to write literature reviews: to position the current state-of-the-art, progress, and lessons learned in a specific research area and probable fruitful directions for the future. Besides that, it is meaningful to base new projects on previous research literature and theoretical models presented earlier. Webster and Watson also pointed out the possibility of finding potential authors for new research projects and articles from the process of exploring the previous literature in the field.

3.2.2 User Experiments

User experiments are very typical in UCD research. Conducting user experiments gives the designer or the researcher authentic data on user behaviour and most preferably a good understanding of user needs (Nielsen, 1993).

It is essential to understand that, when it comes to UCD, where the main goal is to design a good product for users, the focus in user experiments is not on studying the participating person but rather on the development of the product and the user needs and expectations towards it. It is typical that a person participating in a user experiment assumes that the person himself is the one who is being researched or even evaluated, and it is important to emphasize that the person should feel no pressure, as he or she is not evaluated. Otherwise, the participant might feel stress that might have an affect on the experiment results.

I conducted user experiments in two studies and three of my articles: an eye-tracking study in article I and depth perception experiments in articles II and III. The user experiments in articles II and III were about studying the distance estimations of people between real world and AR. The user experiments there might not be the most typical, as there was hardly any interaction between the user and the device. The experiments were about the participant observing the objects on the screen of a device and reporting his or her visual perceptions.

Next, I will discuss the other type of user experiment I used, eye tracking, in more detail.

3.2.3 Eye Tracking

I conducted eye tracking research as empirical study to test the methods' suitability to mobile map research in the wild. The motivation for the eye tracking experiments I conducted in forest came from the assumption that the method helps finding out the different solutions and ways people interpret their environment and to get information of people's focus objects while navigating. This information would be useful when making decisions on, e.g., about what objects and landmarks are needed to emphasize on mobile maps. In the experiments I focused on finding out the challenges of the method while used in mobile settings.

Eye tracking (also gaze tracking) has a long history, starting as early as 1901, when Dodge and Cline made the first photographic records (Land & Tatler, 2009, p. 7). Traditionally, eye tracking has been used in research as a data collection method in stationary environments like laboratories. In recent years, eye tracking has been used typically for marketing research, such as inspecting people's focus while shopping or reading advertisements, or to investigate people's fatigue or perceptions while driving (Duchowski, 2007). More recently, the method has also been adapted to usability studies and the UI design of web sites.

Eye tracking has also been used in research on the use of geographical maps, but mostly with digital maps in stationary 2D environments where the person is sitting in front of a computer, such as in the experiments of Ooms and colleagues (Ooms et al., 2015; Ooms, De Maeyer, & Fack, 2014). Besides the above-mentioned, there have been map related studies on issues like underlying cognitive processes while navigating in a virtually simulated city (Spiers & Maguire, 2006) and the attention of elderly people while using a special AR navigation display placed on a car simulator windshield (Kim & Dey, 2009).

As eye-tracking equipment has become more portable, it has become possible to do studies in mobile settings. Previously, the equipment consisted of a heavy laptop, unwieldy wires, and cameras attached to a helmet, which are restrictive to a person's mobility. In the recent years, eye-tracking cameras embedded in light-weight eye-tracking glasses without a need for wires have been announced.

Although eye tracking could be a suitable method for mobile settings where the person moves in natural environments outdoors, and although suitable technical solutions are beginning to exist, that kind of study has rarely been done. Some experiments have been reported from indoors settings (e.g., (Viaene, Vansteenkiste, Lenoir, Wulf, & De Maeyer, 2016), and Evans and colleagues wrote a major publication on the method's use possibilities and challenges outdoors (Evans, Jacobs, Tarduno, & Peiz, 2012).

An example of mobile situations where the use of an eye-tracking system would be useful is when there is a need to get information about the important objects used in navigation, self-locating, or other map-related tasks—that is, which objects a person notices and which he or she misses in the natural environment. Currently, that kind of information is not exploited systematically in the design of mobile maps, though it should be, based on the flaws of the current mobile map service solutions. Especially in unbuilt nature areas, forests are too often presented just as large zones of green colour, fields as large yellow zones, and lakes as blue zones, although there would be other possible and meaningful landmarks, like pathways, special trees or rocks, topographical information, or the current location of sun. Another typical solution is to present the area as a satellite map that shows outdated, far away, and rough images recorded straight above the area.

The way of presenting map data on traditional paper-printed maps like street maps and orienteering or terrain maps is based on well-grounded and long-lasting research, but when the map data need to be presented in a mobile device, the same visualizations used in paper maps are not usable. The use of mobile devices brings technical and contextual restrictions. As discussed in earlier chapters, the technical restrictions include the small size of the device's screen, the limited capacity of the device's memory resources, the often-limited data transmission capacity, and the often poor capacity of battery. As also discussed in the introduction part of the thesis, the contextual restrictions that affect the use of a mobile map are interruptions from the device, such as incoming calls, and interference from the surrounding environment, like the need to pay extra attention to a small device while there are cars that the person also needs to pay attention to.

The benefits and the challenges of eye tracking in map use are partly the same as in the eye-tracking research in general, and there are also special benefits and challenges. According to Renshaw and Webb (2007), the benefits of eye tracking include the data's independence from user memory and getting the indication of a person's problem solving strategies. Eye tracking also gives a very large amount of both quantitative and qualitative data.

The challenges of using an eye-tracking system as a research tool in general have included common problems of getting the eye-tracking system calibrated properly for different people (Duchowski, 2007), interpreting the relation of the gaze and the cognitive attention (Henderson, 2003), the parallax problem (Pfeiffer, Latoschik, Wachsmuth, & Herder, 2008), and the laborious analysis of the eye-tracking data (Jacob & Karn, 2003). The existence of the first two of these are dependent on the technical solution that is used in eye tracking and can be avoided by choosing the right solution for the specific research case. Some of the novel eye-tracking equipment are able to better avoid these problems. The last one, laborious analysis of eye-tracking data, can be minimized by careful planning of the data analysis process.

When the research is run in a mobile setting, other challenges arise. These challenges include the effect of varying weather and lightning conditions (Kuparinen & Irvankoski, 2011), the possibly of heavy and awkward eye-tracking equipment restricting the person's mobility, and difficulty defining areas of interest (AoI) in 3D data. The first challenge about weather and lightning conditions is an issue that needs planning and looseness of the test schedule and backup plans. The second and the third challenges about the mobility issues and the difficulties to handle 3D data are currently vanishing as eye-tracking solutions are developed to be more applicable for mobile 3D use.

3.2.4 Picture Recognition Test

In article I, a variation of a picture recognition test was used as part of the user experiment to check whether the participant had committed certain views or objects seen in a forest to memory. The participant was shown pictures and asked whether she had or had not seen the view, and the results were compared to the eye-tracking paths. Picture recognition tests are typically used in psychology to measure visual memory of objects or pictures and visual–spatial thinking (Miller, 2013).

A similar method as the test used in the article I, has been used to research the map-reading skills of people in the study of Ooms et al. (2016). There, as part of a bigger questionnaire, the participants received a picture of outside scenery and a map, and they were asked to report from which position on the map the picture was taken. Similarly, Davies and Peebles (2010) used pairs of pictures of scenes and a map and asked the participants to state in which direction they must be facing on the map in order to see the scene. The goal of this study was to examine people's strategies when orienting with a map outdoors. As one more example, Christou and Bülthoff (1999) used a picture recognition test to study human spatial encoding of a 3D navigable space.

3.2.5 Heuristic Usability Evaluation

A heuristic usability evaluation was used in articles IV and V, where we first developed and introduced, and then I validated and developed the heuristics further. The first part of the development was largely based on findings from previous research in literature, but when the heuristics were tested for the first time, we used our newly developed heuristics in a comparison to generic Nielsen heuristics (1994) to evaluate the usability of a mobile map application. In article V, different map applications were evaluated by using the heuristics introduced in article IV, a huge collected-evaluation report data was analysed, and more feedback of the heuristics was collected.

Zhang and Adipat (2005) discussed the issues surrounding the usability testing of mobile applications. They stated that the challenges in the usability testing of mobile applications include the mobile context, multimodality, connectivity, small screen size, different display resolutions, limited processing capability and power, and restrictive data entry methods. The heuristics developed and validated in my studies, are focused on taking these challenges into account. At the same time, these challenges describe the need for domain-specific heuristics.

A heuristic usability evaluation is a "discount method" in the process of developing a product with good usability. Typically, methods that have a strong user participation included user experiments, observation, or at least interviews, which are preferred in UCD and tend to give the widest understanding of the use cases, use habits, user needs, etc. Quite often, especially in the development happening in industry, there is though not enough time for large usability testing, or users are difficult to get in the development process. In those cases, a heuristic usability evaluation offers a good option, as it can be conducted even without the actual users taking part.

Usability heuristics may be used similarly to design guidelines, though heuristics are meant to be used for inspecting the UI of a still-in-development product in a systematic way (Nielsen, 1994), and design guidelines may be used in a more free-form nature in the beginning of development or as a checklist in the later phases of development. In contrary to design guidelines, heuristic usability evaluation is a method of UCD and has been studied widely, concerning things like its effectiveness.

The formal heuristic usability evaluation is conducted in the following manner, to paraphrase Nielsen (1994). Several evaluators, preferably five but at least three, are needed to conduct the evaluation, and each is supposed to do the evaluation independently. The evaluation typically lasts one or two hours. The evaluators go through the UI, preferably several times, and inspect its elements in a comparison of the usability heuristics set. At first, the evaluators are supposed to interact with the system freely to get a general scope. After that should be the turn for focusing on specific interface elements. Typically, there are also specific tasks for the evaluators to complete with the system—tasks that are considered to be the common tasks in the actual use of the system. The found usability problems; issues that violate the usability heuristics are reported on a form, and often, the severity level of the problems is estimated.

3.2.6 Surveys

Using surveys as a research method is not new in general, and that is also the case in the fields of information systems science (IS), map research, and HTI. The method is widely used. In HTI, it is often used with other methods as a mixed methods approach, and is encouraged to be used in the field of IS (Gable, 1994). Using surveys together with other methods was also the case with my studies. I made use of surveys in all but one of my research articles, in some of them only shortly, such as collecting background data and the former amount or type of use of the participants of the experiments, and in some more widely, e.g., to collect insights and experiences of the usability heuristics the participants had been using.

The often-seen advantage of surveys is the easy collection of a large amount of data (Kjeldskov & Graham, 2003) and easy data analysis—as long as the data are numerical. Easy collection should not, however, lead us to believe that the method is easy as a whole. Especially when using surveys with strict questions, it is important that the questions are properly formatted, which requires much effort from the researcher. The challenge of the method also lies in that it may not give very deep insights of the study object to explain the underlying meaning of the data (Gable, 1994). That also encourages the use of the method mixed with other methods.

3.2.7 Interviews

Like surveys, interviews were used as part of mixed-method approaches in my studies, never alone as a single method. Interviews are also a popular method in various disciplines, including IS research (Myers, 1997). In the UCD approach and HTI, it is also typically used together with other methods, whereas in some other disciplines or research approaches, it is more typical used independently.

I used interviews as a method in article I. There we had the goal of understanding more deeply the experiment participants' insights, strategies, and perceptions while navigating and exploring in a forest. Interviews were also needed to validate the findings of eye-tracking data. Accordingly, interviews are often used together with eye tracking, as there are still challenges collecting the eye-tracking data without any losses, and the gaze object is not necessarily the object of attention (Kuparinen & Irvankoski, 2010).

4 RESULTS AND SUMMARY OF ARTICLES

In this thesis, I have presented a wide literature review of topics concerning the design and use of mobile map applications from the point of view of user-centric design and especially supporting users' location awareness. This literature review can be seen as one of the results of this doctoral thesis.

Besides the literature review, I have presented five research articles that are included in this thesis. The first concerns eye tracking as a research method and presents important aspects to take into account when planning to execute eye-tracking research in the wild. The second and the third articles address issues on human depth perception in AR versus the real world. This is interesting from the point of view of the future directions of mobile map applications. In the fourth article, a list for usability heuristics for mobile map applications is presented. Finally, the fifth article presents validation and extension for the mobile map applications' usability heuristics.

4.1 Article 1: Experiences from the Use of an Eye-Tracking System in the Wild

Background and Motivation

Eye tracking is a suitable and interesting method for the research of mobile maps, as it gives indication of person's problem solving strategies and the data are independent from person's memory (Renshaw & Webb, 2007). An eye-tracking system is useful when there is a need to get information about the most important objects used in navigation or to identify which objects in traffic a driver of a car notices and misses.

Conducting research in the field setting elicits more usability problems and problems with interaction style and cognitive load that are not identified in the laboratory (Nielsen, Overgaard, Pedersen, Stage, & Stenild, 2006). When the research target is to investigate wider user experience in a natural context, the importance of a field study is even more evident.

When this study was conducted, there were not many other studies done in a forest environment. Therefore, the goal of this study was to introduce and discuss a suitable, still-fresh method for the research area of map application development. We also presented and demonstrated some challenges affecting the use of eye-tracking research methodology in the field—some of the challenges have been discussed earlier by other researchers in other research environments, mainly stationary settings, while others were representative only in this field setting.

Method

In this study, mixed methods were used. We conducted multiple eye-tracking tests with mobile eye-tracking equipment in a forest environment with different tasks in different conditions.

The first tests were conducted without a mobile phone. In that phase, the goal was to assess the feasibility of using an eye-tracking system in a forest environment and to test task settings for future studies. During the tests, we took the users to the forest to do simple navigation tasks: walking through a certain route with a little guidance (no maps; paper or mobile applications were used), describing what the users saw, describing how the users located themselves, and describing the route in such a way that another person could follow it.

After completing the first experiments without mobile devices and maps, a test with a mobile map application was conducted. In this experiment, the user walked a route according to given instructions and located herself on the map. The user was also asked to navigate on foot to a certain position pointed out on the map.

In addition to recording eye-tracking data and interviewing the users during the experiment, the users were interviewed after the experiments. These interviews were conducted to validate and complete the eye-tracking data and observations made in both of the field test cases.

As part of the interview, we conducted a picture recognition test. After the user had walked the route, she was asked about what she saw and was shown pictures and asked to decide whether they were taken of the route (Kuparinen & Irvankoski, 2010, 2011).

Main Findings

This study reports the issues that need to be taken into account while conducting eye-tracking research in the wild. Some of these issues include difficulties in tracking a person’s eye movements if he or she wears glasses, if the person’s pupil size is small (e.g., when tired), the colour of the iris is light, or if the person has very long, downward, or made-up eyelashes; these are also present in eye-tracking research in stationary environments (Duchowski, 2007).

Eye-tracking systems have been found to be unable to provide definite information about distance of gaze in 3D settings (Pfeiffer et al., 2008). This problem of parallax error was concretized in our experiment where we could not be sure whether the user looked at a tree three metres ahead or a lake that could be seen between the branches of the tree. To avoid this kind of problem, we suggest using thinking aloud method as an addition to eye tracking to confirm the findings.

As the calibration of an eye-tracking system is much more challenging when conducting research in the wild (with distances varying from centimetres to hundreds of metres) than in a laboratory setting (with distances typically less than a metre), we also presented suggestions for that: we used a large rectangular area several metres from the user in the same environment that the test was going to occur. Due to the mobile setting, movement, and varying lighting conditions from nature, the calibration needs to be repeated during long experiments.

Changing weather conditions, rain, brightness or darkness, sometimes wind, cold, or heat place challenges that are not present in laboratory settings. Also, wearing the eye-tracking equipment may have an effect on the person's movement and behaviour. Therefore, we recommend that the actual test not be performed until the user has had time to become familiar with the equipment.

One limiting factor for the use of eye-tracking systems in the wild was the low battery capacity of the eye-tracking system. This needs to be taken into account if planning to conduct multiple experiments during a day.

The issues regarding the person's cognitive processes, such as the person shifting his or her attention to another target without moving eyes (Henderson, 2003), need to be taken into account as well. We suggest combining thinking aloud with eye tracking to tackle this challenge.

Despite the many challenges of using eye-tracking systems in a mobile context, the method is valuable for gathering data that could not be reached by any other method: the data on a person's gaze objects in the present moment and indications of a person's problem-solving strategies.

The problematic issues presented in the study should be considered when preparing a test with an eye-tracking system in the wild. Some of the issues are easy to take into account. Some of the problems, such as the difficulties of defining areas of interest in 3D data, should be reacted to by the eye-tracking systems' manufacturers.

Contribution and My Role in It

I was part of an interest group of mobile map researchers from three different research units: the Helsinki Institute for Information Technology (HIIT), the Department of Cognitive Science of the University of Helsinki, and myself from University of Jyväskylä. Together, we shared knowledge and designed and ran multiple pilot tests on eye tracking in forests. I wrote this article together with Katja Irvankoski (Department of Cognitive Science of the University of Helsinki), with me taking the main responsibility of the writing. As Katja was located in Helsinki and I was in Jyväskylä, and the eye-tracking equipment was also part of the University of Jyväskylä's usability lab, I conducted the final experiments in the forests of Jyväskylä.

4.2 Article 2: Depth Perception in Tablet-Based Augmented Reality at Medium- and Far-Field Distances

Background and Motivation

When thinking about the future of mobile maps and the possibilities to answer the problematic questions of problems perceiving locations and directions while using mobile maps, I thought that one answer might lie in combining AR with mobile maps. I got a chance (thank you to the mobility grants of the University of Jyväskylä) to visit the University of South Australia and its Magic Vision Lab for two months to study this further.

In the research field of human depth perception, multiple studies on depth perception in virtual reality exist, but there are very few that have studied AR. AR systems fail to indicate distances. AR helps the user in paying attention to their real surroundings instead of only the device. There is a need to gain knowledge about AR's coping on distance perception to produce better AR-based mobile map applications.

The research task in this study was to compare depth perception between tablet-based AR and the real world. This was done by replicating and extending the research tasks and setting of Lappin, Shelton, and Rieser (2006).

Method

As in Lappin et al.'s (2006) study, field studies were conducted in different contexts with distance estimation tasks. The field studies, or user experiments to be more precise, consisted of distance estimation tasks in three contexts: in an open field, in a hallway, and on a frozen lake. We used two distances for the tasks: 15 and 30 metres away from the observers or users. In addition to conducting the experiment with an actual person in the real world as in Lappin et al.'s setting, we also developed a tablet-based AR application that presented a virtual person. Furthermore, we varied the presence of feedback about the location of the target person. We had a total of 20 observers in the experiments.

Main Findings

In every experimental situation, the distance estimations on 15 metres were more accurate, more precise, and slightly overestimated, and estimations on 30 metres were underestimated. In addition, we found a positive effect of given feedback at the 30-metre distance, but not at the 15-metre distance. From the results of this paper, much cannot be said yet: for tablet-based AR applications, results found at one distance will not necessarily predict the results at other distances. Hence, with practice and brief feedback of 20 minutes or less, performance on a depth-perception related task in tablet-based AR approaches real-world performance.

Contribution and My Role in It

This article was presented as a poster submission in one of the main conferences on the area of applied perception. It may not be typical to include a poster submission in a thesis, but as the later long version of the paper got a couple of rejections from the journals of the area, where the reviewers stated that, although the work is important and even pioneering for the research area, it may not be accepted, as the paper had already been published earlier in a conference, I find it reasonable to include the original poster submission in the thesis.

I was in charge of conducting all the experiments in the study. The designing of the research began with Dr Christian Sandor when I was a visiting researcher at the University of South Australia. We soon asked one of the best professors in the area, J. Edward Swan II from Mississippi State University, USA, to join us. I had several Skype calls with Dr Swan over several months as we discussed the most suitable research settings and the results. I was also in charge of the writing of the publication, but Sandor and Swan also took an important role in the commenting on and finishing of the article. I presented the study findings at the conference.

4.3 Article 3: Visually Perceived Distance Judgments: Tablet-Based Augmented Reality versus the Real World

Background and Motivation

For me, the goal of the user experiments about depth perception conducted in Australia and in Finland was to gain knowledge needed to discuss the possibilities and challenges of AR from the users' point of view. A small but needed step towards designing better AR map applications in the future was this study of user's perception of distances when using handheld AR. This is important to, for example, make applicable design solutions of presenting POIs over the AR view.

Besides reporting the results from the experiments in depth, we also wanted to deepen the common understanding of depth perception by compiling a thorough literature review of previous research in the field. Another important goal was to discuss this in the research community and publish these results in a long research paper. This research paper serves all of these goals. The article is a continuum for article II, both based on the same experiments, but this article is roughly 9,000 words longer and included a detailed data analysis and a thorough literature review.

Next, I will summarize the background research and motivation arising from it. Recently, a considerable number of AR applications for tablet computers and mobile devices has been developed. Also, the first AR applications combining map elements have been introduced (Kamilakis, Gavalas, & Zaroliagis, 2016; Morrison et al., 2009; Nurminen, Järvi, & Lehtonen, 2014). The current AR map and navigation applications are shown to have problems with supporting users' spatial perception (Rehrl et al., 2014). Although with maps it is easy to understand relative distances to POIs, this is more challenging with AR. The often critical use cases of map use lead to the need to research users' understanding of locations and distances in the context of AR maps.

Method

Besides doing the thorough literature review, we conducted two experiments. In experiment 1, observers saw unconnected AR objects, while in experiment 2 they saw connected AR objects. The first experiment was executed in summer in Australia and the second one in winter in Finland. In both experiments, we used an iPad as a basis for our AR system that was developed for these experiments. We had total of 20 participants in the experiments.

Lappin et al. (2006) previously conducted distance estimation tasks in a real-world setting. We closely replicated Lappin et al.'s (2006) work in tablet AR and real-world conditions. In the AR condition, we made the virtual targets unconnected to real-world locations by modifying Lappin et al.'s procedure: instead of the adjustment person walking both towards and away from the observer, the adjustment person only walked away from the observer.

Within each condition, participants judged targets at two distances, 15 and 30 metres, with two repetitions per distance. Before the second repetition, observers moved to a second location, in order to reduce reliance on environmental cues.

The purpose of experiment 1 was to study how visually perceived distance operates in tablet AR when a virtual target is unconnected to real-world locations. In experiment 1, we used two environmental conditions: an open field and a corridor. Each observer made 8 distance judgments: 2 conditions (AR, real) × 2 locations × 2 distances (30, 15 metres), which were counterbalanced and nested.

The purpose of experiment 2 was to study how visually perceived distance operates in tablet AR when a virtual target is connected to real-world locations. An additional purpose was to replicate experiment 1 in a new environment, with a slightly modified experimental method: the adjustment person walked both towards and away from the observer. Other than this change, we followed the same procedures as in experiment 1. We ran experiment 2 on a frozen lake, replicating the open field environment of experiment 1. Each observer made 16 distance judgments: 2 conditions (AR, real) × 2 locations × 2 distances (30, 15 metres) × 2 directions (away, towards), which were again counterbalanced and nested.

Main Findings

Besides the findings presented in the summary of article II: over both experiments, in the AR condition the pattern for constant error was that observers expanded midpoints at 15 metres and compressed them at 30 metres. Likewise, Bodenheimer et al. (2007) also found expanded midpoints at 15 metres and compressed midpoints at 30 metres for VR targets. Given how different the two virtual environments are—the head-mounted display (HMD) virtual reality that Bodenheimer et al. used and the tablet AR we used—the similarity of this pattern is striking. For virtual targets, both we and Bodenheimer et al. found more variable error at 30 metres than at 15 metres. Overall, these experiments suggest that observers are consistently 2 to 3% less precise when the target is virtual instead of real, and for virtual targets are about 2% less precise at 30 as opposed to 15 metres.

We conclude that perceived distance operates differently in tablet AR and the real world. The pattern of expanded midpoints at 15 metres and compressed midpoints at 30 metres can be explained by the geometry of virtual picture space and how that geometry is perceived. In addition, many previous studies have indicated that perceived pictorial distance is increasingly compressed as depicted distance increases (Cutting, 2003; Rogers, 1995), and this can explain the compression of midpoints at 30 meters in experiment 1.

The compression of virtual targets at 30 metres was only significant in experiment 1, when the targets were unconnected to real-world locations. In Experiment 2, the virtual targets were connected to real-world locations, and if observers therefore paid more attention to the real world relative to experiment 1, then this could explain why there was less compression at 30 metres in experiment 2.

Contribution and My Role in It

The results of this are a good step towards understanding the depth perception of AR users. The presented results are also a step towards helping the development of AR map applications to tackle the challenges of perceiving distances correctly, as the results inform AR application developers of the distortions in depth judgments that they can expect users to make.

To our knowledge, the literature review presented in the paper is the first thorough review in the AR field to consider the substantial previous work in picture perception. The novelty of the research is that this is the first to directly compare distance judgments of real and virtual objects in a tablet-based AR system.

The depth perception research has been very detailed, which it needs to be to fully confirm the results. This research is in the line of the similar previous studies concerning the research methodology and preciseness of data analysis and the level of detail when considering what can and what cannot be stated based on the results. It has been interesting to see the way of doing research work in this—not only user psychology-related, but overall psychology-related. As in the field of studying the use of ready-made or at least prototype-level information systems as typical in HTI, there is often no chance to go into very deep detail in the findings; it was challenging to work with such a deep level of details in this study.

But more than just seeing the way of doing research in the field of human depth perception, I have been allowed to do this work with one of the pioneers in the research field of human depth perception concerning virtual and augmented reality: Dr. J. Edward Swan II. Dr Swan is the first author of this paper.

Although the first motivation to conduct the study came from me and I was in charge of performing the experiments, the eminent experience and knowledge of Dr Swan in the field, as well as some personal boundary conditions of mine from life both in academia and outside it, turned the outcome to be that Dr Swan was kind enough to take the first author responsibility to write the paper. Dr Swan also compiled the data analysis with a great deal of respect towards all the details. Another great scientist and pioneer here was Dr Christian Sandor, whose expertise and experience is marvellous in the field of AR development. As reported already in the summary of article II, Dr Sandor made this whole study possible by taking me to work in his laboratory and by connecting me with Dr Swan. We had numerous discussions with Swan and Sandor in the design, execution, analysis, and writing phases of this study. A fourth person, without whom this study could not have been done, was the great programmer Scott Rapson. Rapson had the talent to code the pioneering AR application used in the study and also assisted me in conducting the experiments in Australia.

4.4 Article 4: Introducing Usability Heuristics for Mobile Map Applications

Background and Motivation

As stated in the Introduction part of the thesis, mobile map applications are not free of usability problems. Heuristic usability evaluation is a discount method for evaluating usability, as heuristic evaluation can be conducted with low resources in a short timeframe (Nielsen, 1992). Another advantage is that, besides usability professionals, non-professionals can also use the heuristic evaluation method to evaluate product usability with some success (Baker, Greenberg, & Gutwin, 2002).

The most common usability heuristics, the heuristics of Nielsen (1994), are often used to evaluate the usability of different kinds of applications, but as they are very general, they are not suitable for evaluating mobile map services. From the perspective of mobile map applications, they lack the aspects of location awareness, mobility and interruptions, and cartographic visual design. This is why novel domain-specific heuristics are needed for evaluating the usability of mobile map applications.

Method

The study was implemented in four phases. First, the generic usability heuristics (Nielsen, 1994) were explored and their limitations for evaluating the usability of mobile map applications was pointed out. Second, background research on some of the current domain-specific heuristics (Alsumait & Al-Osaimi, 2009; Jaferian, Hawkey, Sotirakopoulos, Velez-Rojas, & Beznosov, 2011; Pinelle, Wong, & Stach, 2008) and their development methods was performed, i.e., studying the content and the development methods of the previously presented heuristics. The third phase was to formulate the new heuristics. That was performed by deriving the initial usability heuristics from Nielsen's (1994) generic usability heuristics by using a conceptual-theoretical approach.

Finally, the applicability of the initial usability heuristics for mobile map applications was tested by four usability specialists who evaluated a mobile map application by completing specific map-related tasks (self-locating, searching addresses, exploring the map, wayfinding, and using POIs). Similar to Jaferian et al. (2011), half of the evaluators used the original Nielsen heuristics to perform the evaluation, and half used the new heuristics. In the evaluation, an application that was not familiar to the evaluators was used. After completing the evaluation, the evaluators were asked to rate the applicability of the heuristics for evaluating mobile map applications and the intelligibility of each of the heuristics.

Main Findings

We were the first to introduce usability heuristics for mobile map applications. The testing of the new heuristics (Kuparinen, Silvennoinen, et al., 2013) compared to the Nielsen (1994) heuristics pointed out that, with the new heuristics, more usability problems were found. Also, the suitability of the new heuristics was rated better than the Nielsen heuristics. The proposed heuristics also include in-depth insights into the heuristic evaluation of visual mobile map design.

The introduced heuristics are presented in TABLE 2.

TABLE 2 The usability heuristics for mobile map applications

Heuristic	Explanation
1. Visibility of the contextual map functions and important locations	The map application should always interact with the user by giving informative feedback within reasonable time. The map functions should be visible. The map view should constantly stay visible when the map application is in use.
2. Match between the system and the physical surroundings of the user	The map application should show clear indications of the user's location and other important locations (e.g., destinations and POIs) on the map. It is essential that the map corresponds in an understandable way with the physical surroundings of the user. The map should be up-to-date.
3. User control over map functions	Allow the user to take control of the map application when interruptions (from the mobile device: phone calls, message, other applications' notifications; from concrete surroundings: traffic, weather, traffic lights) happen. Allow multitasking.
4. Consistency and standards	Follow platform conventions in the user interface design. Be consistent within the use of interaction gestures, controls, functions, elements of user interface and map features. Use clear, intuitive, commonly known map symbols.

5. Error prevention	Make the map application free of errors. If errors still happen, be sure to offer the possibility to recover from them. Prevent the user from getting lost.
6. Recognition rather than recall	Minimize the user's memory load. Make sure that the main functions of the map application (e.g., exploring, route guidance, zooming, panning, POI selection) are easily accessible. Use short menu paths for the main functions or keep the main functions present all the time.
7. Flexibility, scalability, and efficiency of use	Offer flexible options for the main map functions. Allow the user to save locations to be used as shortcuts (e.g., home) and support POI information. Give easy access to additional information (metadata, links, user-generated content). Make sure the user interface is scalable for different screen sizes of mobile devices.
8. Balanced and simplistic visual design	Harmonious overall appearance should consist of clear contrast between visual elements, balanced layout, and informative colours. Visual elements should guide users gaze at important elements. Avoid visual clutter.
9. Recognizing, diagnosing, and recovering from errors	Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution. Indicate clearly the reasons for why the searched locations are not found. Save the user's previous searches for fast repetition.
10. Offering help	Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Provide both: fast guidance focused on the user's task and more detailed documentation with search functions. Pay attention to the understandability of the help.

Contribution and My Role in It

As this study was at the core of my research topic, I was in charge of the study and writing the paper. Johanna Silvennoinen took the role of the formulation of the heuristics that concerned the visual design. Hannakaisa Isomäki supervised the choices within the methodology.

4.5 Article 5: Validation and Extension of the Usability Heuristics for Mobile Map Applications

Background and Motivation

As stated in the article (Kuparinen, 2016), several usability heuristics for various different domains have been introduced. The domains that are close to mobile map applications include mobile computing (Bertini, Gabrielli, & Kimani, 2006), information visualization (Forsell & Johansson, 2010; Zuk, Schlesier, Neumann, Hancock, & Carpendale, 2006), web-based GIS (Komarkova, Visek, & Novak, 2007), and mobile devices (Machado Neto & Pimentel, 2013). Kuparinen et al. (2013) introduced the first usability heuristics for mobile map applications.

Hermawati and Lawson (2016) performed a comparison of the development processes of usability heuristics for various domains and summarized that over 30% of the 70 inspected heuristic development processes did not report any validation. To prove the effectiveness of heuristics, Hermawati and Lawson suggest that establishing heuristics should not stop at proposal. Although the Kuparinen et al. (2013) heuristics were tested by usability specialists by using the heuristics in comparison to Nielsen heuristics, a validation with higher amount of data was still needed. This validation is presented in this article.

Method

The research method consisted of three phases. At first, the previously introduced heuristics for mobile map applications (Kuparinen, Silvennoinen, et al., 2013) were used to evaluate four different map applications by 58 evaluators. In the evaluation, the evaluators performed predefined tasks that are typical of mobile map applications. Three of the evaluated applications were mobile map applications, and one was an Internet browser-based map application used with a computer. The evaluated application was chosen by each evaluator. Some 28% of the evaluators used an application that was used with a computer, and 72% used a mobile application. The amount and severity of the found problems were analysed.

Second, the evaluators filled in a questionnaire about the understandability of each of the heuristics, and these data were analysed. There was also a opportunity to make comments on each of the heuristics. Although it was voluntary to fill in this questionnaire, 41 evaluators took part. Third, the heuristics were further developed on the basis of the findings.

Main Findings

In this article, I validated the previously introduced usability heuristics and extended and reformatted them to better find the usability problems of mobile map services.

A total of 903 usability problems was reported in the evaluation reports. Heuristics 1 (visibility of the contextual map functions and important locations) and 7 (flexibility, scalability, and efficiency of use) were most efficient for finding the problems, and heuristics 3 (user control over map functions) and 8 (balanced and simplistic visual design) were in use to find the least amount of problems. The most critical problems were found with heuristics 2 (match between the system and the physical surroundings of the user), 3 (user control over map functions), 5 (error prevention), and 9 (recognizing, diagnosing, and recovering from errors). Although the least severe problems were found with heuristics 6 (recognition rather than recall) and 8 (balanced and simplistic visual design), these heuristics cannot be seen as totally useless, as the percentage of found major or catastrophic problems was still over 30%.

There was only small amount of usability problems that were not categorized under any of the heuristics and any of the assigned tasks. This indicates two conclusions. First, the heuristics seem to work well in finding usability problems. Second, the tasks seem to be adequate for pointing out problems. It is still noteworthy that there were some usability problems that were not categorized under any of the tasks, and these problems were mostly related to the outlook, colour, and aesthetics of the application. This leads to a conclusion that the evaluation of the overall aesthetics of the UI should always be part of the heuristic usability evaluation even though it would not be a part of the actual tasks.

As there was an equal amount of usability problems found per user with both mobile and browser-based map application, it is probable that most of the heuristics work sufficiently with map applications that are used in a stationary manner with browser-based applications.

As the usability analysis was conducted for a total of four different applications, the information about the suitability and understandability of the heuristics became clear in the analysis phase. The overall understandability of the heuristics was good based on the questionnaire: a mean of 4.0 on a scale from 1 (very difficult to understand) to 5 (very well understood). The heuristics that were the most difficult to understand were numbers 7 (flexibility, scalability, and efficiency of use) and 9 (recognizing, diagnosing, and recovering from errors). Problems understanding some of the heuristics were pointed out in the verbal reports. As the heuristics are also supposed to be used by non-usability professionals, it is essential that the evaluators understand the heuristics and their terminology correctly. Based on the evaluators' comments of understandability, it is preferable to also have an "other problems" section in the heuristic evaluation form.

Many problems (a total of 166, or 18% of the overall amount) were marked as breaking multiple heuristics. Especially common were the combinations of heuristics 1 and 6 (overlapping 23 times) and 6 and 7 (overlapping 17 times). This finding indicates a need to clarify the difference of these overlapping heuristics. The overlapping of heuristics 5 and 9 was also reported in the verbal reports, so these heuristics needed special attention in the formulation of the updated heuristics.

To make the heuristics clearer, verbs were included in the titles of the heuristics. To avoid the overlapping that was realized with the tested heuristics, the heuristic titles were detailed, and descriptions were updated. Two more heuristics were added in the simplification phase of the contents of the previous heuristics. The heuristics were also reorganized to have similar but differing heuristics consecutive to each other in order to make the understanding of the differences easier.

The validated and extended new heuristics are presented inTABLE 3.

TABLE 3 The new usability heuristics for mobile map applications (vol. 2)

Heuristic	Explanation
1. Match the map and the physical surroundings	To prevent the user from getting lost, the map application should show clear indications of the user's location and other important locations (e.g., destinations and Point-of-Interests, POIs). It is essential that the map corresponds in an understandable way with the physical surroundings of the user. The map should be up-to-date.
2. Keep the map visible when needed	The map view should stay visible as often as possible when the user is actively using the application, and especially when there is a need for critical navigation guidance. If there is advertisement shown in the application, keep it away from covering any critical parts of the user interface or map view.
3. Keep the important functions easily accessible	Make sure that the main map functions (e.g., exploration, search, wayfinding) are easily accessible. Use short menu paths for the main functions or keep the main functions present all the time. Make it clear which part or function of the user interface is currently used.
4. Offer shortcuts for locations	Minimize the user's memory load by allowing the use of shortcuts for important locations (e.g., home, previous searches, addresses from contact book). Support the use of POIs. Give easy access to additional information (metadata, links, user-generated content).
5. Allow multitasking and interruptions	Allow the user to take control of the map application when interruptions (from the mobile device: phone calls, messages, notifications, etc.; or from the concrete surroundings: traffic, having a break in a café, bad weather, etc.) happen. Allow multitasking and keep it easy to return to the last state of the map application after the use of other applications.
6. Prefer commonly used graphical and functional design solutions	Use well-known design solutions in the user interface if you do not have a new solution that is strongly proven to be intuitive. Be consistent within the use of interaction gestures (e.g., zooming and panning), controls, functions, elements of user interface and map features in different parts of the application. Use clear, intuitive, commonly known map symbols (e.g., arrows for directions, magnifying glass for search, plus and minus for zoom).
7. Consistently use understandable terminology	Avoid the use of special terminology. Make sure to use the same words with same meanings in different parts of the application. Use the language that is preferred by the user.
8. Prevent errors and recover from them	Make the map application free of errors. If errors still happen, be sure to offer the possibility to recover from them easily.
9. Recognize errors and clearly inform the user of them	When errors happen, the error messages should be expressed in plain language (error codes only behind a

	link), precisely indicate the problem, and constructively suggest a solution. Indicate clearly the reasons for why the searched locations are not found.
10. Provide flexibility, adaptability, and scalability	The application should interact with the user by giving informative feedback within a reasonable time. The application needs to adapt to different use cases (e.g., pedestrian navigation in a forest, driving). Make sure the user interface is scalable for different screen sizes. Let the user adjust the power saving options to lengthen the device's battery life.
11. Follow a balanced and simplistic visual design	Use clear contrast between visual elements, a balanced layout, and informative colours (map: forests as green etc., user interface: alarms as red). Visual elements should guide users' gaze to important elements. Avoid visual clutter.
12. Offer help	Even though it is better if the system can be used without documentation, it is necessary to provide help and documentation. Provide fast guidance focused on the user's task and more detailed documentation with search functions. Pay attention to the understandability of the help.

The new, validated, and extended usability heuristics are supposed to be widely usable in the development of mobile map applications.

Contribution and My Role in It

I was the only author of this paper. My previous co-authors, Hannakaisa Isomäki and Johanna Silvennoinen, however, helped me in the design of the data collection. The actual data collection, the wide analysis of data, and the paper writing were all done by me.

4.6 Answers to the Research Questions

The main research question for this thesis was: How can we support users' location awareness with mobile map applications? To answer this, I have gone through a wide variety of previous research and conducted many studies myself in cooperation with my colleagues. Also, the answer to my main research question is presented in the following answers to my sub-questions.

The first sub question was: "Why do people get lost even when having a mobile map application along?" This question was answered in the literature review of the thesis. People get lost for several reasons: because of the map application's insufficient support for human spatial abilities; because of not taking the user, use context, or user's tasks properly into account; or because of making the user trust too much in the mobile map application and not paying enough attention to their physical surroundings. Often, the reason for the map service not matching with user needs is in the service design process; UCD methods have not been used properly.

The second sub-question was: "What are the best practices to support navigation?" The answers to this question were formulated on the basis of the findings of the previous research. Several solutions were suggested: using context awareness in mobile map services, using adequate and well-presented landmarks in maps, taking steps towards AR with map use to support the user maintaining attention to their physical surroundings, using multimodal feedback in the interaction between the map service and the user, making use of user-generated content to make the UX of map services more personal and memorable, and following the presented design guidelines and other research-based design suggestions.

The third sub-question was: "How can we research what the important objects in the natural environment are that should be emphasized in mobile maps?" As a one possible solution to this question, I studied the eye-tracking research method (article I), and with my colleagues, I conducted several experiments with the method in forests. We found still-existing challenges especially with the technical issues of the eye-tracking equipment. Still, we suggest that eye tracking could be a suitable method to research what the important objects are that should be emphasized in mobile maps. The method is best used as a mixed-method approach, together with other methods, such as thinking aloud, to validate the results of eye-tracking data.

The fourth sub question was: "How can we prevent the user from focusing on the map service at the expense of perceiving their location in the real environment?" As a possible solution, I suggested beginning to examine the possibilities of AR combined with mobile maps (articles II and III). My hypothesis was that, when the view on the screen shows the map objects together with the real-world view, the user would pay more attention to the real world. To find the answer to this hypothesis, much more user research is needed with various different implementations of the combination of mobile maps and AR. Although I was not able to find validated answers to this research question, a step towards designing AR objects to fulfil the human distance perception was taken.

The fifth and the last sub-question was: "What would a good mobile map application be like concerning the usability and user experience?" This question was answered partly in the literature review of the thesis, but my main contribution to answering this was the formulation and introduction of (article IV) and validation and extension (article V) to the usability heuristics for mobile map applications. A good mobile map application concerning usability and the UX is suitable to the intended tasks of the user, is easily learnt and easy to remember, is efficient and comfortable to use, and contains very few errors. The map view of it matches well, in an understandable manner, with the user's physical surroundings. The map view also stays visible when there is a need for navigational guidance. The main map functions are easily accessible, and the user interface will not disturb the user, but supports completing the user's tasks. It offers shortcuts to important functions and locations and easy access to additional data on locations if needed. It allows interruption by other applications of the device and by the user's surroundings. The design solutions and map symbols are natural and comfortable to the user, and the supported interaction gestures are intuitive to use. The used language and terminology are understandable. The application is free of errors, and the reasons for searched locations not being found are reported clearly. It interacts with the user with no delays, and it adapts to different use cases. The map view is scalable, and power-saving options exist. The visual layout is balanced and informative, and finally, the application provides help when the user needs it.

To sum up, I can state that the main research question of the thesis is answered from different perspectives in the above-presented answers to the subquestions. I will still open this a bit more with overall answers to my main research question. I state that users' location awareness may be supported by many technical and design-based solutions as well as taking user-centred design approach as part of the development process.

Augmented reality is one possibility to keep users paying attention to the real world and through that, to stay aware of their location. Still, as it is more difficult for the users to perceive distances correctly when using augmented reality versus real world, there is a need for more research to support the presentation of location information in augmented reality.

Other solutions to support user's location awareness are, e.g., using multimodal interaction techniques and making use of user-generated content to make the user experience of application more personal and locations memorable.

There are also dozens of design recommendations presented in the previous research and in the usability heuristics I introduce in this thesis, and following these is needed to support users' location awareness. These recommendations include, e.g., taking into account the changes in the scenery between different seasons when choosing which landmarks to show in the map (e.g., snow in wintertime may hide small landmarks), making the map view scalable for different screen sizes and preparing for interruptions that are typical in mobile use.

To continue with answering the main research question, when the development of mobile map services is conducted with user-centred design approach, it is more probable that the applications will support users' location awareness than without it. One good method to be used in this approach is eye-tracking, which is valuable method for studying users' areas of interest while navigating and self-locating. This information is needed to understand what are the objects that need to be shown on the map applications. When used in the later phases of design and development process, when there is already a map application or prototype of it to test, eye-tracking together with other methods, such as thinking aloud, may also open the user experience.

The new usability heuristics for mobile map applications are profitable to evaluate the map application and to further develop it. Through that, the usability issues are to be found. A mobile map application providing good usability and good user experience, supports users' location awareness.

5 DISCUSSION

This doctoral thesis discusses the topic of designing and evaluating UIs of mobile map applications from the viewpoint of supporting users' location awareness.

The thesis has four different parts. First, in the Introduction, the topic is discussed and oriented on the basis of the previous research.

The second part is about examining a novel research method, eye tracking, as a method to use in mobile map application development. This part is presented in the first included article of the thesis.

The third part of the thesis is present in articles two and three, and when it concerns human depth perception in AR, from the more practically oriented point of view offers indications for designing and locating POIs in a possible future field: mobile maps with AR.

The fourth part of the thesis is articles four and five, introducing, validating, and further developing the usability heuristics for mobile map applications. This fourth part is probably the part that is most usable as-is in the hands-on development of mobile map applications, as it offers the most easily applicable and wide recommendations for the development and evaluation of mobile map applications.

Personally, I am satisfied that this thesis has given me a chance to process my thesis topic from different perspectives, with different UCD research methods and with researchers from varied backgrounds. The four parts of this thesis vary from each other, but handling all those different perspectives and different research methods has taught me much. From this point of view, besides this thesis extending the common research-based knowledge of designing mobile map applications, in my opinion, it also works well as a doctoral student's thesis when it has offered me a view of such a wide variety of research methods and backgrounds.

After all, it is evident that this thesis has deficiencies as does every research bid has. Perhaps the main issue is that when the topic is approached from these different viewpoints of sub-studies highly differing with each other, the package is not as tight as it could ideally be. The presented work also may arise a question about why there were no follow-up studies about eye-tracking. Why the eye-tracking method was not used to study what are the important landmarks and other areas of interest users use to navigate and locate themselves in natural environments. That would have been important study, but that was not conducted due to the problems to get access to the proper eye-tracking equipment. It would also have been good to publish the usability heuristics in a journal paper to possibly to bring them to the awareness of more scientists and practitioners working in the field.

5.1 The Future of Mobile Map Services

As a conclusion to this thesis, I state that, although there are problems concerning the usability and UX of mobile map applications, the field has received increasing amounts of research interest towards it, and this ensures that mobile map applications will get better from the user point-of-view.

It is impossible to state how the spectrum of mobile map applications will change in the future. Some educated guesses can be made, however. It is probable that there will be new solutions to the UIs of mobile map applications. As the use of virtual and augmented reality has become more popular in recent years, with the first examples of AR within in-vehicle navigation systems (Kim & Dey, 2009; Medenica, Kun, Paek, & Palinko, 2011; Narzt et al., 2006; Rao, Tropper, Grunler, Hammori, & Chakraborty, 2014; Yamaguchi et al., 2007), it is probable that, in the future, AR will be combined more often with mobile maps and mobile maps used by pedestrians. Up to this point, there have not been many thorough applications presented, but many first ideas and models towards them have been introduced (Mulloni et al., 2011; Narzt et al., 2006; Reitmayr & Schmalstieg, 2003).

Besides AR, the other future trends of mobile map applications may be the utilization of multimodal and especially audio and haptic feedback and overall interaction in mobile map applications. Besides serving visually impaired users, they also free the user’s resources for his or her actual tasks. Magnusson et al. (2009) presented a roadmap of mobile maps and location-based services for the future, together with introducing their then-starting project. They believed in utilizing haptic and auditory channels more in the future. Besides that, they emphasized the need for better finding out user needs, what the users want, and when they want it. The third challenge Magnusson et al. recognized is the need to “understand that accessibility is for ‘us’ not for ‘them’” (p. 3). They remind us that everyone may experience problems with seeing or cognitively processing complex information.

Beinat and Steenbruggen (2009) approached future scenarios from the point of view of location awareness. They name a list of future trends, such as increased availability of personalized and intelligent services, public and business services (such as emergency calls) requiring location, and governments beginning to regulate services due to privacy and security reasons, as with the spread of Internet of Things (IoT). These are interesting views that will have an effect on the development of mobile map applications.

The use of mobile map applications has increased dramatically in recent years, and most probably will increase in the future, particularly relative to the use amount, user amount, and amount of use cases. Therefore, the input of this thesis is important for the future development of user-friendly mobile map services.

YHTEENVETO (FINNISH SUMMARY)

Motivaatio tälle väitöskirjatutkimukselle nousee siitä ongelmasta, että ihmiset tapaavat eksyä ympäristössään. Tämän on todettu tapahtuvan yhtä lailla kartan kanssa kuin ilmankin karttaa, ja yhtä lailla perinteisen paperikartan kuin myös mobiililaitteella käytettävän, automaattisesti sijainnin osoittavan kartan kanssa.

Syyt eksymisiin löytyvät ihmisen kognitiivisista ja erityisesti tilan kognitiiviseen havainnointiin liittyvistä kyvyistä. Mobiililaitteiden ja mobiilikarttapalveluiden on tarkoitus tukea käyttäjää sijaintinsa hahmottamisessa ja navigoinnissa, mutta mistä johtuu, että eksymistä tapahtuu myös mobiilikarttapalveluita käytettäessä? Aiempi tutkimus osoittaa tähän syiksi mobiililaitteiden ja mobiilikarttapalveluiden käytettävyysongelmat; esimerkiksi sen, että kartta ja reaalimaailma eivät vastaa ymmärrettävällä tavalla toisiaan, mobiilikarttapalvelun käyttöliittymä on sekava tai käytetyt karttaobjektit käyttäjälle vieraita. Usein palvelua suunniteltaessa ei ole myöskään osattu ottaa huomioon käyttäjien erilaisia ominaisuuksia tai tarpeita, kuten rajoitteita liikkumisessa tai näkemisessä, tai ympäristön luomia haasteita, kuten kiirettä, liikenteen melua tai useiden samanaikaisten tehtävien suorittamista. Mielenkiintoinen seikka on sekin, että toisinaan käyttäjä voi luottaa mobiilikarttapalvelun antamaan opastukseen niin vahvasti, että unohtaa kiinnittää huomiota ympäristöönsä. Tällöin käyttäjä ei tule tietoiseksi ympäristöstään ja eksyy esimerkiksi mobiililaitteen akun loppuessa kesken.

Tässä väitöskirjatutkimuksessa olen tarttunut eksymisen haasteeseen siitä näkökulmasta, kuinka mobiilikarttapalveluista voisi tehdä parempia niin, että ne tukisivat käyttäjänsä sijaintitietoisuutta mahdollisimman hyvin. Olen lähestynyt aihetta sekä laajan kirjallisuuskatsauksen, että useiden empiiristen tutkimusten kautta. Empiirisissä tutkimuksissa olen käyttänyt useita käyttäjäkeskeisen suunnittelun ja ihmisen ja teknologian välisen vuorovaikutuksen tutkimuksen metodeita: käyttäjäkokeita kenttäolosuhteissa, silmänliiketutkimusta, heuristista käytettävyyden arviointia, kyselyjä ja haastatteluja.

Esitän useita ratkaisuja eksymisen ongelmaan ja käyttäjän sijaintitietoisuuden tukemiseen. Ensinnäkin mobiilikarttapalveluiden tulee olla kontekstitietoisia ja sopeutua kulloiseenkin käyttötilanteeseen. Käyttäjälle oleelliset maamerkit täytyy näyttää kartalla. Karttapalvelun ja käyttäjän välisessä vuorovaikutuksessa tulee käyttää muitakin kuin visuaalisia keinoja; usein tunto- tai äänipalaute sopii paremmin tiedon välittämiseen kuormittuneessa käyttötilanteessa. Käyttäjien itsensä karttapalveluun luoma sisältö vahvistaa sijantien merkittävyyttä ja huomion kiinnittämistä ympäristöön. Luonnollisesti myös aiemmasta tutkimuksesta nousseita karttapalveluiden toteuttamisen suuntaviivoja on syytä noudattaa.

Yhtenä mielenkiintoisena mahdollisena ratkaisuna esitän lisätyn todellisuuden hyödyntämistä karttatiedon esittämisen yhteydessä. Oletan, että karttapalvelun esittäessä sijainti- ja suuntatietoa ja navigointiohjeita reaalimaailman näkymän päällä tai yhteydessä, käyttäjä kiinnittäisi ympäristöönsä enemmän huomiota kuin vain karttanäkymää katsoessaan. Tämän hypoteesin testaamiseen tarvitaan kuitenkin vielä paljon lisää käyttäjäkeskeistä tutkimusta erilaisten lisättyä todellisuutta ja karttapalveluja yhdistävien ratkaisuiden parissa. Lisätyn todellisuuden parissa tekemieni kokeiden perusteella näyttää myös siltä, että etäisyyksien hahmottaminen lisättyä todellisuutta käytettäessä on käyttäjälle vaikeampaa kuin reaalimaailmassa. Näin ollen tarvitaan myös lisää kehitystyötä, jotta lisätyn todellisuuden kohdalla objektit opitaan näyttämään siten, että ne tukevat käyttäjää paremmin sijainnin hahmottamisessa.

Osana väitöskirjaani esittelen käytettävyysheuristiikat mobiilikarttapalveluille. Näitä heuristiikkoja voi käyttää mobiilikarttapalveluiden kehittämisprosessissa joko itsenäisenä kehittämisen ja testauksen apuvälineenä tai yhdessä muiden käyttäjäkeskeisen suunnittelun metodien kanssa.

REFERENCES

Abd Hamid, N. N., & Edwards, A. D. N. (2013). Facilitating route learning using interactive audio-tactile maps for blind and visually impaired people. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (pp. 37–42). ACM Press. https://doi.org/10.1145/2468356.2468364

Abowd, G. D., Atkeson, C. G., Hong, J., Long, S., Kooper, R., & Pinkerton, M. (1997). Cyberguide: A mobile context ‐ aware tour guide. *Wireless Networks*, *3*(5), 421–433.

Albert, G., Virág, I., Dávid, K., Csaba, S., & Dávid, V. (2016). Testing the Map Reading Skills of University Students. In B. T. & M. Konecny (Eds.), *Proceedings, 6th International Conference on Cartography and GIS* (pp. 188–199). Albena, Bulgaria.

Alsumait, A., & Al-Osaimi, A. (2009). Usability heuristics evaluation for child e-learning applications. In *Proceedings of the 11th International Conference on Information Integration and Web-based Applications & Services* (pp. 425–430). New York, NY, USA: ACM. https://doi.org/10.1145/1806338.1806417

Azuma, R. T. (1997). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385.

Baker, K., Greenberg, S., & Gutwin, C. (2002). Empirical development of a heuristic evaluation methodology for shared workspace groupware. In *Proceedings of the 2002 ACM conference on Computer supported cooperative work* (pp. 96–105). New York, NY, USA: ACM. https://doi.org/10.1145/587078.587093

Beinat, E., & Steenbruggen, J. (2009). Location Awareness 2020: Addressing Auto-identification and Location in the 2020s. In H. J. Scholten, R. Velde, & N. Manen (Eds.), *Geospatial Technology and the Role of Location in Science* (Vol. 96, pp. 31–45). Dordrecht: Springer Netherlands. Retrieved from http://www.springerlink.com/index/10.1007/978-90-481-2620-0_3

Bertini, E., Gabrielli, S., & Kimani, S. (2006). Appropriating and assessing heuristics for mobile computing. In *Proceedings of the working conference on Advanced visual interfaces* (pp. 119–126). New York, NY, USA: ACM. https://doi.org/10.1145/1133265.1133291

Bodenheimer, B., Meng, J., Wu, H., Narasimham, G., Rump, B., McNamara, T. P., … Rieser, J. J. (2007). Distance estimation in virtual and real environments using bisection. In *Proceedings of the 4th symposium on Applied perception in graphics and visualization* (pp. 35–40). ACM Press. https://doi.org/10.1145/1272582.1272589

Bolla, R., Giribaldi, M., Khan, R., & Repetto, M. (2013). Smart proxying: An optimal strategy for improving battery life of mobile devices (pp. 1–6). Presented at the International Green Computing Conference (IGCC), Arlington, VA: IEEE. https://doi.org/10.1109/IGCC.2013.6604478

Borrego-Jaraba, F., Luque Ruiz, I., & Gómez-Nieto, M. Á. (2011). A NFC-based pervasive solution for city touristic surfing. *Personal and Ubiquitous Computing*, *15*(7), 731–742. https://doi.org/10.1007/s00779-010-0364-y

Bourges-Waldegg, P., & Scrivener, S. A. R. (1998). Meaning, the central issue in cross-cultural HCI design. *Interacting with Computers*, *9*(3), 287–309. https://doi.org/10.1016/S0953-5438(97)00032-5

Bouwer, A., Nack, F., & El Ali, A. (2012). Lost in navigation: evaluating a mobile map app for a fair. In *Proceedings of the 14th ACM international conference on Multimodal interaction* (pp. 173–180). ACM Press. https://doi.org/10.1145/2388676.2388712

Brewster, S. (2002). Overcoming the Lack of Screen Space on Mobile Computers. *Personal and Ubiquitous Computing*, *6*(3), 188–205. https://doi.org/10.1007/s007790200019

Burigat, S., & Chittaro, L. (2007). Geographical Data Visualization on Mobile Devices for Useer's Navigation and Decision Support Activites. In A. Belussi, B. Catania, E. Clementini, & E. Ferrari (Eds.), *Spatial Data on the Web - Modeling and Management* (pp. 261–284). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-540-69878-4_12

Carlson, L. A., Holscher, C., Shipley, T. F., & Dalton, R. C. (2010). Getting Lost in Buildings. *Current Directions in Psychological Science*, *19*(5), 284–289. https://doi.org/10.1177/0963721410383243

Chen, S., Wang, Y., & Pedram, M. (2014). Optimal offloading control for a mobile device based on a realistic battery model and semi-Markov decision process (pp. 369–375). IEEE. https://doi.org/10.1109/ICCAD.2014.7001378

Cheverst, K., Smith, G., Mitchell, K., Friday, A., & Davies, N. (2001). The role of shared context in supporting cooperation between city visitors. *Computers & Graphics*, *25*(4), 555–562. https://doi.org/10.1016/S0097-8493(01)00083-8

Chittaro, L., & Burigat, S. (2004). Location-aware visualization of a 3D world to select tourist information on a mobile device. In *Proceedings of the 3rd International Workshop on HCI in Mobile Guides*. Glasgow, UK.

Chittaro, L., & De Marco, L. (2004). Driver Distraction Caused by Mobile Devices: Studying and Reducing Safety Risks. In *Proceedings of International Workshop on Mobile Technologies and Health: Benefits and Risks* (pp. 1–19). Udine, Italy: University of Udine.

Chittaro, L., & Nadalutti, D. (2008). Presenting evacuation instructions on mobile devices by means of location-aware 3D virtual environments. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services* (pp. 395–398). ACM Press. https://doi.org/10.1145/1409240.1409297

Christou, C. G., & Bülthoff, H. H. (1999). View dependence in scene recognition after active learning. *Memory & Cognition*, *27*(6), 996–1007. https://doi.org/10.3758/BF03201230

Cope, M. (2015). Commentary: Geographies of digital lives: Trajectories in the production of knowledge with user-generated content. *Landscape and Urban Planning*, *142*, 212–214. https://doi.org/10.1016/j.landurbplan.2015.08.009

Crabtree, A., Chamberlain, A., Grinter, R. E., Jones, M., Rodden, T., & Rogers, Y. (2013). Introduction to the Special Issue of 'The Turn to The Wild'. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *20*(3), 1–4. https://doi.org/10.1145/2491500.2491501

Curran, K., Furey, E., Lunney, T., Santos, J., Woods, D., & McCaughey, A. (2011). An evaluation of indoor location determination technologies. *Journal of Location Based Services*, *5*(2), 61–78. https://doi.org/10.1080/17489725.2011.562927

Cutting, J. E. (2003). Reconceiving perceptual space. In Heiko Hecht, Robert Schwartz, & Margaret Atherton, *Looking into pictures: An interdisciplinary approach to pictorial space* (pp. 215–238). Cambridge, MA, US: MIT Press.

Darken, R. P., & Cevik, H. (1999). Map usage in virtual environments: orientation issues. In *Proceedings IEEE Virtual Reality* (pp. 133–140). Houston, TX, USA. https://doi.org/10.1109/VR.1999.756944

Darken, R. P., & Durost, R. (2005). Mixed-dimension interaction in virtual environments. In *Proceedings of the ACM symposium on Virtual reality software and technology - VRST '05* (pp. 38–45). Monterey, CA, USA. https://doi.org/10.1145/1101616.1101625

Darken, R. P., & Goerger, S. R. (1999). The Transfer of Strategies from Virtual to Real Environments: An Explanation for Performance Differences? In *Proceedings of Virtual Worlds and Simulations* (pp. 159–164).

Darken, R. P., & Sibert, J. L. (1993). A toolset for navigation in virtual environments. In *Proceedings of the 6th annual ACM symposium on User interface software and technology - UIST '93* (pp. 157–165). Atlanta, Georgia, United States. https://doi.org/10.1145/168642.168658

Darken, R. P., & Sibert, J. L. (1996). Wayfinding strategies and behaviors in large virtual worlds. In *Proceedings of the SIGCHI conference on Human factors in computing systems common ground - CHI '96* (pp. 142–149). Vancouver, British Columbia, Canada. https://doi.org/10.1145/238386.238459

Davies, C., & Peebles, D. (2010). Spaces or Scenes: Map-based Orientation in Urban Environments. *Spatial Cognition & Computation*, *10*(2–3), 135–156. https://doi.org/10.1080/13875861003759289

Dearman, D., Inkpen, K. M., & Truong, K. N. (2008). Mobile map interactions during a rendezvous: exploring the implications of automation. *Personal and Ubiquitous Computing*, *14*(1), 1–13. https://doi.org/10.1007/s00779-008-0195-2

Delikostidis, I., van Elzakker, C. P. J. M., & Kraak, M.-J. (2016). Overcoming challenges in developing more usable pedestrian navigation systems. *Cartography and Geographic Information Science*, *43*(3), 189–207. https://doi.org/10.1080/15230406.2015.1031180

Dey, A. K. (2001). Understanding and Using Context. *Personal and Ubiquitous Computing*, (5), 4–7.

Downs, R. M., & Stea, D. (Eds.). (1973). *Image and Environment. Cognitive mapping and spatial behavior*. Chicago: Aldine Publishing Company.

Duchowski, A. T. (2007). *Eye tracking methodology theory and practice*. New York; London: Springer.

Duckham, M., Winter, S., & Robinson, M. (2010). Including landmarks in routing instructions. *Journal of Location Based Services*, *4*(1), 28–52. https://doi.org/10.1080/17489721003785602

Dünser, A., Grasset, R., & Billinghurst, M. (2008). A survey of evaluation techniques used in augmented reality studies (pp. 1–27). New Zealand: Human Interface Technology Laboratory. https://doi.org/10.1145/1508044.1508049

Edwardes, A., Burghardt, D., & Weibel, L. (2003). WebPark - Location Based Services for Species Search in Recreation Area. In *Proceedings of the 21st International Cartographic Conference (ICC)* (pp. 1012–1021). Durban, South Africa.

Elvins, T. T. (1997). VisFiles: virtually lost in virtual worlds---wayfinding without a cognitive map. *ACM SIGGRAPH Computer Graphics*, *31*(3), 15–17. https://doi.org/10.1145/262171.262177

ESRI. (2016). GIS Dictionary. Retrieved from http://support.esri.com/sitecore/content/support/Home/other-resources/gis-dictionary

Evans, G. W., Marrero, D. G., & Butler, P. A. (1981). Environmental Learning and Cognitive Mapping. *Environment and Behavior*, *13*(1), 83–104. https://doi.org/10.1177/0013916581131005

Evans, G. W., Smith, C., & Pezdek, K. (1982). Cognitive Maps and Urban Form. *Journal of the American Planning Association*, *48*(2), 232–244. https://doi.org/10.1080/01944368208976543

Evans, K. M., Jacobs, R. A., Tarduno, J. A., & Peiz, J. B. (2012). Collecting and Analyzing Eye-Tracking Data in Outdoor Environments. *Journal of Eye Movement Research*, *5*(2), 6,1-19.

Fallah, N., Apostolopoulos, I., Bekris, K., & Folmer, E. (2013). Indoor Human Navigation Systems: A Survey. *Interacting with Computers*, *25*(1), 21–33. https://doi.org/10.1093/iwc/iws010

Ferroni, M., Cazzola, A., Matteo, D., Nacci, A. A., Sciuto, D., & Santambrogio, M. D. (2013). MPower: gain back your android battery life! In *Proceedings of the 2013 ACM conference on Pervasive and ubiquitous computing adjunct publication UbiComp '13 Adjunct* (pp. 171–174). ACM Press. https://doi.org/10.1145/2494091.2494147

FitzGerald, E. (2012). Creating user-generated content for location-based learning: an authoring framework: Creating user-generated content for location-based learning. *Journal of Computer Assisted Learning*, *28*(3), 195–207. https://doi.org/10.1111/j.1365-2729.2012.00481.x

Forsell, C., & Johansson, J. (2010). An heuristic set for evaluation in information visualization. In *Proceedings of the International Conference on Advanced Visual Interfaces* (pp. 199–206). New York, NY, USA: ACM. https://doi.org/10.1145/1842993.1843029

Fröhlich, P., Oulasvirta, A., Baldauf, M., & Nurminen, A. (2011). On the move, wirelessly connected to the world. *Communications of the ACM*, *54*(1), 132–138. https://doi.org/10.1145/1866739.1866766

Gable, G. G. (1994). Integrating case study and survey research methods: an example in information systems. *European Journal of Information Systems*, *3*(2), 112–126. https://doi.org/10.1057/ejis.1994.12

Genovese, E., Cotteret, G., Roche, S., Caron, C., & Feick, R. (2009). Evaluating the socio-economic impact of Geographic Information: A classification of the literature. *International Journal of Spatial Data Infrastructures Research*, *4*, 218–238.

Ghiani, G., Paternò, F., Santoro, C., & Spano, L. D. (2009). UbiCicero: A location-aware, multi-device museum guide. *Interacting with Computers*, *21*(4), 288–303. https://doi.org/10.1016/j.intcom.2009.06.001

Golledge, R. G., & Stimson, R. J. (1997). *Spatial Behavior. A Geographic Perspective*. New York: The Guilford Press.

Goodman, J., Gray, P., Khammampad, K., & Brewster, S. (2004). Using Landmarks to Support Older People in Navigation. In S. Brewster & M. Dunlop (Eds.), *Mobile Human-Computer Interaction - MobileHCI 2004* (Vol. 3160, pp. 38–48). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/978-3-540-28637-0_4

Groundspeak, Inc. (2016). *Geocaching*.

Hagen, P., Robertson, T., Kan, M., & Sadler, K. (2005). Emerging research methods for understanding mobile technology use. In *OZCHI '05 Proceedings of the 17th Australia conference on Computer-Human Interaction: Citizens Online: Considerations for Today and the Future* (pp. 1–10). Australia: Computer-Human Interaction Special Interest Group (CHISIG) of Australia Narrabundah.

Hampe, M., & Elias, B. (2004). Integrating Topographic Information and Landmarks for Mobile Applications. In G. Gartner (Ed.), *Location Based Services and Telecartography, Proceedings of the Symposium 2004, Geowissenschaftliche Mitteilungen, Nr. 66* (pp. 147–155). TU Wien.

Harrison, R., Flood, D., & Duce, D. (2013). Usability of mobile applications: literature review and rationale for a new usability model. *Journal of Interaction Science*, *1*(1), 1–16. https://doi.org/10.1186/2194-0827-1-1

Harrower, M., & Sheesley, B. (2005). Designing Better Map Interfaces: A Framework for Panning and Zooming. *Transactions in GIS*, *9*(2), 77–89. https://doi.org/10.1111/j.1467-9671.2005.00207.x

Hart, R. A., & Moore, G. T. (1973). The development of spatial cognition: a review. In R. M. Downs & D. Stea, *Image and Environment. Cognitive mappig and spatial behavior*. Aldine Publishing Company.

Hatfield, G. (1990). *The natural and the normative : theories of spatial perception from Kant to Helmholtz*. Cambridge, Mass; London: MIT Press.

Henderson, J. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Sciences*, *7*(11), 498–504. https://doi.org/10.1016/j.tics.2003.09.006

Herman, F., & Heidmann, F. (2002). User Requirement Analysis and Interface Conception for a Mobile, Location-Based Fair Guide. In F. Paternò (Ed.), *Human Computer Interaction with Mobile Devices - Proceedings of the 4th International Symposium MobileHCI 2002* (Vol. 2411, pp. 388–392). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/3-540-45756-9_45

Hermawati, S., & Lawson, G. (2016). Establishing usability heuristics for heuristics evaluation in a specific domain: Is there a consensus? *Applied Ergonomics*, *56*, 34–51. https://doi.org/10.1016/j.apergo.2015.11.016

Heuten, W., Henze, N., Boll, S., & Pielot, M. (2008). Tactile wayfinder: A Non-Visual Support System for Wayfinding. In *Proceedings of the 5th Nordic conference on Human-computer interaction building bridges - NordiCHI '08* (pp. 172–181). Lund, Sweden. https://doi.org/10.1145/1463160.1463179

Hightower, J., & Borriello, G. (2001). Location systems for ubiquitous computing. *Computer*, *34*(8), 57–66. https://doi.org/10.1109/2.940014

Hoggan, E., & Brewster, S. A. (2010). Crosstrainer. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10* (pp. 333–342). Atlanta, Georgia, USA. https://doi.org/10.1145/1753326.1753378

Hund, A. M., & Minarik, J. L. (2006). Getting From Here to There: Spatial Anxiety, Wayfinding Strategies, Direction Type, and Wayfinding Efficiency. *Spatial Cognition & Computation*, *6*(3), 179–201. https://doi.org/10.1207/s15427633scc0603_1

Häkkilä, J., & Mäntyjärvi, J. (2006). Developing design guidelines for context-aware mobile applications. In *Mobility '06 Proceedings of the 3rd international conference on Mobile technology, applications & systems* (pp. 1–7). ACM Press. https://doi.org/10.1145/1292331.1292358

Häkkilä, J., Schmidt, A., Mäntyjärvi, J., Sahami, A., Åkerman, P., & Dey, A. K. (2009). Context-Aware Mobile Media and Social Networks. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (pp. 1–3). New York, NY, USA: ACM. https://doi.org/10.1145/1613858.1613982

iPlay Games Store. (2016). Live Map Caller Locator (Version 4.4).

ISO. (1998). Ergonomic Requirements for Office Work with Visual Display Terminals, ISO 9241-11. Geneva.

ISO. (2010). Ergonomics of human-system interaction -- Part 210: Human-centred design for interactive systems ISO 9241-210:2010.

Jacob, R. J., & Karn, K. S. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. *Mind*, *2*(3), 573–605.

Jaferian, P., Hawkey, K., Sotirakopoulos, A., Velez-Rojas, M., & Beznosov, K. (2011). Heuristics for evaluating IT security management tools. In *Proceedings of the Seventh Symposium on Usable Privacy and Security SOUPS '11* (pp. 1–20). New York, NY, USA: ACM. https://doi.org/10.1145/2078827.2078837

Johns, C. (2003). Spatial learning: cognitive mapping in abstract virtual environments. In *Proceedings of the 2nd international conference on Computer graphics, virtual Reality, visualisation and interaction in Africa - AFRIGRAPH '03* (pp. 7–16). Cape Town, South Africa. https://doi.org/10.1145/602330.602332

Johnson, J. A. (1995). A comparison of user interfaces for panning on a touch-controlled display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '95* (pp. 218–225). ACM Press. https://doi.org/10.1145/223904.223932

Kaasinen, E. (2003). User needs for location-aware mobile services. *Personal and Ubiquitous Computing*, *7*(1), 70–79. https://doi.org/10.1007/s00779-002-0214-7

Kaikkonen, A., Kekäläinen, A., Cankar, M., Kallio, T., & Kankainen, A. (2005). Usability Testing of Mobile Applications: A Comparison between Laboratory and Field Testing. *Journal of Usability Studies*, *1*(1), 4–16.

Kamilakis, M., Gavalas, D., & Zaroliagis, C. (2016). Mobile User Experience in Augmented Reality vs Maps Interfaces: A Case Study in Public Transportation. In Lucio Tommaso De Paolis & Antonio Mongelli (Eds.), *Lecture Notes in Computer Science (LNCS) - Augmented Reality, Virtual Reality, and Computer Graphics - Third International Conference, AVR 2016, Lecce, Italy, June 15-18, 2016. Proceedings, Part I* (Vol. 9768, pp. 388–396). Springer International Publishing.

Kaplan, S. (1973). Cognitive maps in perception and thought. In R. M. Downs & D. Stea (Eds.), *Image and Environment*. Chicago: Aldine Publishing Company.

Karimi, H. (2011). *Universal navigation on smartphones*. New York; London: Springer.

Karvonen, H., Kujala, T., & Saariluoma, P. (2006). In-Car Ubiquitous Computing: Driver Tutoring Messages Presented on a Head-Up Display. In *2006 IEEE Intelligent Transportation Systems Conference* (pp. 560–565). Toronto, Ont.: IEEE. https://doi.org/10.1109/ITSC.2006.1706800

Kässi, J., Krause, C. M., Kovanen, J., & Sarjakoski, L. T. (2013). Effects of Positioning Aids on Understanding the Relationship Between a Mobile Map and the Environment. *Human Technology*, *9*(1), 92–108.

Kettunen, P., Putto, K., Gyselinck, V., Krause, C. M., & Sarjakoski, L. T. (2015). Perception and Recall of Landmarks for Personal Navigation in Nature at Night Versus Day. In J. Brus, A. Vondrakova, & V. Vozenilek (Eds.), *Modern Trends in Cartography* (pp. 281–301). Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-07926-4_22

Kettunen, P., Sarjakoski, L. T., Ylirisku, S., & Sarjakoski, T. (2012). Web Map Design for a Multipublishing Environment Based on Open APIs. In M. P. Peterson (Ed.), *Online Maps with APIs and WebServices* (pp. 177–193). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-642-27485-5_12

Kim, S., & Dey, A. K. (2009). Simulated augmented reality windshield display as a cognitive mapping aid for elder driver navigation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '09* (pp. 133–142). ACM Press. https://doi.org/10.1145/1518701.1518724

Kitchin, R. M. (1994). Cognitive maps: What are they and why study them? *Journal of Environmental Psychology*, *14*(1), 1–19. https://doi.org/10.1016/S0272-4944(05)80194-X

Kjeldskov, J., & Graham, C. (2003). A Review of Mobile HCI Research Methods. In L. Chittaro (Ed.), *Human-Computer Interaction with Mobile Devices and Services - 5th International Symposium, Mobile HCI 2003, Udine, Italy, September 2003. Proceedings* (Vol. 2795, pp. 317–335). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/978-3-540-45233-1_23

Komarkova, J., Visek, O., & Novak, M. (2007). Heuristic Evaluation of Usability of GeoWeb Sites. In J. M. Ware & G. E. Taylor (Eds.), *Web and Wireless Geographical Information Systems* (Vol. 4857, pp. 264–278). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-540-76925-5_20

Koo, J., & Cha, H. (2012). Unsupervised Locating of WiFi Access Points Using Smartphones. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *42*(6), 1341–1353. https://doi.org/10.1109/TSMCC.2012.2186800

Krumm, J., Davies, N., & Narayanaswami, C. (2008). User-Generated Content. *IEEE Pervasive Computing*, *7*(4), 10–11. https://doi.org/10.1109/MPRV.2008.85

Kuniavsky, M. (2010). *Smart things: ubiquitous computing user experience design*. Elsevier.

Kuparinen, L. (2008). *Käytettävyyden merkitys ohjelmiston valinnassa* (Master's thesis). University of Jyväskylä. Retrieved from https://jyx.jyu.fi/dspace/handle/123456789/18307

Kuparinen, L. (2016). Validation and extension of the usability heuristics for mobile map applications. In *Proceedings of the 6th International Conference on Cartography and GIS (ICC&GIS2016)* (pp. 414–423). Albena, Bulgaria. https://doi.org/10.13140/RG.2.1.4834.4563

Kuparinen, L., & Irvankoski, K. (2010). Experiences from the Use of an Eye-Tracking System in the Wild. In *Proceedings of the 1st international workshop. held in conjunction with nordichi.* (Vol. 1, pp. 49–51). Reykjavik, Iceland: HaptiMap. Retrieved from http://omue10.offis.de/files/OMUE10-Proceedings.pdf

Kuparinen, L., & Irvankoski, K. (2011). Experiences from the Use of an Eye-Tracking System in the Wild. *Wi: Journal of Mobile Media*, *6*(1). Retrieved from http://wi.hexagram.ca/?p=90

Kuparinen, L., Silvennoinen, J., & Isomäki, H. (2013). Introducing usability heuristics for mobile map applications. In *Proceedings of the 26th International Cartographic Conference*. Dresden, Germany: International Cartographic Association. Retrieved from http://icaci.org/files/documents/ICC_proceedings/ICC2013/_extended Abstract/424_proceeding.pdf

Kuparinen, L., Swan, J. E., Rapson, S., & Sandor, C. (2013). Depth perception in tablet-based augmented reality at medium- and far-field distances. In *SAP '13 Proceedings of the ACM Symposium on Applied Perception* (p. 121). Dublin, Ireland: ACM Press. https://doi.org/10.1145/2492494.2514654

Küpper, A. (2005). *Location-based services: fundamentals and operation*. Chichester, England ; Hoboken, NJ: John Wiley.

LaMarca, A., Chawathe, Y., Consolvo, S., Hightower, J., Smith, I., Scott, J., … Schilit, B. (2005). Place Lab: Device Positioning Using Radio Beacons in the Wild. In H.-W. Gellersen, R. Want, & A. Schmidt (Eds.), *Pervasive Computing* (Vol. 3468, pp. 116–133). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/11428572_8

Land, M. F., & Tatler, B. W. (2009). *Looking and acting : vision and eye movements in natural behaviour*. Oxford; New York: Oxford University Press.

Lanir, J., Kuflik, T., Wecker, A. J., Stock, O., & Zancanaro, M. (2011). Examining proactiveness and choice in a location-aware mobile museum guide. *Interacting with Computers*, *23*(5), 513–524. https://doi.org/10.1016/j.intcom.2011.05.007

Lappin, J. S., Shelton, A. L., & Rieser, J. J. (2006). Environmental context influences visually perceived distance. *Perception & Psychophysics*, *68*(4), 571–581.

Lei, P.-L., Kao, G. Y.-M., Lin, S. S. J., & Sun, C.-T. (2009). Impacts of geographical knowledge, spatial ability and environmental cognition on image searches supported by GIS software. *Computers in Human Behavior*, *25*(6), 1270–1279. https://doi.org/10.1016/j.chb.2009.05.003

Lei, Z., & Coulton, P. (2009). A mobile geo-wand enabling gesture based POI search an user generated directional POI photography. In *Proceedings of the International Conference on Advances in Computer Enterntainment Technology ACE '09* (pp. 392–395). ACM Press. https://doi.org/10.1145/1690388.1690469

Life360. (2016). *Find My Phone*.

Lin, W. (2015). The hearing, the mapping, and the Web: Investigating emerging online sound mapping practices. *Landscape and Urban Planning*, *142*, 187–197. https://doi.org/10.1016/j.landurbplan.2015.08.007

Link, J. Á. B., Smith, P., Viol, N., & Wehrle, K. (2013). Accurate map-based indoor navigation on the mobile. *Journal of Location Based Services*, *7*(1), 23–43. https://doi.org/10.1080/17489725.2012.692620

Livingston, M. A., Rosenblum, L. J., Brown, D. G., Schmidt, G. S., Julier, S. J., Baillot, Y., … Maassel, P. (2011). Military Applications of Augmented Reality. In B. Furht (Ed.), *Handbook of Augmented Reality* (pp. 671–706). New York, NY: Springer New York. Retrieved from http://link.springer.com/10.1007/978-1-4614-0064-6_31

Looije, R., te Brake, G. M., & Neerincx, M. A. (2007). Usability engineering for mobile maps. In *Proceedings of the 4th international conference on mobile technology, applications, and systems and the 1st international symposium on Computer human interaction in mobile technology* (pp. 532–539). New York, NY, USA: ACM. https://doi.org/10.1145/1378063.1378150

Lorenz, A., Thierbach, C., Baur, N., & Kolbe, T. H. (2013). Map design aspects, route complexity, or social background? Factors influencing user satisfaction with indoor navigation maps. *Cartography and Geographic Information Science*, *40*(3), 201–209. https://doi.org/10.1080/15230406.2013.807029

Lynch, K. (1960). *The Image Of the City*. Cambridge, MA, USA: The MIT Press.

MacEachren, A. M. (1995). *How maps work: representation, visualization, and design*. The Guilford Press.

Machado Neto, O., & Pimentel, M. da G. (2013). Heuristics for the assessment of interfaces of mobile devices. In *Proceedings of the 19th Brazilian symposium on Multimedia and the web - WebMedia '13* (pp. 93–96). ACM Press. https://doi.org/10.1145/2526188.2526237

Mack, A., & Rock, I. (1998). *Inattentional blindness* (Vol. 33). Cambridge, MA: MIT press.

Magnusson, C., Tollmar, K., Brewster, S., Sarjakoski, T., Sarjakoski, T., & Roselier, S. (2009). Exploring future challenges for haptic, audio and visual interfaces for mobile maps and location based services. In *Proceedings of the 2nd International Workshop on Location and the Web - LOCWEB '09* (pp. 1–4).

Mallot, H. A., & Basten, K. (2009). Embodied spatial cognition: Biological and artificial systems. *Image and Vision Computing*, *27*(11), 1658–1670. https://doi.org/10.1016/j.imavis.2008.09.001

Mao, J., & Yeung, K. H. (2014). A BLE-Based Mobile Cloud Architecture for Longer Smart Mobile Device Battery Life. In R. C.-H. Hsu & S. Wang (Eds.), *Internet of Vehicles – Technologies and Services* (Vol. 8662, pp. 337–344). Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-11167-4_33

MapMyFitness, Inc. (2016). *MapMyDogWalk*. Retrieved from http://www.mapmyfitness.com/

Marmasse, N., & Schmandt, C. (2000). Location-Aware Information Delivery withComMotion. In P. Thomas & H.-W. Gellersen (Eds.), *Handheld and Ubiquitous Computing - Proceeding of the second International Symposium, HUC 2000* (Vol. 1927, pp. 157–171). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/3-540-39959-3_12

Marshall, J. C., & Fink, G. R. (2001). Spatial Cognition: Where We Were and Where We Are. *NeuroImage*, *14*(1), S2–S7. https://doi.org/10.1006/nimg.2001.0834

Medenica, Z., Kun, A. L., Paek, T., & Palinko, O. (2011). Augmented reality vs. street views: a driving simulator study comparing two emerging navigation aids. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services - MobileHCI '11* (pp. 265–274). ACM Press. https://doi.org/10.1145/2037373.2037414

Meilinger, T., Hölscher, C., Büchner, S. J., & Brösamle, M. (2007). How Much Information Do You Need? Schematic Maps in Wayfinding and Self Localisation. In T. Barkowsky, M. Knauff, G. Ligozat, & D. R. Montello (Eds.), *Spatial Cognition V Reasoning, Action, Interaction* (Vol. 4387, pp. 381–400). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/978-3-540-75666-8_22

Meng, L. (2008). The State of the Art of Map-Based Mobile Services. In L. Meng, A. Zipf, & S. Winter (Eds.), *Map-based Mobile Services* (pp. 1–12). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-540-37110-6_1

Miller, D. C. (2013). *Essentials of school neuropsychological assessment* (2nd ed). Hoboken, N.J: John Wiley and Sons.

Mizobuchi, S., Chignell, M., & Newton, D. (2005). Mobile text entry: relationship between walking speed and text input task difficulty. In *Proceedings of the 7th international conference on Human computer interaction with mobile devices & services MobileHCI '05* (pp. 122–128). ACM Press. https://doi.org/10.1145/1085777.1085798

Montello, D. R. (2010). You Are Where? The Function and Frustration of You-Are-Here (YAH) Maps. *Spatial Cognition & Computation*, *10*(2–3), 94–104. https://doi.org/10.1080/13875860903585323

Moore, G. T., & Golledge, R. G. (1976). *Environmental knowing theories, research, and methods.* Stroudsburg, Pa: Dowden, Hutchinson and Ross.

Morrison, A., Oulasvirta, A., Peltonen, P., Lemmela, S., Jacucci, G., Reitmayr, G., … Juustila, A. (2009). Like bees around the hive: a comparative study of a mobile augmented reality map. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '09* (pp. 1889–1898). ACM Press. https://doi.org/10.1145/1518701.1518991

Morville, P. (2004, June 21). User Experience Design. Semantic Studios. Retrieved from http://semanticstudios.com/user_experience_design/

Morville, P. (2005). Experience design unplugged. In *SIGGRAPH '05 ACM SIGGRAPH 2005 Web program* (p. 10). ACM Press. https://doi.org/10.1145/1187335.1187347

Mulloni, A., Seichter, H., & Schmalstieg, D. (2011). Handheld augmented reality indoor navigation with activity-based instructions. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services - MobileHCI '11* (pp. 211–220). ACM Press. https://doi.org/10.1145/2037373.2037406

Myers, M. D. (1997). Qualitative Research in Information Systems. *MIS Quarterly*, *21*(2), 241–242. https://doi.org/10.2307/249422

Narzt, W., Pomberger, G., Ferscha, A., Kolb, D., Müller, R., Wieghardt, J., Lindinger, C. (2006). Augmented reality navigation systems. *Universal Access in the Information Society*, *4*(3), 177–187. https://doi.org/10.1007/s10209-005-0017-5

Naukkarinen, A., Sutela, J., Botero, A., & Kommonen, K.-H. (2009). Designing locative media for creative misuse. In *Proceedings of the 13th International MindTrek Conference: Everyday Life in the Ubiquitous Era on - MindTrek '09* (pp. 124–127). Tampere, Finland. https://doi.org/10.1145/1621841.1621865

Nee, A. Y. C., Ong, S. K., Chryssolouris, G., & Mourtzis, D. (2012). Augmented reality applications in design and manufacturing. *CIRP Annals - Manufacturing Technology*, *61*(2), 657–679. https://doi.org/10.1016/j.cirp.2012.05.010

Niantic. (2016). *Pokémon Go*.

Nielsen, C. M., Overgaard, M., Pedersen, M. B., Stage, J., & Stenild, S. (2006). It's worth the hassle!: the added value of evaluating the usability of mobile systems in the field. In *Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles NordiCHI '06* (pp. 272–280). ACM Press. https://doi.org/10.1145/1182475.1182504

Nielsen, J. (1992). Finding usability problems through heuristic evaluation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '92* (pp. 373–380). New York, NY, USA: ACM. https://doi.org/10.1145/142750.142834

Nielsen, J. (1993). *Usability Engineering*. Boston, MA: Academic Press.

Nielsen, J. (1994). Heuristic evaluation. In J. Nielsen & R. L. Mack, *Usability Inspection Methods*. New York, NY: John Wiley & Sons.

Nivala, A.-M. (2007). *Usability perspectives for the design of interactive maps* (PhD thesis). Helsinki University of Technology.

Nivala, A.-M., Brewster, S., & Sarjakoski, T. L. (2008). Usability Evaluation of Web Mapping Sites. *Cartographic Journal, The*, *45*(2), 129–138. https://doi.org/10.1179/174327708X305120

Nivala, A.-M., & Sarjakoski, L. T. (2005). Adapting Map Symbols for Mobile Users. In *Proceedings of the 22nd International Cartographic Conference*. Spain: International Cartographic Association.

Nivala, A.-M., Sarjakoski, L. T., Jakobsson, A., & Kaasinen, E. (2003). Usability evaluation of topographic maps in mobile devices. In *Proceedings of the 21st International Cartographic Conference* (pp. 10–16).

Nivala, A.-M., Sarjakoski, L. T., & Sarjakoski, T. (2005). User-centred design and development of a mobile map service. In *Proceedings of the 10th Scandinavian Research Conference on Geographical Information Sciences - ScanGIS'2005*.

Nivala, A.-M., Sarjakoski, L. T., & Sarjakoski, T. (2007). Usability methods' familiarity among map application developers. *International Journal of Human-Computer Studies*, *65*(9), 784–795. https://doi.org/10.1016/j.ijhcs.2007.04.002

Nivala, A.-M., & Sarjakoski, T. L. (2003). Need for Context-Aware Topographic Maps in Mobile Devices. In *Proceedings of the 9th Scandinavian Research Conference on Geographical Information Science*. Espoo, Finland. Retrieved from https://www.researchgate.net/publication/221013385_Need_for_Context-Aware_Topographic_Maps_in_Mobile_Devices

Norman, D. A. (2003). *Things that make us smart: defending human attributes in the age of the machine* (16. print.). Reading, Mass: Perseus Books.

Nurminen, A. (2008). Mobile 3D City Maps. *IEEE Computer Graphics and Applications*, *28*(4), 20–31. https://doi.org/10.1109/MCG.2008.75

Nurminen, A., Järvi, J., & Lehtonen, M. (2014). A Mixed Reality Interface for Real Time Tracked Public Transportation. Presented at the 10th ITS European Congress, Helsinki, Finland.

Nurminen, A., & Oulasvirta, A. (2008). Designing Interactions for Navigation in 3D Mobile Maps. In L. Meng, A. Zipf, & S. Winter (Eds.), *Map-based Mobile Services* (pp. 198–227). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/978-3-540-37110-6_10

O'Hara, K. (2008). Understanding geocaching practices and motivations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '08* (pp. 1177–1186). ACM Press. https://doi.org/10.1145/1357054.1357239

Ohm, C., Müller, M., & Ludwig, B. (2015). Displaying landmarks and the user's surroundings in indoor pedestrian navigation systems. *Journal of Ambient Intelligence and Smart Environments*, *7*(5), 635–657. https://doi.org/10.3233/AIS-150335

Olsson, T., & Salo, M. (2012). Narratives of satisfying and unsatisfying experiences of current mobile augmented reality applications. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '12* (pp. 2779–2788). ACM Press. https://doi.org/10.1145/2207676.2208677

Ooms, K., Coltekin, A., De Maeyer, P., Dupont, L., Fabrikant, S., Incoul, A., … Van der Haegen, L. (2015). Combining user logging with eye tracking for interactive and dynamic applications. *Behavior Research Methods*, *47*(4), 977–993. https://doi.org/10.3758/s13428-014-0542-3

Ooms, K., De Maeyer, P., Dupont, L., Van Der Veken, N., Van de Weghe, N., & Verplaetse, S. (2016). Education in cartography: what is the status of young people's map-reading skills? *Cartography and Geographic Information Science*, *43*(2), 134–153. https://doi.org/10.1080/15230406.2015.1021713

Ooms, K., De Maeyer, P., & Fack, V. (2014). Study of the attentive behavior of novice and expert map users using eye tracking. *Cartography and Geographic Information Science*, *41*(1), 37–54. https://doi.org/10.1080/15230406.2013.860255

Oulasvirta, A. (2004). Finding meaningful uses for context-aware technologies: the humanistic research strategy. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 247–254).

Oulasvirta, A., Estlander, S., & Nurminen, A. (2008). Embodied interaction with a 3D versus 2D mobile map. *Personal and Ubiquitous Computing*, *13*(4), 303–320. https://doi.org/10.1007/s00779-008-0209-0

Parhi, P., Karlson, A. K., & Bederson, B. B. (2006). Target size study for one-handed thumb use on small touchscreen devices. In *Proceedings of the 8th conference on Human-computer interaction with mobile devices and services* (pp. 203–210). ACM Press. https://doi.org/10.1145/1152215.1152260

Pfeiffer, T., Latoschik, M. E., Wachsmuth, I., & Herder, J. (2008). Evaluation of binocular eye trackers and algorithms for 3d gaze interaction in virtual reality environments. *Journal of Virtual Reality and Broadcasting*, *5*(16), 1–13.

Pielot, M., Henze, N., & Boll, S. (2009). Supporting map-based wayfinding with tactile cues. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services MobileHCI '09* (pp. 1–10). New York, NY, USA: ACM. https://doi.org/10.1145/1613858.1613888

Pielot, M., Krull, O., & Boll, S. (2010). Where is my team: supporting situation awareness with tactile displays. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10* (pp. 1705–1714). Atlanta, Georgia, USA. https://doi.org/10.1145/1753326.1753581

Pielot, M., Poppinga, B., Heuten, W., & Boll, S. (2011). 6th senses for everyone!: the value of multimodal feedback in handheld navigation aids. In *Proceedings of the 13th international conference on multimodal interfaces* (pp. 65–72). ACM Press. https://doi.org/10.1145/2070481.2070496

Pinelle, D., Wong, N., & Stach, T. (2008). Heuristic evaluation for games: usability principles for video game design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1453–1462). New York, NY, USA: ACM. https://doi.org/10.1145/1357054.1357282

Puikkonen, A., Sarjanoja, A.-H., Haveri, M., Huhtala, J., & Häkkilä, J. (2009). Towards Designing Better Maps for Indoor Navigation - Experiences from a Case Study. In *Proceedings of the 8th International Conference on Mobile and Ubiquitous Multimedia MUM '09* (pp. 1–4). Cambridge, UK.: ACM.

Qian, H., & Andresen, D. (2015). Extending mobile device's battery life by offloading computation to cloud. In *Proceedings of the Second ACM International Conference on Mobile Software Engineering and Systems* (pp. 150–151). IEEE Press Piscataway.

Raento, M., Oulasvirta, A., Petit, R., & Toivonen, H. (2005). ContextPhone: A Prototyping Platform for Context-Aware Mobile Applications. *IEEE Pervasive Computing*, *4*(2), 51–59. https://doi.org/10.1109/MPRV.2005.29

Rao, Q., Tropper, T., Grunler, C., Hammori, M., & Chakraborty, S. (2014). AR-IVI - Implementation of In-Vehicle Augmented Reality. In *Mixed and Augmented Reality (ISMAR), 2014 IEEE International Symposium on* (pp. 3–8). IEEE. https://doi.org/10.1109/ISMAR.2014.6948402

Raper, J., Gartner, G., Karimi, H., & Rizos, C. (2007). A critical evaluation of location based services and their potential. *Journal of Location Based Services*, *1*(1), 5–45. https://doi.org/10.1080/17489720701584069

Raubal, M. (2015). Mobile Cognition: Balancing User Support and Learning. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services MobileHCI '15* (pp. 1018–1023). ACM Press. https://doi.org/10.1145/2786567.2794321

Raubal, M., & Winter, S. (2002). Enriching Wayfinding Instructions with Local Landmarks. In M. J. Egenhofer & D. M. Mark (Eds.), *Geographic Information Science* (Vol. 2478, pp. 243–259). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/3-540-45799-2_17

Recargo Inc. (2016). PlugShare (Version 3.1.4).

Reddy, S., Shilton, K., Denisov, G., Cenizal, C., Estrin, D., & Srivastava, M. (2010). Biketastic: sensing and mapping for better biking. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10* (pp. 1817–1820). Atlanta, Georgia, USA. https://doi.org/10.1145/1753326.1753598

Rehrl, K., Häusler, E., Leitinger, S., & Bell, D. (2014). Pedestrian navigation with augmented reality, voice and digital map: final results from an in situ field study assessing performance and user experience. *Journal of Location Based Services*, *8*(2), 75–96. https://doi.org/10.1080/17489725.2014.946975

Rehrl, K., Häusler, E., Steinmann, R., Leitinger, S., Bell, D., & Weber, M. (2012). Pedestrian Navigation with Augmented Reality, Voice and Digital Map: Results from a Field Study assessing Performance and User Experience. In G. Gartner & F. Ortag (Eds.), *Advances in Location-Based Services* (pp. 3–20). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-642-24198-7_1

Reitmayr, G., & Schmalstieg, D. (2003). Location based applications for mobile augmented reality. In R. Biddle & B. Thomas (Eds.), *Proceedings of the Fourth Australasian user interface conference on User interfaces 2003* (Vol. 18, pp. 65–73). Darlinghurst, Australia: Australian Computer Society, Inc.

Renshaw, J. A., & Webb, N. (2007). Eye tracking in practice. In *Proceedings of the 21st British HCI Group Annual Conference on People and Computers: HCI... but not as we know it-Volume 2* (pp. 239–241).

Reponen, E., & Keränen, J. (2010). Mobile interaction with real-time geospatial data by pointing through transparent Earth. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (pp. 403–412). ACM Press. https://doi.org/10.1145/1868914.1868961

Roger, M., Bonnardel, N., & Le Bigot, L. (2007). Spatial cognition in a navigation task: effects of initial knowledge of an environment and spatial abilities on route description. In *Proceedings of the 14th European conference on Cognitive ergonomics invent! explore! - ECCE '07* (pp. 237–242). London, United Kingdom. https://doi.org/10.1145/1362550.1362598

Rogers, S. (1995). Perceiving Pictorial Space. In W. Epstein & S. Rogers, *Perception of Space and Motion: Handbook of Perception and Cognition* (pp. 119–163). Elsevier. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/B9780122405303500067

Rosson, M. B., & Carroll, J. M. (2002). *Usability engineering: scenario-based development of human-computer interaction* (Repr., 2. Druck). San Francisco, Calif.: Kaufmann.

Roto, V., Law, E., Vermeeren, A., & Hoonhout, J. (Eds.). (2011). User Experience White Paper. Bringing clarity to the concept of user experience. Presented at the Dagstuhl Seminar on Demarcating User Experience. Retrieved from www.allaboutux.org/uxwhitepaper

Rousi, R. (2010). A cultural approach to human-centered design - Measuring user perceptions of attractiveness in smartphone icons. In W. S. Yeo (Ed.), *Proceedings of the Young Investigators' Forum on Culture Technology - engaging culture and technology* (pp. 23–33). Daejeon: KAIST.

Sarjakoski, L. T., Kettunen, P., Flink, H.-M., Laakso, M., Rönneberg, M., & Sarjakoski, T. (2011). Analysis of verbal route descriptions and landmarks for hiking. *Personal and Ubiquitous Computing*, 1001–1011. https://doi.org/10.1007/s00779-011-0460-7

Schall, M. C., Rusch, M. L., Lee, J. D., Dawson, J. D., Thomas, G., Aksan, N., & Rizzo, M. (2013). Augmented Reality Cues and Elderly Driver Hazard Perception. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *55*(3), 643–658. https://doi.org/10.1177/0018720812462029

Schifferstein, H., & Hekkert, P. (Eds.). (2008). *Product experience* (1st ed). San Diego, CA: Elsevier.

Schilit, B., Adams, N., & Want, R. (1994). Context-aware computing applications. In *Mobile Computing Systems and Applications, 1994. WMCSA 1994. First Workshop on* (pp. 85–90).

Schmid, F., Janetzek, H., Wladysiak, M., & Hu, B. (2013). OpenScienceMap: open and free vector maps for low bandwidth applications. In *Proceedings of the 3rd ACM Symposium on Computing for Development* (pp. 1–2). ACM Press. https://doi.org/10.1145/2442882.2442939

Schnitzler, V., Giannopoulos, I., Hölscher, C., & Barisic, I. (2016). The interplay of pedestrian navigation, wayfinding devices, and environmental features in indoor settings. In *Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications ETRA '16* (pp. 85–93). ACM Press. https://doi.org/10.1145/2857491.2857533

Schobesberger, D. (2009). Towards principles for usability evaluation in web mapping-Usability research for cartographic information systems. In *Proceedings of the 24th International Cartographic Conference ICC*. Santiago de Chile.

Schöning, J., Hecht, B., & Kuhn, W. (2014). Informing online and mobile map design with the collective wisdom of cartographers. In *Proceedings of the 2014 conference on Designing interactive systems DIS '14* (pp. 765–774). ACM Press. https://doi.org/10.1145/2598510.2598543

Sciacchitano, B., Cerwinski, C., Brown, I., Sampat, M., Lee, J. C., & McCrickard, D. S. (2006). Intelligent library navigation using location-aware systems: the Newman project. In *Proceedings of the 44th annual Southeast regional conference ACM-SE 44* (pp. 371–376). ACM Press. https://doi.org/10.1145/1185448.1185531

Self, C. M., & Golledge, R. G. (1994). Sex-related Differences in Spatial Ability: What Every Geography Educator Should Know. *Journal of Geography*, *93*, 234–243. https://doi.org/10.1080/00221349408979727

Sielhorst, T., Feuerstein, M., & Navab, N. (2008). Advanced Medical Displays: A Literature Review of Augmented Reality. *Journal of Display Technology*, *4*(4), 451–467. https://doi.org/10.1109/JDT.2008.2001575

Silvennoinen, M., & Kuparinen, L. (2009). Usability challenges in surgical simulator training. In *Proceedings of the ITI 2009 31st International Conference on Information Technology Interfaces* (pp. 455–460). Cavtat/Dubrovnik, Croatia. https://doi.org/10.1109/ITI.2009.5196126

Skarlatidou, A., Cheng, T., & Haklay, M. (2013). Guidelines for trust interface design for public engagement Web GIS. *International Journal of Geographical Information Science*, *27*(8), 1668–1687. https://doi.org/10.1080/13658816.2013.766336

Sluter, R. C., Brandalize, M. C. B., van Elzakker, C. P. J. M., & Ivanova, I. (2013). Defining standard symbols for street network maps for urban planning based on user requirements. In *From pole to pole : proceedings of the 26th international cartographic conference ICC2013*.

Snowdon, C., & Kray, C. (2009). Exploring the use of landmarks for mobile navigation support in natural environments. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '09* (pp. 1–10). Bonn, Germany. https://doi.org/10.1145/1613858.1613875

Spiers, H. J., & Maguire, E. A. (2006). Thoughts, behaviour, and brain dynamics during navigation in the real world. *NeuroImage*, *31*(4), 1826–1840. https://doi.org/10.1016/j.neuroimage.2006.01.037

Sports Tracking Technologies. (2016). *Sports Tracker*. Retrieved from http://www.sports-tracker.com/

Srikulwong, M., & O'Neill, E. (2011). Wearable Tactile Display of Landmarks and Direction for Pedestrian Navigation. *International Journal of Mobile Human Computer Interaction*, *3*(3), 31–49. https://doi.org/10.4018/jmhci.2011070103

Steiniger, S., & Hunter, A. J. S. (2012). Free and Open Source GIS Software for Building a Spatial Data Infrastructure. In E. Bocher & M. Neteler (Eds.), *Geospatial Free and Open Source Software in the 21st Century* (pp. 247–261).

Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-642-10595-1_15

Suh, Y., Shin, C., Woo, W., Dow, S., & MacIntyre, B. (2010). Enhancing and evaluating users' social experience with a mobile phone guide applied to cultural heritage. *Personal and Ubiquitous Computing*, *15*(6), 649–665. https://doi.org/10.1007/s00779-010-0344-2

Swan, J. E. I., & Gabbard, J. L. (2005). Survey of User-Based Experimentation in Augmented Reality. In *Proceedings 1st International Conference on Virtual Reality* (pp. 1–9). Las Vegas, Nevada, US.

Swan, J. E. I., Kuparinen, L., Sandor, C., & Rapson, S. (2016, February 6). *Visually Perceived Distance Judgments: Tablet-Based Augmented Reali-ty versus the Real World*. Submitted to International Journal of Human-Computer Interaction (IJHCI).

Tamminen, S., Oulasvirta, A., Toiskallio, K., & Kankainen, A. (2004). Understanding mobile contexts. *Personal and Ubiquitous Computing*, *8*(2), 135–143. https://doi.org/10.1007/s00779-004-0263-1

Tiru, M., Kuusik, A., Lamp, M.-L., & Ahas, R. (2010). LBS in marketing and tourism management: measuring destination loyalty with mobile positioning data. *Journal of Location Based Services*, *4*(2), 120–140. https://doi.org/10.1080/17489725.2010.508752

Tlauka, M., Brolese, A., Pomeroy, D., & Hobbs, W. (2005). Gender differences in spatial knowledge acquired through simulated exploration of a virtual shopping centre. *Journal of Environmental Psychology*, *25*, 111–118. https://doi.org/10.1016/j.jenvp.2004.12.002

Tractive. (2016). *Tractive GPS*.

Trapp, M., Schneider, L., Lehmann, C., Holz, N., & Döllner, J. (2011). Strategies for visualising 3D points-of-interest on mobile devices. *Journal of Location Based Services*, *5*(2), 79–99. https://doi.org/10.1080/17489725.2011.579579

Tsalgatidou, A., Veijalainen, J., Markkula, J., Katasonov, A., & Hadjiefthymiades, S. (2003). Mobile E-Commerce and Location-Based Services: Technology and Requirements. In *Proceedings of the 9th Scandinavian Research Conference on Geographical Information Services* (pp. 1–14).

Ubyca. (2016). *Bolets*. Retrieved from http://www.ubyca.com/

Uusitalo, S., Eskolin, P., & Belimpasakis, P. (2009). A solution for navigating user-generated content. In *IEEE International Symposium on Mixed and Augmented Reality ISMAR 2009* (pp. 219–220). Orlando, FL, USA. https://doi.org/10.1109/ISMAR.2009.5336451

Vainio, T. (2011). Designing multimodal tracks for mobile users in unfamiliar urban environments. *Digital Creativity*, *22*(1), 26–39. https://doi.org/10.1080/14626268.2011.538929

Vainio, T., & Kotala, O. (2002). Developing 3D information systems for mobile users. In *Proceedings of the second Nordic conference on Human-computer interaction - NordiCHI '02* (pp. 231–234). Aarhus, Denmark. https://doi.org/10.1145/572020.572053

Vainio, T., & Kulju, M. (2007). So James, can you find your way any faster? In *Proceedings of the 4th international conference on mobile technology, applications, and systems and the 1st international symposium on Computer human interaction in mobile technology - Mobility '07* (pp. 645–652). Singapore. https://doi.org/10.1145/1378063.1378174

Vaittinen, T., Laakso, K., & Itäranta, J. (2008). Kuukkeli: design and evaluation of location-based service with touch UI for hikers. In *Proceedings of the 5th Nordic conference on Human-computer interaction building bridges - NordiCHI '08* (pp. 373–382). Lund, Sweden. https://doi.org/10.1145/1463160.1463201

van Elzakker, C. P. J. M. van. (2004). *The use of maps in the exploration of geographic data*. Utrecht: Koninklijk Nederlands Aardrijkskundig Genootschap [u.a.].

Van Erp, J. B. F., Van Veen, H. A. H. C., Jansen, C., & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception*, *2*(2), 106–117. https://doi.org/10.1145/1060581.1060585

Veryzer, R. W., & Borja de Mozota, B. (2005). The Impact of User-Oriented Design on New Product Development: An Examination of Fundamental Relationships*. *Journal of Product Innovation Management*, *22*(2), 128–143. https://doi.org/10.1111/j.0737-6782.2005.00110.x

Viaene, P., Vansteenkiste, P., Lenoir, M., Wulf, A. D., & De Maeyer, P. (2016). Examining the validity of the total dwell time of eye fixations to identify landmarks in a building. *Journal of Eye Movement Research*, *9*(3), 1–11.

Vinson, N. G. (1999). Design guidelines for landmarks to support navigation in virtual environments. In *Proceedings of the SIGCHI conference on Human factors in computing systems the CHI is the limit - CHI '99* (pp. 278–285). Pittsburgh, Pennsylvania, United States. https://doi.org/10.1145/302979.303062

VR Group. (2013). Junat kartalla (Version 1.0.5).

Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: writing a literature review. *MIS Quarterly*, *26*(2), 13–23.

Werner, H. (1948). *Comparative psychology of mental development*. New York: International Universities Press.

Wiener, J. M., Büchner, S. J., & Hölscher, C. (2009). Taxonomy of Human Wayfinding Tasks: A Knowledge-Based Approach. *Spatial Cognition & Computation*, *9*(2), 152–165. https://doi.org/10.1080/13875860902906496

WiFi Map. (2014). *WiFi Map*. Retrieved from http://www.wifimap.io

Willis, K. S., Hölscher, C., & Wilbertz, G. (2009). Understanding Mobile Spatial Interaction in Urban Environments. In A. D. Kameas, V. Callagan, H. Hagras, M. Weber, & W. Minker (Eds.), *Advanced Intelligent Environments* (pp. 119–138). Boston, MA: Springer US. Retrieved from http://www.springerlink.com/index/10.1007/978-0-387-76485-6_6

Willis, K. S., Hölscher, C., Wilbertz, G., & Li, C. (2009). A comparison of spatial knowledge acquisition with maps and mobile maps. *Computers,* *Environment and Urban Systems*, *33*(2), 100–110. https://doi.org/10.1016/j.compenvurbsys.2009.01.004

Winter, S. (2003). Route Adaptive Selection of Salient Features. In W. Kuhn, M. F. Worboys, & S. Timpf (Eds.), *Spatial Information Theory. Foundations of Geographic Information Science* (Vol. 2825, pp. 349–361). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://www.springerlink.com/index/10.1007/978-3-540-39923-0_23

Yamaguchi, Y., Nakagawa, T., Akaho, K., Honda, M., Kato, H., & Nishida, S. (2007). AR-Navi: An In-Vehicle Navigation System Using Video-Based Augmented Reality Technology. In M. J. Smith & G. Salvendy (Eds.), *Human Interface and the Management of Information. Interacting in Information Environments* (Vol. 4558, pp. 1139–1147). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-540-73354-6_124

Zandbergen, P. A. (2009). Accuracy of iPhone Locations: A Comparison of Assisted GPS, WiFi and Cellular Positioning. *Transactions in GIS*, *13*, 5–25. https://doi.org/10.1111/j.1467-9671.2009.01152.x

Zentai, L. (2016). ICA's Modern Cartography. In *Proceedings, 6th International Conference on Cartography and GIS* (pp. 15–23). Albena, Bulgaria.

Zhang, D., & Adipat, B. (2005). Challenges, Methodologies, and Issues in the Usability Testing of Mobile Applications. *International Journal of Human-Computer Interaction*, *18*(3), 293–308. https://doi.org/10.1207/s15327590ijhc1803_3

Zuk, T., Schlesier, L., Neumann, P., Hancock, M. S., & Carpendale, S. (2006). Heuristics for information visualization evaluation. In *Proceedings of the 2006 AVI workshop on BEyond time and errors: novel evaluation methods for information visualization* (pp. 1–6). ACM Press. https://doi.org/10.1145/1168149.1168162

ORIGINAL ARTICLES

I

EXPERIENCES FROM THE USE OF AN EYE-TRACKING SYSTEM IN THE WILD

by

Kuparinen, L. & Irvankoski, K. 2011

Wi: Journal of Mobile Media, vol 6

Published also in B. Poppinga (Ed.), Observing the mobile user experience (OMUE), proceedings of the 1st international workshop, held in conjunction with NordiCHI 2010.

Reproduced with kind permission by Wi: Journal of Mobile Media
and the editor of OMUE10 proceedings.

Experiences from the Use of an Eye-Tracking System in the Wild

Kuparinen Liisa
Department of Computer Science and
Information Systems
University of Jyväskylä
Finland
+358 (0)400 248079
liisa.kuparinen@jyu.fi

Irvankoski Katja
Department of Cognitive Science,
Institute of Behavioural Sciences
University of Helsinki
Finland
+358 (0)40 5962861
katja.irvankoski@helsinki.fi

ABSTRACT

Eye-tracking systems have been widely used as a data collection method in the human–computer interaction research field. Eye-tracking has typically been applied in stationary environments to evaluate the usability of desktop applications. In the mobile context, user studies with eye-tracking are far more infrequent. In this paper, we report our findings from user tests performed with an eye-tracking system in a forest environment. We present some of the most relevant issues that should be considered when planning a mobile study in the wild using eye-tracking as a data collection method. One of the most challenging findings was the difficulty in identifying where the user actually looked in the three-dimensional environment from the two-dimensional scene video. This means it is difficult to assure whether the gaze is directed to an object short of the user or to a distant object that is partly occluded by the closer one.

1. INTRODUCTION

According to Renshaw and Webb [10], the benefits of eye-tracking include the independence of data from user memory, the indication of problem solving strategies and a large amount of quantitative data. Examples of situations where the use of an eye-tracking system would be useful are when there is a need to get information about the most important objects used in navigation or to identify which objects in traffic a driver of a car notices and misses. In addition to eye-tracking, other methods such as interviews, observation and performance accuracy are applied to validate or to complete the findings observed in the eye-tracking data.

Another issue is the need to research mobile user experience in the field instead of the laboratory. For example, Nielsen et al. [8] stated that the field setting elicits a significantly increased amount of usability problems, as well as problems with interaction style and cognitive load that are not identified in the laboratory setting. If the research target is to investigate wider user experience in a natural context as well as to identify usability problems, the importance of a field study is even more evident.

The use of eye-tracking systems has been very sparse in the research of mobile user experience. Along with stationary environments, they have been used for example in the research of shopping behaviour, infants' natural interactions, and various everyday tasks [2][4][5]. To our knowledge, the research of mobile user experience in a forest environment is virtually non-existent.

In this paper, we focus on using an eye-tracking camera in a typical Finnish rural environment – a forest. Our focus is more in the validity testing of the eye-tracking method than on the use of mobile devices in order to discover the issues that must be considered when planning eye-tracking tests in the wild.

2. TESTS IN THE WILD

We executed multiple pilot eye-tracking tests in a forest environment with different tasks in different conditions. The eye-tracking system we used was iView X™ HED from SensoMotoric Instruments. This monocular system consists of an eye camera and a scene video camera which are attached to a bicycle helmet. The first tests were executed without a mobile phone. In that phase, the goal was to assess the feasibility of using an eye-tracking system in a forest environment and to pilot test task settings for future studies. During the tests, we took the users to the forest area to do simple navigation tasks. The tasks included, for example, walking through a certain route with a little guidance (no maps, paper or mobile applications were used), describing what he or she saw, describing how he or she located him/herself and describing the route in such a way that another person could follow it.

After completing the first experiments, a test with a mobile map service was executed. In this single experiment, the user walked a route according to given instructions and located herself on the map. The user was also asked to navigate on foot to a certain position pointed on the map. The composition of the test is presented in Figure 1.

In addition to recording eye-tracking data and interviewing the user during the test situation, the users were interviewed after the tests as well. These post-experiment interviews were conducted to validate and complete the eye-tracking data and observations made in both of the field test cases.

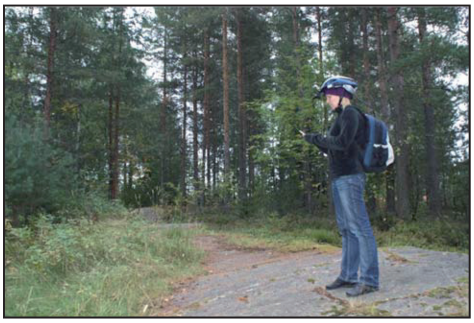


Figure 1. The goals of the test tasks were to resolve the current location on the mobile map and to navigate to a predefined position. The eye-tracking camera was attached on the bicycle helmet and the laptop used for data recording was carried in the backpack.

3. CHALLENGES

In this section, we present the main findings of using an eye-tracking system in a mobile context.

Some problems concerning the use of eye-tracking systems are commonly recognised in stationery environments. Those issues include, for example, the difficulties of tracking a person's eye movements if he or she wears glasses, if his or her pupil size is very small (e.g. when tired), the colour of iris is light or if the person has very long, downward or made-up eyelashes [3].

Along with these problems, we also discovered some special issues that should be considered when conducting eye-tracking research in a mobile context.

3.1 Data Quality

There are some issues in using an eye-tracking system in the wild that may risk the quality of data. Perhaps the most challenging issue in executing an eye-tracking test in a field setting is that the off-the-shelf eye-tracking systems are unable to provide definite information about distance of focused gaze in three-dimensional setting [9]. The monocular system we used provides data consisting only of gaze cursor on the recorded scene video, that is gaze position relative to the head (and video frame) [7]. Therefore, we faced situations where we could not be sure whether the user focused his or her gaze on a tree three meters ahead or to the lake that could be seen between the branches of the tree.

Few commercial binocular eye-tracking systems are available such as NAC Image Technology's EMR-9, which has some parallax error compensation. In addition to these, different labs using eye-tracking methodology have been developing eye-tracking systems that resolve the parallax problem and head movement both in natural environment and virtual reality [9][11]. One solution to this problem is the use of thinking-aloud. In addition to the lack of head tracking and depth information, the features of a forest environment make it difficult to define explicit areas-of-interests on recorded scene video data.

Calibration of an eye-tracking camera is much more difficult in the mobile context than in stationary conditions. In a mobile context, especially when investigating mobile device use, the gaze distance varies from a few dozen centimetres to hundreds of metres. However, the gaze data is the most accurate at the calibration distance due to parallax errors [7]. We handled the calibration by using a large rectangular area, wall or a large paperboard several metres away from the user in the same environment that the test was going to occur. The calibration was then tested by comparing the equivalence of what the video showed and what the user said he or she was looking at. Generally, the calibration needed to be corrected several times. We discovered that calibration should be repeated during the test because it quite easily weakened in motion even though the helmet with the eye-tracking camera was strapped very tight.

Due to the unreliability of the calibration and parallax errors the eye-tracking system may not be trustworthy enough to examine eye movements in the mobile device's small screen. However, the eye-tracking system is very suitable for tracking situations in which a user takes the mobile device in hand and checks it for location or direction.

3.2 Experimental Conditions

Regarding the experimental conditions, the most obvious ones concern weather conditions, which differ from the stable environment of a research laboratory. It is important to take into account that, for example, rain may prevent executing the tests at the planned time. The use of eye-tracking cameras also requires adequate light, thus, it is typically also impossible to execute tests early in morning or late in the night – at least in the winter time. Moreover, the lighting conditions may vary during one single experiment session.

Wearing a helmet or other attachment object with an eye-tracking camera, which has multiple hanging wires, and carrying a laptop in a backpack or a shoulder-case handicaps the movements of the user and influences his or her behaviour, at least until he or she gets used to the equipment. For that reason, it is recommended that the actual test is not performed until the user has had some time to become familiar with the equipment. Improvements to the mobility of eye-tracking systems are being made, but to the best of our knowledge, the current solutions are not yet unobtrusive to the user. For example, in 2008, a research executed with a new kind of eye-tracking solution, light-weighted EOG goggles, was reported by Bulling et al. [1], but also on that solution the user has to carry a laptop with him or her. On the other hand, Tobii Technology has recently introduced Glasses Eye Tracker, which uses a smaller recording unit instead of a laptop.

One limiting factor in eye-tracking tests in the mobile context is the low battery capacity that applies to many eye-tracking systems. Keeping that in mind, it is impossible to plan a user test that would last for hours. With our test equipment, the maximum duration for test recordings was about half an hour. The weather conditions (e.g. cold or hot) as well as the bag for the recording laptop also influence this factor.

Finally, it is essential to pay attention to the careful design and definition of test tasks in order to be aware of the user's goals and to interpret the gaze data [5].

3.3 Underlying Cognitive Processes

One should be aware that eye-tracking data does not give all-encompassing data about the allocation of the user's attention. Eye movements can be an indication of a shift in attention (overt attention); on the other hand, a user may shift his or her attention to another target without moving his or her eyes (covert attention) [6]. In our study, the dissociation between where the user looked and what she paid attention to was evident in the picture recognition test as well. After the user had walked the route in the forest, she was asked about what she saw and was then shown pictures and asked to decide whether they were taken of the route. The user was shown 16 pictures, of which five were from the route (see example in the Figure 2) and nine were from other forest scenes. The recognition rate was very low; only a couple of the pictures were recognized properly. The results of our recognition test cannot be completely trusted though because they are based on a very small amount of data.

Figure 2. One of the pictures used in the recognition test. The task given to the user after walking a certain route in the forest was to identify whether the shown pictures were taken on the route.

4. CONCLUSIONS

Despite the many challenges of using eye-tracking systems in a mobile context, they provide a valuable method for gathering data that could not be reached by any other method; for example, behavioural methods such as think-aloud verbal reports and reaction-time-based methods lack the kind of data that can be gathered by eye-tracking solutions. The problematic issues presented should be considered when preparing a test with an eye-tracking system in the wild. Some of the issues, such as the weather and light conditions, are easy to take into account. Some of the problems identified in this study, such as the difficulties of defining area of interests in three-dimensional data, should be reacted by the eye-tracking systems' manufacturers.

Please note that this is a position paper. Many of the findings presented still require validation.

ACKNOWLEDGMENTS

This work was supported by the Graduate School in User-Centered Information Technology (UCIT), the Nokia Foundation and Academy of Finland (project 1129346). Great thanks also go to Antti Nurminen, Mikko Berg, Ville Lehtinen and Tuomo Nyyssönen for helping with the research.

REFERENCES

[1] Bulling, A., Roggen, D., and Tröster, G. 2008. It's in your eyes: towards context-awareness and mobile HCI using wearable EOG goggles. In Proceedings of the 10th International Conference on Ubiquitous Computing (Seoul, Korea, September 21-24, 2008).

[2] Castagnos, S., Jones, N., and Pu, P. 2009. Recommenders' influence on buyers' decision process. In Proceedings of the Third ACM Conference on Recommender Systems (New York, USA, October 23-25, 2009).

[3] Duchowski, A. T. 2007. Eye Tracking Methodology: Theory and Practice. London: Springer-Verlag.

[4] Franchak, J. M., Kretch, K. S., Soska, K. C., Babcock, J. S., and Adolph, K. E. 2010. Head-Mounted eye-tracking of infants' natural interactions: A new method. In ETRA '10: Proceedings of the 2010 symposium on eye-tracking research & applications. ACM.

[5] Hayhoe, M. and Ballard, D. 2005. Eye movements in natural behavior. Trends in Cognitive Sciences. 9, 4, 188-94.

[6] Henderson, J. M. 2003. Human gaze control during real-world scene perception. Trends in Cognitive Sciences. 7, 11, 498-504.

[7] iView X System Manual. Version 2.2. SensoMotoric Instruments.

[8] Nielsen, C. M., Overgaard, M., Pedersen, M. B., Stage, J., and Stenild, S. 2006. It's worth the hassle!: the added value of evaluating the usability of mobile systems in the field. In NordiCHI '06: Proceedings of the 4th Nordic Conference on Human-Computer Interaction (Oslo, Norway, October 14-18, 2006).

[9] Pfeiffer, T., Latoschik, M. E., Wachsmuth, I., and Herder, J. 2008. Evaluation of binocular eye trackers and algorithms for 3d gaze interaction in virtual reality environments. Journal of Virtual Reality and Broadcasting, 5, 16.

[10] Renshaw, J. A. and Webb, N. 2007. Eye tracking in practice. In Proceedings of the 21st BCS HCI Group Conference HCI 2007 (Lancaster University, UK, September 03-07, 2007).

[11] Wagner, P., Bartl, K., Günthner, W., Schneider, E., Brandt, T., and Ulbrich, H. 2006. A pivotable head mounted camera system that is aligned by three-dimensional eye movements. In Proceedings of the 2006 symposium on eye tracking research & applications.

II

DEPTH PERCEPTION IN TABLET-BASED AUGMENTED REALITY AT MEDIUM- AND FAR-FIELD DISTANCES

by

Kuparinen, L, Swan, J. E. II, Rapson, S. & Sandor, C. 2013

Proceedings of the ACM Symposium on Applied Perception (ACM SAP 2013)

Reproduced with kind permission by ACM.

Depth Perception in Tablet-Based Augmented Reality at Medium- and Far-Field Distances

Liisa Kuparinen
University of Jyväskylä
Finland
liisa.kuparinen@jyu.fi

J. Edward Swan II
Mississippi State University
USA
swan@acm.org

Scott Rapson
The University of South Australia
Australia
scott.rapson@magicvisionlab.com

Christian Sandor
The University of South Australia
Australia
christian.sandor@magicvisionlab.com

Current augmented reality (AR) systems often fail to indicate the distance between the user and points of interest in the environment. Empirical evaluations of human depth perception in AR settings compared to real world settings are needed. Our goal in this study was to understand tablet-based AR depth perception by comparing it with real-world depth perception.

Human depth perception has been studied widely for decades. Multiple studies on depth perception in virtual reality (VR) exist, but there are very few which have studied AR. To fill this gap, we replicated and extended a previous study by Lappin et al. [2006], which focused on depth perception in a real world setting. They employed *perceptual bisection*, in which the observer directs an adjustment person to walk until they are standing halfway between the observer and a target person. They found that observers conduct this task differently depending on the observer's environmental context; they studied an open field, a hallway and a lobby, and had the target person stand either 15 or 30 meters from the observer.

We replicated this task in three contexts: in an open field and a hallway in Australia (Figures 1a and 1b), and on a frozen lake in Finland (Figures 1c-d). In addition to conducting the experiment with an actual target person in the real world (as in Lappin et al. [2006]), we also developed a tablet-based AR application which presented a virtual target person (Figure 1). Furthermore, we varied the presence of feedback about the location of the target person. Observers who saw the virtual target person in the field and hallway did not receive any feedback regarding the target person's distance. In these settings, the adjustment person always began walking next to the observer, and walked towards the target person until directed to stop. However, observers who saw the virtual target person on the lake did receive feedback about the target person's distance. In this setting, during half of the trials the adjustment person started their walk by standing at the same distance (either 15 or 30 meters) as the virtual target person, and walked towards the observer until directed to stop. Furthermore, we told the observers that when the adjustment person stood at these distances, they were standing at the same distance as the virtual target person. On every other trial, this provided feedback about where the virtual target person was standing.

We had a total of 20 observers in the experiments (10 male, 10 female, age range of 22–65, average 34 years).

The strongest and most consistent result is that both accuracy and precision varied according to the distance of the target. In every experimental situation, we found that the 15 m result was more accurate, more precise, and slightly overestimated, and that the 30 m result was less accurate, less precise, and underestimated. In addition, we found a positive effect of feedback at the 30 m distance, but not at the 15 meter distance. Overall, with feedback, there was no difference between observers' judgments of real and AR targets at 30 m (average error of –39 cm), but there were differences at 15 m (average error of +32 cm in the real world versus +103 cm in AR). In addition, the real-world results failed to replicate several findings of Lappin et al. [2006].

These experiments suggest that, for tablet-based AR applications, results found at one distance will not necessarily predict the results at other distances. In addition, with practice and brief feedback of 20 minutes or less, performance on a depth perception-related task in tablet-based AR approaches real-world performance.

Reference

LAPPIN, J. S., SHELTON, A. L., AND RIESER, J. J. 2006. Environmental context influences visually perceived distance. *Perception & Psychophysics 68*, 4, 571–581.

Figure 1 *In our experiments, observers bisected egocentric distances in different contexts by directing an adjustment person towards the middle of the distance to a target person. The target person was either virtual, appearing in an augmented-reality application which ran on a tablet (Figures 1a, 1b, and 1c), or a real person (Figure 1d). Environments included an open field (Figure 1a), a corridor (Figure 1b), and an ice-covered lake (Figures 1c and 1d). We also varied feedback about the location of the virtual person; in the open field and hallway observers received no feedback, but they did receive feedback on the lake.*

SAP 2013, August 22 – 23, 2013, Dublin, Ireland.

ACM 978-1-4503-2262-1/13/08

III

VISUALLY PERCEIVED DISTANCE JUDGMENTS: TABLET-BASED AUGMENTED REALITY VERSUS THE REAL WORLD

by

Swan, J.E. II, Kuparinen, L., Rapson, S. & Sandor, C. 2016

Provisionally accepted for publication (pending minor revisions):
International Journal of Human-Computer Interaction (IJHCI) 17.10.2016.

IV

INTRODUCING USABILITY HEURISTICS FOR MOBILE MAP APPLICATIONS

by

Kuparinen, L., Silvennoinen, J. & Isomäki, H. 2013

Proceedings of the 26th International Cartographic Conference (ICC 2013)

Reproduced with kind permission by International Cartographic Association (ICA).

Introducing Usability Heuristics for Mobile Map Applications

Liisa Kuparinen*, Johanna Silvennoinen*, Hannakaisa Isomäki**

* Department of Computer Science and Information Systems
** Department of Mathematical Information Technology
University of Jyväskylä, Finland

Abstract. In this paper, a set of heuristics for evaluating the usability of mobile map applications is introduced. We developed the heuristics by exploring the present generic heuristics and then forming new theory-based heuristics. Usability specialists tested the heuristics by evaluating the usability of a mobile map application with both generic and domain-specific heuristics. As a result, more usability problems were found with the proposed domain-specific heuristics. In addition, based on the evaluators' views the initial domain-specific heuristics were further developed. We conclude by proposing domain-specific usability heuristics for evaluating the mobile map applications.

Keywords: mobile map applications, domain-specific heuristics, heuristic evaluation, cartography, usability, visual design

1. Introduction

Mobile map applications (MMAs) are a current trend of today. Nowadays not only IT oriented people, but also almost everyone who has a smart phone uses MMAs. However, currently usability problems concerning MMAs are not taken in proper consideration. One typical reason for these problems is that there are not enough resources, such as knowledge, time or money, to put into the usability engineering of a map development project.

Analyzing the application's usability with usability heuristics during the development phase is a low-cost and easily implementable way to improve usability. The problem though is that the currently existing usability heuristics are too general to be applicable for evaluating the usability of MMAs. Many research reports (e.g., Bertini et al. 2006) state that domain-specific usability heuristics have been more suitable for evaluating the usability of special applications than general heuristics such as Nielsen's set of usability heuristics (Nielsen & Molich 1990, Nielsen 1994). Domain-specific usability heuristics have been introduced for example to evaluate computer games (Pinelle et al. 2008), children's e-learning applications (Alsumait & Al-Osaimi 2009) and IT security management tools (Jaferian et al. 2011). Still there are no suitable heuristics for MMAs. To additionally evaluate, support and improve the usability of MMAs there is the need to develop domain-specific usability heuristics.

In this study, we test and propose a new set of usability heuristics to support the development of MMAs. Firstly, the heuristics were derived via a theoretical-conceptual procedure based on theories from cartography (MacEachren 1995, Van Laar 2001, Nivala & Sarjakoski 2005, Tyner 2010, Krygier & Wood 2011) and visual design (Mullet & Sano 1995, Lidwell 2003) in relation to the Nielsen's (1994) general heuristics. Special attention was paid towards the visual design of the user interface (UI) of map applications. This is due to the fact that mobile maps deploy specialized visual elements rendering it essential that the user understands their meaning. The proposed heuristics also cover information about the user's location, unambiguous route guidance, map scalability, adaptability of visible information depending on the device's screen size, up-to-date maps, application customizability to support user's personal interests and use of shortcuts to save important locations.

The rest of the paper is organized as follows. First, we discuss the background of the topic, including the previously indicated usability problems and the usability inspection methods of MMAs. Additionally we highlight the gaps of current general usability heuristics. Second, we describe our research method. Third, we discuss the resulting initial domain-specific heuristics in detail. Finally, we conclude by describing our findings.

2. Background

The usability of MMAs is not trouble-free. The problems are related to, for example, the small screen size of the mobile device, interaction limitations of the device, connection speed and limited battery life. This is in addition to several visualization related issues, such as choice of level of detail, enhancement effects, color choices, hierarchy in the use of symbols and visualization of off-screen information (Looije et al. 2007).

Although the problems have been pointed out, they typically still exist in the mobile map services. There are some reasons for this. For instance, map application developers are often not very familiar with usability related issues. Nivala et al. (2007) maintain that although usability is seen as an advantage in the competition to be successful on the map application market, companies often fail to implement the usability engineering approach due to lack of knowledge and resources. Moreover, one problematic issue still is that usability has not played an important role in product development (Jerome & Kazman 2005).

Heuristics evaluation (HE) is a discount method for evaluating usability, as HE can be conducted with low resources in a short timeframe (Nielsen 1992). Another advantage is that although the best results can be achieved with usability professionals performing HE, also non-professionals can use the method to evaluate product usability with some success (Baker et al. 2002). HE has gained criticism for example concerning the variability and in-depth results depending on the evaluator's expertise and commitment (Hertzum & Jacobsen 2003). De Kock et al. (2009) emphasize the type of information HE conveys compared to empirical user testing in that HE is focusing on identifying errors, whereas empirical user testing is determined by effectiveness, efficiency and user satisfaction. They also point out that as empirical user testing deals with the questions such as what and how, HE focuses on a meta-level which considers the questions why and when.

The applicability of Nielsen's heuristics (1994) is limited in terms of evaluating MMAs. This is because the heuristic set does not cover the specific aspects of MMAs such as location awareness, mobility and interruptions. The visual design of mobile maps comprises multiple viewpoints to visual design (e.g., Tyner 2010). Further, Nielsen's heuristics which relate to visual design do not properly take into account cartographic visual design principles. Therefore, these existing heuristics lack many essential viewpoints to effective visual mobile map design, and novel domain-specific heuristics are needed.

3. Research Method

The study was implemented in four phases. First, we explored the generic heuristics (Nielsen 1994) and pointed out their limitations for evaluating the usability of MMAs. Second, we familiarized ourselves with current domain-specific heuristic sets (Pinelle et al. 2008, Alsumait & Al-Osaimi 2009, Jaferian et al. 2011) and explored which methods were used to develop these heuristics. The third phase was to formulate the new heuristics. We derived the initial usability heuristics from Nielsen's (1994) generic usability heuristics by using a conceptual-theoretical approach suitable for the evaluation of MMAs. A similar approach has also been used in the development of other domain-specific usability heuristics (Alsumait & Al-Osaimi 2009, Inostroza et al. 2012).

Finally, the applicability of the initial usability heuristics for MMAs was tested. We asked four usability specialists to evaluate an MMA by completing specific map-related tasks (self-locating, searching address, exploring the map, wayfinding and using POIs). Similar to Jaferian et al. (2011) half of the evaluators were asked to use the original Nielsen heuristics to do the evaluation and half were asked to use our initial heuristics that are presented in *Table 1*. The evaluated application was NavFree (Navmii Holding plc. 2013). The application was chosen because it was not familiar to the evaluators, but is still widely used, offering common MMA functionalities. All four evaluators used a smart phone to do the evaluation: Apple iPhone 3GS (3), and an Android phone Samsung Galaxy Nexus (1). After completing the evaluation, we asked the evaluators to rate the applicability of the heuristics for evaluating the MMA and the intelligibility of each of the heuristics. We also asked for specific feedback of the heuristics.

Jakob Nielsen's Heuristics	Proposed Heuristics for Mobile Map Applications
1. Visibility of system status The system should always keep users informed about what is going on, through appropriate feedback within reasonable time.	**1. Visibility of the contextual map functions** The map application should always keep the user informed about what is going on, through appropriate feedback within a reasonable time. The map functions should be visible.
2. Match between system and the real world The system should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.	**2. Match between the system and the physical surroundings of the user** The map application should show clear indication of the user's current location on the map and of the possible target location. It is essential that the map compares in an understandable way with the physical surroundings of the user. The map should be up-to-date.
3. User control and freedom Users often choose system functions by mistake and will need a clearly marked "emergency exit" to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.	**3. User control over map functions and locations** Allow the user to take control over map application when interruptions (from the mobile device: phone call, message, other applications' notifications, from the concrete surroundings: traffic, weather, traffic lights) happen.
4. Consistency and standards Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform conventions.	**4. Consistency and standards** Follow platform conventions. Use clear, intuitive, commonly known map symbols.
5. Error prevention Even better than good error messages is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.	**5. Error prevention** Even better than good error messages is a careful design, which prevents a problem from occurring in the first place. If errors still happen, make sure to offer the possibility to recover from them.

6. Recognition rather than recall Minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.	**6. Recognition rather than recall** Make sure that the main functions of the map application (e.g. search, route guidance, zooming, panning) are easily accessible. Use short menu paths for the main functions or keep the main functions visible at all times.
7. Flexibility and efficiency of use Accelerators -- unseen by the novice user -- may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.	**7. Flexibility and efficiency of use** Offer flexible options for the main map functions. Allow the user to save locations to be used as shortcuts (e.g. home) and support POI information. Give easy access to additional information (metadata, links, user-generated content). Make sure the user interface is scalable for different screen sizes of mobile devices.
8. Aesthetic and minimalist design Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.	**8. Balanced and simplistic visual design** Harmonious overall appearance should consist of clear contrast between visual elements, balanced layout and informative colors. Avoid visual clutter.
9. Help users recognize, diagnose, and recover from errors Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.	**9. Help users recognize, diagnose, and recover from errors** Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution. Indicate clearly the reasons if the searched locations are not found. Save the user's previous searches for fast repetition.
10. Help and documentation Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.	**10. Help and documentation** Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Provide both: fast guidance focused on the user's task and a more detailed guide with search functions.

Table 1. General and domain-specific heuristics

4. Results

The testing of the proposed MMA heuristics compared to the Nielsen (1994) heuristics pointed out that with the MMA heuristics more usability problems (19, of which 6 were severe) were found than with the Nielsen heuristics (15, of which 5 were severe). On a scale from 1 to 5, where 1 is the least suitable and 5 is the most suitable, the suitability of the MMA heuristics was rated twice as 4 and the Nielsen heuristics as 2 and 3.

The initial heuristics (*Table 1*) have been further elaborated by feedback of the applicability of the heuristics given by the usability specialists. In the following list we introduce the proposed usability heuristics for MMAs and present the justification for each of the heuristics.

1. **Visibility of the contextual map functions and important locations.** The map application should always interact with the user by giving informative feedback within reasonable time. The map functions should be visible. The map view should constantly stay visible when the map application is in use.

The limited display size of the mobile devices causes challenges for both setting map functions and making important map locations visible (Burigat et al. 2008). The power saving mode should not turn on if the user is in constant need of the map application's assistance.

2. **Match between the system and the physical surroundings of the user.** The map application should show clear indication of the user's location and other important locations (e.g. destinations and POIs) on the map. It is essential that the map corresponds in an understandable way with the physical surroundings of the user. The map should be up-to-date.

Oulasvirta et al. (2008) have compared the embodied interaction of 2D versus 3D mobile maps and summarized that 3D maps present realistic representation of objects, variable views from first-person perspective and more degrees of freedom in movement. 2D maps guide users into using environmental cues like street names and crossings. Meilinger et al. (2007) point out that different map types suit different tasks.

3. **User control over map functions.** Allow the user to take control of the map application when interruptions (from the mobile device: phone call, message, other applications' notifications, from the concrete surroundings: traffic, weather, traffic lights) happen. Allow multitasking.

Interruptions such as incoming emails, SMSs and phone calls influence interaction with mobile devices. When such interruptions occur, the application should save its current state and still be able to give the needed navigation instructions. As the use of a MMA is often concurrent with other tasks (Tamminen et al. 2004), allowing multitasking is essential. The MMA should also be context-aware, i.e. adapt to the surrounding conditions as that may enable more efficient uses of mobile applications (Häkkilä et al. 2009). For example, the MMA should adjust the visibility of screen size according to the lighting conditions and time of day.

4. **Consistency and standards.** Follow platform conventions in the user interface design. Be consistent within the use of interaction gestures, controls, functions, elements of user interface and map features. Use clear, intuitive, commonly known map symbols.

Symbols for mobile maps are designed for small screen size in which it is essentially important to consider clarity, intuitiveness and map symbol conventions. In order for the map symbols to be clear, simplification and abstraction are essential (Mullet & Sano 1995). Krygier and Wood (2011) emphasize that map symbols should work through resemblance, relationship, convention, difference, and standardization.

5. **Error prevention.** Make the map application free of errors. If errors still happen, be sure to offer the possibility to recover from them. Prevent the user from getting lost.

Careful testing of the MMA should be performed in order to reduce the amount of errors. Wayfinding support prevents users from getting lost (Schmid et al. 2010) – as long as the wayfinding instructions are correct. Besides visual and audible instructions, also tactile feedback can be given to the users (Pielot et al. 2009). Tversky (2003) emphasizes the use of local environmental cues.

6. **Recognition rather than recall.** Minimize the user's memory load. Make sure that the main functions of the map application (e.g. exploring, route guidance, zooming, panning, POI selection) are easily accessible. Use short menu paths for the main functions or keep the main functions present all the time.

Mayer and Moreno (2003) discuss cognitive overload in the context of multimedia learning. To avoid overload, they suggest solutions, such as offloading by using different multimedia channels to present information, providing cues about how the user can select and organize the data and aligning the content in a balanced way.

7. **Flexibility, scalability and efficiency of use.** Offer flexible options for the main map functions. Allow the user to save locations to be used as shortcuts (e.g. home) and support POI information. Give easy access to additional information (metadata, links, user-generated content). Make sure the user interface is scalable for different screen sizes of mobile devices.

Setlur et al. (2010) present three types of optimizations implemented to enhance the usability of specific MMAs. They emphasize the rendering techniques, interaction paradigms and optimizing the system's performance.

8. **Balanced and simplistic visual design.** Harmonious overall appearance should consist of clear contrast between visual elements, balanced layout and informative colors. Visual elements should guide users gaze to important elements. Avoid visual clutter.

In harmonious overall appearance all elements should work well together and complement each other (Tyner 2010). Harmony plays an important role in evaluating the overall appearance of mobile maps (Nivala & Sarjakoski 2005). According to Tyner (2010), balance, clarity and contrast are important in effective map design. The composition of a map should be balanced. Clarity of the map is mainly achieved through contrast, which can be created with opposites, such as dark and light. Visual clutter should be avoided. MacEachren (1995) states that the distinction between insignificant and significant visual elements needs to be made clear in order to guide attention to specific details. Color is beneficial in the context of locating and searching information (Van Laar 2001) and for grouping elements (Lidwell 2003). Krygier and Wood (2011) point out that colors should be more intense because of varying lighting conditions in use contexts of mobile maps.

9. **Recognizing, diagnosing and recovering from errors.** Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution. Indicate clearly the reasons for why the searched locations are not found. Save the user's previous searches for fast repetition.

When errors occur, recovering from them should be straightforward. Haklay and Nivala (2010) state: "Actions that are reversible are important for relieving anxiety because it is clear to the user that errors can be undone and they should not feel that they will 'break' the system by one mistaken action."

10. **Offering help.** Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Provide both: fast guidance focused on the user's task and more detailed documentation with search functions. Pay attention to the understandability of the help.

Skarlatidou (2010) emphasize the careful design of help and documentation based on the purposes of the application and the user context. He points out that it is essential to offer instructions for the description and use of the tasks that are included in the application. Moreover, he states that as the majority of map application users are not familiar with the special terminology of the field, the vocabulary and instructions should be simple.

5. Conclusion

We propose domain specific heuristics for evaluating the usability of MMAs. Four usability specialists tested initial, theoretically derived MMA heuristics versus the general Nielsen (1994) heuristics to evaluate the usability of MMA. As a result, more usability problems were found with the initial domain-specific heuristics. Also, the initial heuristics were rated more applicable for the MMA domain. The proposed heuristics also include in-depth insights to the heuristic evaluation of visual mobile map design. Based on the results of this study it can be summarized that domain-specific usability heuristics are needed in order to properly evaluate MMAs.

A limitation in this study is the small amount of evaluators for testing the proposed heuristics. The results of HE are also known for being dependent on the evaluators (Hertzum & Jacobsen 2003). Also, the generalizability of the heuristics is uncertain at this stage, as the field of MMAs is wide. We will further validate the proposed MMA heuristics. Future steps will include testing the proposed heuristics with a larger data collection.

6. Acknowledgements

We want to thank Rebekah Rousi, Jussi Jokinen, Piia Perälä and Mazhar Sadiq for carrying out testing of the initial MMA usability heuristics.

References

Alsumait A, Al-Osaimi A (2009) Usability heuristics evaluation for child e-learning applications. In Proceedings of the 11th International Conference on Information Integration and Web-based Applications & Services. ACM, New York, USA. 425–430

Baker K, Greenberg S, Gutwin C (2002) Empirical development of a heuristic evaluation methodology for shared workspace groupware. In Proceedings of the 2002 ACM Conference on Computer Supported Cooperative Work. ACM, New York, NY, USA. 96–105

Bertini E, Gabrielli S, Kimani S (2006) Appropriating and assessing heuristics for mobile computing. In Proceedings of the Working Conference on Advanced Visual Interfaces. ACM: New York, NY, USA. 119–126

Burigat S, Chittaro L, Gabrielli S (2008) Navigation techniques for small-screen devices: An evaluation on maps and web pages. International Journal of Human-Computer Studies 66:78–97

Haklay M, Nivala A-M (2010) User-Centred Design. In Interacting with Geospatial Technologies, M. Haklay, ed. John Wiley & Sons, Ltd, Chichester, UK. 89–106

Hertzum M, Jacobsen NE (2003) The Evaluator Effect: A Chilling Fact About Usability Evaluation Methods. International Journal of Human-Computer Interaction 15:183–204

Häkkilä J, Schmidt A, Mäntyjärvi J, Sahami A, Åkerman P, Dey AK (2009) Context-Aware Mobile Media and Social Networks. In Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services. ACM: New York, NY, USA. 3

Inostroza R, Rusu C, Roncagliolo S, Jimenez C, Rusu V (2012) Usability Heuristics for Touchscreen-based Mobile Devices. In The Ninth International Conference on Information Technology: New Generations. IEEE, Las Vegas, NV, USA. 662–667

Jaferian P, Hawkey K, Sotirakopoulos A, Velez-Rojas M, Beznosov K (2011) Heuristics for evaluating IT security management tools. In Proceedings of the Seventh Symposium on Usable Privacy and Security. ACM: New York, NY, USA. 20

Jerome B, Kazman R (2005) Surveying the Solitudes: An Investigation into the Relationships between Human Computer Interaction and Software Engineering in Practice. In Human-Centered Software Engineering — Integrating Usability in the Software Development Lifecycle, A Seffah, J Gulliksen, MC Desmarais, eds. Springer-Verlag, Berlin/Heidelberg. 59–70

de Kock E, van Biljon J, Pretorius M (2009) Usability evaluation methods: mind the gaps. In Proceedings of the 2009 Annual Research Conference of the South African Institute of Computer Scientists and Information Technologists. ACM: New York, NY, USA. 122–131

Krygier J, Wood D (2011) Making maps: a visual guide to map design for GIS. Guilford Press, New York

Van Laar DL (2001) Psychological and cartographic principles for the production of visual layering effects in computer displays. Displays 22(4):125–135

Lidwell W (2003) Universal principles of design. Rockport, Gloucester, Mass

Looije R, te Brake GM, Neerincx MA (2007) Usability engineering for mobile maps. In Proceedings of the 4th International Conference on Mobile Technology, Applications, and Systems and the 1st International Symposium on Computer Human Interaction in Mobile Technology. ACM, New York, NY, USA. 532–539

MacEachren AM (1995) How maps work: representation, visualization, and design. The Guilford Press

Mayer RE, Moreno R (2003) Nine Ways to Reduce Cognitive Load in Multimedia Learning. Educational Psychologist 38(1):43–52

Meilinger T, Hölscher C, Büchner SJ, Brösamle M (2007) How Much Information Do You Need? Schematic Maps in Wayfinding and Self Localisation. In Spatial Cognition V Reasoning, Action, Interaction, T Barkowsky, M Knauff, G Ligozat, DR Montello, eds. Springer, Berlin Heidelberg. 381–400

Mullet K, Sano D (1995) Designing visual interfaces: communication oriented techniques. SunSoft Press, Englewood Cliffs, NJ

Navmii Holding plc (2013) Navmii. http://www.navmii.com. Accessed 12 April 2013

Nielsen J (1992) Finding usability problems through heuristic evaluation. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA. 373–380

Nielsen J (1994) Heuristic evaluation. In Usability Inspection Methods, Nielsen J, Mack RL, eds. John Wiley & Sons, New York, NY, USA

Nielsen J, Molich R (1990) Heuristic evaluation of user interfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA. 249–256

Nivala A-M, Sarjakoski LT (2005) Adapting Map Symbols for Mobile Users. In Proceedings of the 22nd International Cartographic Conference. International Cartographic Association, Spain

Nivala A-M, Sarjakoski LT, Sarjakoski T (2007) Usability methods' familiarity among map application developers. International Journal of Human-Computer Studies 65(9):784–795

Oulasvirta A, Estlander S, Nurminen A (2008) Embodied interaction with a 3D versus 2D mobile map. Personal and Ubiquitous Computing 13(4):303–320

Pielot M, Henze N, Boll S (2009) Supporting map-based wayfinding with tactile cues. In Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services. ACM, New York, NY, USA. 10

Pinelle D, Wong N, Stach T (2008) Heuristic evaluation for games: usability principles for video game design. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA. 1453–1462

Schmid F, Richter K-F, Peters D (2010) Route Aware Maps: Multigranular Wayfinding Assistance. Spatial Cognition & Computation 10(2-3):184–206

Setlur V, Kuo C, Mikelsons P (2010) Towards designing better map interfaces for the mobile. In Proceedings of the 1st International Conference and Exhibition on Computing for Geospatial Research & Application. ACM, New York, NY, USA. 4

Skarlatidou A (2010) Web-Mapping Applications and HCI Considerations for their Design. In Interacting with Geospatial Technologies, MM Haklay, ed. John Wiley & Sons, Ltd, Chichester, UK. 245–264

Tamminen S, Oulasvirta A, Toiskallio K, Kankainen A (2004) Understanding mobile contexts. Personal and Ubiquitous Computing 8(2):135–143

Tversky B (2003) Navigating by Mind and by Body. In Spatial Cognition III. Routes and Navigation, Human Memory and Learning, Spatial Representation and Spatial Learning, C Freksa, W Brauer, C Habel, KF Wender, eds. Springer Berlin Heidelberg, Berlin, Heidelberg. 1–10

Tyner JA (2010) Principles of map design. Guilford Press, New York

V

VALIDATION AND EXTENSION OF THE USABILITY HEURISTICS FOR MOBILE MAP APPLICATIONS

by

Kuparinen, L. 2016

Proceedings of the 6th International Conference on Cartography and GIS
(ICC&GIS 2016).

VALIDATION AND EXTENSION OF THE USABILITY HEURISTICS FOR MOBILE MAP APPLICATIONS

Liisa Kuparinen

Doctoral student, Liisa, Kuparinen;
Department of Computer Science and Information Systems,
University of Jyväskylä, Finland;
+358 44 3737425
liisa.kuparinen@jyu.fi

Abstract
Heuristic usability evaluation is light but efficient method for finding usability problems. In this paper, we report the process of validation and further development of the previously introduced usability heuristics for mobile map applications. The validation began by testing the heuristics by 58 evaluators who used them for usability evaluation of four different map applications. The evaluators also filled a questionnaire about the understandability of the heuristics. The amount, severity and quality of the problems found with the heuristics were reviewed and the heuristics' understandability analyzed. As a result, it was shown that the heuristics were efficient for finding usability problems from mobile map applications. The analysis of the understandability pointed out the need to clarify the heuristics. On the basis of the findings, the heuristics were further developed. The usability heuristics introduced in this paper are supposed to be widely usable in the development of mobile map applications.

Keywords: *mobile map applications, map application development, usability heuristics, heuristic evaluation, domain-specific heuristics, usability evaluation, cartography, usability*

INTRODUCTION

The mobile map applications have become widely used in various situations. As the use cases of them are typically critical concerning for example safety (e.g. traffic and avoid getting lost) and timetables (being in time), it is also important that the usability of the mobile map applications is in a decent level. Heuristic evaluation is light but efficient way for finding usability problems in different applications (Nielsen, 1992). The another advantage of the method is that it is suitable to be used also by the evaluators that are non-professionals with usability (Nielsen, 1992).

Several usability heuristics for various different domains have been introduced earlier. The domains that are close to mobile map applications and that are having their own heuristics, include mobile computing (Bertini, Gabrielli, & Kimani, 2006), information visualization (Forsell & Johansson, 2010; Zuk, Schlesier, Neumann, Hancock, & Carpendale, 2006), Web-based GIS (Komarkova, Visek, & Novak, 2007) and mobile devices (Machado Neto & Pimentel, 2013). The most known and the most used heuristics are though the Nielsen heuristics introduced in (1994).

Kuparinen et al. (2013) introduced the first usability heuristics for mobile map applications. Since publishing the heuristics in the International Cartographic Conference 2013, they have also been presented for cartographers in the meeting of Finland's cartographic association in 2013. The received feedback in these occasions indicated high interest towards development of the usability heuristics for map area. The heuristics have also been noticed in various scientific publications since 2013. The development process has continued and is further discussed as follows.

Hermawati and Lawson (2016) have done a wide comparison of the development processes of usability heuristics for various domains. They summarized that 34 % of the 70 inspected heuristic development processes did not report any validation. To prove the effectiveness of heuristics, Hermawati and Lawson also suggest that establishing heuristics should not stop on the proposal of them. Although the Kuparinen et al. heuristics were tested by four usability specialists (Kuparinen et al., 2013) by using the heuristics in comparison to Nielsen heuristics, a validation with higher amount of data was still needed. This validation is presented in this paper.

The validation of the previously introduced heuristics began by testing the heuristics by 58 evaluators. The evaluators used the heuristics for the usability evaluation of three different mobile map applications and, as a point of reference, also for one map application used with a computer and a web browser. The test reports were collated and the amount, severity and quality of the problems found with each of the heuristics were reviewed. After the evaluation, 41 evaluators filled a questionnaire about the understandability of each of the heuristics. After analyzing these data sets, the heuristics were further developed on the basis of the findings.

The rest of the paper is organized as follows. First, we discuss the background of the topic, including the previously indicated usability problems. Second, we describe our research method; the used heuristics and the validation process. Third, we report the analysis of testing the heuristics and the analysis of the questionnaire answers of the heuristics' understandability. Finally, we present the overall results and the validated and extended heuristics. The conclusion and discussion come as last.

RESEARCH METHOD

The research method consisted of three phases. At first, the heuristics were used to evaluate map applications and the amount and severity of the findings were analyzed. At second, the evaluators filled a questionnaire about the understandability of each of the heuristics and this data was analyzed. At third, the heuristics were further developed on the basis of the findings. This process is described in this section in more detail.

Used Heuristics

The following heuristics by Kuparinen et al. (2013) were used in the evaluation. A Finnish translation of the heuristics was given to the evaluators as they were all Finnish speakers.

1. **Visibility of the contextual map functions and important locations.** The map application should always interact with the user by giving informative feedback within reasonable time. The map functions should be visible. The map view should constantly stay visible when the map application is in use.
2. **Match between the system and the physical surroundings of the user.** The map application should show clear indication of the user's location and other important locations (e.g. destinations and POIs) on the map. It is essential that the map corresponds in an understandable way with the physical surroundings of the user. The map should be up-to-date.
3. **User control over map functions.** Allow the user to take control of the map application when interruptions (from the mobile device: phone call, message, other applications' notifications, from the concrete surroundings: traffic, weather, traffic lights) happen. Allow multitasking.
4. **Consistency and standards.** Follow platform conventions in the user interface design. Be consistent within the use of interaction gestures, controls, functions, elements of user interface and map features. Use clear, intuitive, commonly known map symbols.
5. **Error prevention.** Make the map application free of errors. If errors still happen, be sure to offer the possibility to recover from them. Prevent the user from getting lost.
6. **Recognition rather than recall.** Minimize the user's memory load. Make sure that the main functions of the map application (e.g. exploring, route guidance, zooming, panning, POI selection) are easily accessible. Use short menu paths for the main functions or keep the main functions present all the time.
7. **Flexibility, scalability and efficiency of use.** Offer flexible options for the main map functions. Allow the user to save locations to be used as shortcuts (e.g. home) and support POI information. Give easy access to additional information (metadata, links, user-generated content). Make sure the user interface is scalable for different screen sizes of mobile devices.
8. **Balanced and simplistic visual design.** Harmonious overall appearance should consist of clear contrast between visual elements, balanced layout and informative colors. Visual elements should guide users gaze to important elements. Avoid visual clutter.
9. **Recognizing, diagnosing and recovering from errors.** Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution. Indicate clearly the reasons for why the searched locations are not found. Save the user's previous searches for fast repetition.
10. **Offering help.** Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Provide both: fast guidance focused on the user's task and more detailed documentation with search functions. Pay attention to the understandability of the help.

Validation Process

As part of the university course User-Centered Software Development 66 Finnish students performed a usability heuristic evaluation for a map application by using the heuristics introduced by Kuparinen et al. (2013). 58 of the evaluators gave their permission to use their usability analysis report in part of the research when updating the usability heuristics for mobile map applications.

The task for the evaluators was to conduct a usability analysis for a mobile map application by a smart phone, or in the case of not having a smart phone, for an internet browser based map application by a laptop or desktop computer. Depending of the smart phone's operating system, three options were offered for the analysis of a mobile map application: MapFactor Navigator Free (MapFactor, 2013) for Android, MapFactor Navigator Free (MapFactor, 2013) or Nokia Maps (Nokia, 2013) for Windows Phone and NavFree (Navmii, 2013) for iOS. Three different applications were offered because of the problem of finding one suitable mobile map application for every operation system. As there were a total of 138 students registered for the course and all of them were possible participants also to conduct the usability analysis, we were not able to arrange a smart phone with consistent operating system for all of them. Instead, the students were allowed to use their own smart phone, or one of the loanable smart phones, to complete the analysis. If a student could not use a smart phone, he was allowed to conduct the analysis by a computer. In that case, the used map application was Fonecta Maps (Fonecta, 2013).

The number of evaluators using each of the applications was following:

- MapFactor Navigator Free (Android): 17 evaluators (29 %)
- Nokia Maps (Windows Phone: 12, Symbian: 4, Meego: 1): 17 evaluators (29 %)
- NavFree (iOs): 8 evaluators (14 %)
- Fonecta Maps (Computer and web browser): 16 evaluators (28 %)

To clear it up, 28 % of the analyses were completed with computer and a browser-based map application and total of 72 % with mobile map applications.

The tasks the evaluators executed were:

1. Locate yourself on the map so that you can see your current street address.
2. Find a predefined address by using the search function of the map service.
3. Scroll the map. Try to perceive the target location in relation to your current address. Do not use navigational tools, but only scroll the map.
4. Get navigation guidance: You want to walk to your predefined target location. Get pedestrian guidance. Check the estimated travel time.
5. Find a Point-of-Interest. You are planning to have lunch after your meeting in the predefined target location. Find a restaurant which is located a maximum 500 meters from your target location.
6. Find another predefined address: Use the search function of the map service.

The task number 6 was a trick question. The predefined address didn't really exist and the goal of the task was to see how the map service works in a case when it cannot find the address – and how will the heuristics answer to an error like that.

The tasks were chosen to fulfill the typical tasks for mobile map applications. For example, Wiener et al.'s (2009) taxonomy of wayfinding, including i.e. exploration, search, undirected and directed wayfinding, target approximation and path planning, was used as the basis for formulating the tasks.

The evaluators were also asked about the understandability of each of the heuristics. The questionnaire used in this asked numerical estimation of the understandability of each of the heuristics in a scale from 1 to 5. There was also a possibility to give comments of each of the heuristics. Although it was voluntary to fill this questionnaire, still 41 evaluators took part also on this part of the study.

As the author of this paper is one of the developers of the validated heuristics, and by that the research may be seen as participatory action research (PAR), it was essentially important to describe the research method strictly – so that has been the goal in this research report.

ANALYSIS OF TESTING THE HEURISTICS

A total of 903 usability problems were reported in the evaluation reports. The summary of the quantitative analysis of the evaluation is presented in Table 1.

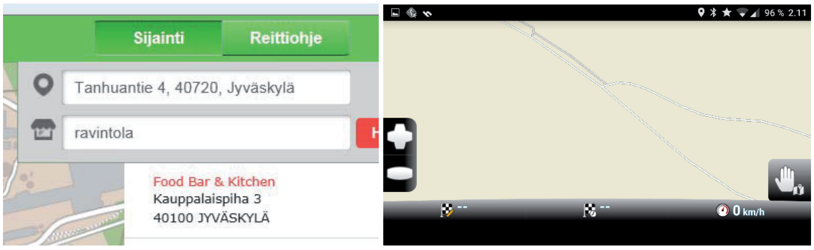
Table 1. *Found problems with the heuristics. The especially low and high values in the category All are bolded.*

Heuristic	Amount of problems found per evaluator	Severity of problems, mean (0-4, 4=the worst)	Major or catastrophic problems	Understandability, mean (1-5, 5=the best)
1. Visibility of the contextual map functions and important locations.	**All: 2,6**	minor (2,3)	42 %	3,9
	Mobile: 2,8	minor (2,3)	42 %	3,9
	Browser: 1,9	minor (2,3)	43 %	3,9
2. Match between the system and the physical surroundings of the user.	All: 1,9	**major (2,8)**	**59 %**	4,1
	Mobile: 1,9	major (2,8)	63 %	4,0
	Browser: 1,8	major (2,7)	50 %	4,2
3. User control over map functions.	**All: 0,7**	**major (2,6)**	49 %	4,0
	Mobile: 0,5	major (2,5)	36 %	3,9
	Browser: 0,9	major (2,8)	67 %	4,4
4. Consistency and standards	All: 1,7	minor (2,4)	50 %	4,0
	Mobile: 1,8	minor (2,3)	47 %	3,9
	Browser: 1,7	major (2,6)	58 %	4,1
5. Error prevention.	All: 1,0	**major (2,6)**	**54 %**	4,0
	Mobile: 1,2	major (2,7)	54 %	4,0
	Browser: 0,7	minor (2,4)	55 %	4,1
6. Recognition rather than recall.	All: 1,6	**minor (2,2)**	**38 %**	4,0
	Mobile: 1,7	minor (2,1)	36 %	3,9
	Browser: 1,3	major (2,6)	45 %	4,4
7. Flexibility, scalability and efficiency of use	**All: 2,3**	minor (2,4)	47 %	**3,8**
	Mobile: 1,8	minor (2,4)	51 %	3,8
	Browser: 3,8	minor (2,3)	43 %	4,0
8. Balanced and simplistic visual design	**All: 0,8**	**minor (2,2)**	**35 %**	4,1
	Mobile: 0,6	minor (2,3)	38 %	4,1
	Browser: 1,3	minor (2,1)	30 %	4,3
9. Recognizing, diagnosing and recovering from errors	All: 1,1	**major (2,6)**	51 %	**3,8**
	Mobile: 1,2	major (2,7)	56 %	3,8
	Browser: 0,7	minor (2,1)	27 %	3,7
10. Offering help.	All: 1,7	major (2,5)	53 %	4,1
	Mobile: 1,8	minor (2,4)	53 %	4,0
	Browser: 1,6	major (2,6)	52 %	4,3
Undefined heuristic	All: 0,2	cosmetic (1,2)	27 %	XX
	Mobile: 0,2	cosmetic (1,3)	33 %	XX
	Browser: 0,2	cosmetic (0,5)	0 %	XX
All of the heuristics, mean	All: 1,6	minor (2,4)	48 %	4,0
	Mobile: 1,6	minor (2,4)	48 %	3,9
	Browser: 1,6	minor (2,4)	46 %	4,1

The heuristics number 1 (Visibility of the contextual map functions and important locations) and 7 (Flexibility, scalability and efficiency of use) were most efficient for finding the problems. The heuristics number 3 (User control over map functions) and 8 (Balanced and simplistic visual design) were in use to find the least amount of problems.

The most critical problems were found with the heuristics 2 (Match between the system and the physical surroundings of the user), 3 (User control over map functions), 5 (Error prevention) and 9 (Recognizing, diagnosing and recovering from errors). This finding indicates these heuristics to be essentially important. Although the least severe problems were found with the heuristics 6 (Recognition rather than recall) and 8 (Balanced and simplistic visual design), these heuristics cannot be seen as totally useless as the percentage of found major or catastrophic problems was still over 30 %.

Examples of the problems are presented in Figure 1.



Tanhuantie 4, 40720, Jyväskylä

ravintola

Food Bar & Kitchen
Kauppalaispiha 3
40100 JYVÄSKYLÄ

Figures 1A (left) and 1B (right). 1A: From the evaluator's problem report: A usability problem concerning the heuristic number 3: User control over map functions. The evaluator reported that when he was trying to mark a POI on the map, all the search results were reset. 1B: An example of catastrophic problem: the map is not corresponding the physical surroundings; there is too little map data, road names or even the roads are missing.

There were 10 reported problems (1 % of all) that were not categorized under any of the heuristics. As the amount is very small, that indicates that the heuristics work well in finding the usability problems as well as supporting to revolve the solutions for the usability problems.

33 of the reported problems (4 % of all) were not connected to any of the assigned tasks. It seems that most of these are because of neglected completion of the analysis report but at least some of them were problems that were not connected to any of the tasks. These problems were mostly related to the outlook, color and aesthetics of the application. This raises the suggestion that, besides the specific tasks in the heuristic analysis, there should always be included the overall evaluation of the aesthetics of the user interface.

Although the analysis is done also between the mobile and browser-based map applications, there should not be too much attention paid on the differences of these. That is because the applications differed between each other and naturally had differences also by means of usability. It is though interesting that the heuristics were equally effective in finding usability problems with both, mobile and browser-based applications. Naturally there were heuristics that did not work that well with browser-based application that is typically used in a stationary manner and not by mobile device.

Understandability of the Heuristics

Also the overall data of the understandability is presented in Table 1. The data of one of the evaluators had to be excluded as the evaluator hadn't understand the questions correctly.

The overall understandability of the heuristics was good: mean 4,0 in the scale from 1 (very difficult to understand) to 5 (very well understood). The understandability of the heuristics was also compared to each other. The heuristics that were the most difficult to understand were numbers 7 (Flexibility, scalability and efficiency of use) and 9 (Recognizing, diagnosing and recovering from errors).

Some of the comments that were seen as the most substantive in the development of the heuristics, are presented following.

Conflicting with the heuristic 1, it was stated that the map view is not natural to stay visible at all times in a mobile device when the screen is small and the active use of functions covers it. Also the different use cases concerning transportation methods were noticed.

Concerning the heuristic 4, the evaluators stated that the standards or commonly known symbols are not always clear to the evaluators. It was also pointed out that the language problems are not identified to any of the heuristics and they could be put part of the heuristic number 4. Also the need for allowing differing solutions for example because of company-wide practices was discussed.

Heuristic number 5 was commented with the notice that the prevention of user getting lost could refer also to getting lost in the application menus. One evaluator identified overlapping of the specification "offer possibility to recover from errors" and the heuristic number 9.

About heuristic 8 one evaluator pointed out that the capability to obey this heuristic depends on the experience of visual design and that is why this heuristic may lead to undesirable results. The problem is similar to heuristic number 4 – if the evaluator isn't experienced with using map applications, he may not have the needed experience of the standards.

In the comments of heuristic number 9 it was stated that it is good to show also the exact error code e.g. behind a link for the power users that are willing to find out more about the errors. Two evaluators felt that saving the user's previous searches for fast repetition should not be part of this heuristic.

Many problems (total 166, 18 % of the overall amount of problems of 903) were marked to break multiple heuristics. Especially common were the combinations of the heuristics 1 and 6 (overlapping 23 times) and 6 and 7 (overlapping 17 times). All the common cases of overlapping were:

- 23 times: heuristic 1+6
- 17 times: heuristic 6+7
- 15 times: heuristics 7+10 and 9+10
- 14 times: heuristics 1+2, and 1+4, and 1+7, and 2+5
- 13 times: heuristics 1+10, and 4+6, and 5+10
- 12 times: heuristics 2+6, and 5+9

The findings indicate the need to clarify the difference of these possibly overlapping heuristics. The overlapping of the heuristics 5 and 9 was also reported in the verbal reports so these heuristics need special attention in the formation of the updated heuristics.

RESULTS

At first the overall results of testing the heuristics and analysis of the heuristics' understandability are presented. After that the validated and extended heuristics are introduced.

Results of the Validation

In the evaluation reports, there were only small amount of usability problems that were not categorized under any of the heuristics and any of the assigned tasks. This indicates two conclusions. At first, the heuristics seem to work well in finding the usability problems. At second, the tasks seem to be adequate to point out the problems. It is still noteworthy that there were some usability problems that were not categorized under any of the tasks and these problems were mostly related to the outlook, color and aesthetics of the application. This leads to a conclusion that the evaluation of the overall aesthetics of the user interface should always be part of the heuristic usability evaluation even though it wouldn't be a part of the actual tasks.

Also the low severity value of the problems that were found outside the heuristic set indicates that the original heuristic set covers the typical and the most influential usability problems well.

As there was equal amount of usability problems found per user with both, mobile and browser-based map application, it is probable that most of the heuristics work sufficiently also with map applications that are used in stationary manner with browser-based applications.

It is essential that the evaluators understand the heuristics correctly, so it is needed to improve the understandability of the heuristics that were unclear to the evaluators. As we conducted the usability analysis for the total of four different applications, the information about the suitability and understandability of the heuristics became clear in the analysis phase. As the heuristics are supposed to be used also by non-usability professionals, also a need to simplify the used terminology is real.

Based on the evaluators comments of understandability, it is preferable to have also “other problems” section in the heuristic evaluation form.

Validated and Extended Heuristics

To make the heuristics clearer, verbs were included already in the titles of the heuristics. To avoid the overlapping that realized with the tested heuristics, the heuristic titles were detailed and descriptions updated. Also, two more heuristics were added in the simplification phase of the contents of the previous heuristics. The heuristics were also reorganized to have the similar but differing heuristics consecutively to each other in order to make the understanding of the differences easier. Next, the most remarkable changes are presented.

Heuristic 1: The heuristic was moved to be the first one as this can be seen to be the most important heuristic for map applications. The importance of preventing the user from getting lost is emphasized. (Old heuristic was number 2.)

Heuristic 2: Detailed guidance of the need for having map view visible is added. A mention about the locating the advertisement is included. The mention of giving feedback within reasonable time is relocated to heuristic 10 and the mention of map functions is divided to a new heuristic, number 3. (Old heuristic was number 1.)

Heuristic 3: The main map functions are specified. The need to indicate also the location in the application functions is added. (Old heuristic were numbers 1 and 6.)

Heuristic 4: As the support for the shortcuts of locations and previous searches is typical and useful function of map applications, it is separated to be a new heuristic. Also the notice of minimizing user’s memory load is more coherent in the context of providing shortcuts for locations and additional information than with the visibility of still typically quite few and simple map functions. The confusing heuristic title “Recognition rather than recall” was also simplified in this heuristic. “Addresses from contact book” is now mentioned. (This heuristic is mainly new.)

Heuristic 5: As the heuristic “User control over map functions” was the least efficient in the finding of usability problems and previously it was not presented in a very clear title, it is reformulated. The possible interruptions are widened. A need for returning to the previous application state after using other applications is added. (Old heuristic was number 3.)

Heuristic 6: Mentioning the standards was found challenging as the evaluators pointed out that the standards may be unknown to evaluators. Heuristic is clarified in this manner. It is clarified that the consistency refers to the implementation of the map features in different parts of the application. Examples of the preferred map symbols are given. It is not anymore strict requirement to use commonly used design solutions. (Old heuristic was number 4.)

Heuristic 7: The evaluators pointed out that there was no heuristic for the consistent use of terminology and use of language so this heuristic is added. (This heuristic is new.)

Heuristic 8: The title is clarified and the mention of preventing user of getting lost is relocated to heuristic 1. (Old heuristic was number 5.)

Heuristic 9: The error codes are guided to be shown behind links. Saving previous locations is moved under heuristic 4. (Old heuristic was number 9.)

Heuristic 10: A mention of map functions is moved to heuristic 3. The need to adapt to different use cases is added. The need of letting the user adjust the power saving options is added. (Old heuristic was number 7.)

Heuristic 11: The description is simplified. Examples of informative colors are added. (Old heuristic was number 8.)

Heuristic 12: “May be necessary” is changed to “is necessary”. (Old heuristic was number 10.)

The validated and extended, new heuristics are:

1. **Match the map and the physical surroundings.** To prevent the user from getting lost the map application should show clear indication of the user's location and other important locations (e.g. destinations and Point-of-Interests, POIs). It is essential that the map corresponds in an understandable way with the physical surroundings of the user. The map should be up-to-date.
2. **Keep the map visible when needed.** The map view should stay visible as often as possible when the user is actively using the application and especially when there is a need for critical navigation guidance. If there is advertisement shown in the application, keep it away from covering any critical parts of the user interface or map view.
3. **Keep the important functions easily accessible.** Make sure that the main map functions (e.g. exploration, search, wayfinding) are easily accessible. Use short menu paths for the main functions or keep the main functions present all the time. Make it clear of which part or function of the user interface is currently used.
4. **Offer shortcuts for locations.** Minimize user's memory load by allowing the use of shortcuts for important locations (e.g. home, previous searches, addresses from contact book). Support the use of POIs. Give easy access to additional information (metadata, links, user-generated content).
5. **Allow multitasking and interruptions.** Allow the user to take control of the map application when interruptions (from the mobile device: phone call, message, notifications, etc.; or from the concrete surroundings: traffic, having a break in a cafe, bad weather, etc.) happen. Allow multitasking and keep it easy to return to the last state of the map application after use of other applications.
6. **Prefer commonly used graphical and functional design solutions.** Use well-known design solutions in the user interface if you do not have a new solution that is strongly proven to be intuitive. Be consistent within the use of interaction gestures (e.g. zooming and panning), controls, functions, elements of user interface and map features in different parts of the application. Use clear, intuitive, commonly known map symbols (e.g. arrows for directions, magnifying class for search, plus and minus for zoom).
7. **Use understandable terminology consistently.** Avoid use of special terminology. Make sure to use the same words with same meanings in different parts of the application. Use the language that is preferred to the user.
8. **Prevent errors and recover from them.** Make the map application free of errors. If errors still happen, be sure to offer the possibility to recover from them easily.
9. **Recognize errors and inform of them clearly.** When errors happen, the error messages should be expressed in plain language (error codes only behind a link), precisely indicate the problem, and constructively suggest a solution. Indicate clearly also the reasons for why the searched locations are not found.
10. **Provide flexibility, adaptability and scalability.** The application should interact with the user by giving informative feedback within reasonable time. The application needs to adapt to different use cases (e.g. pedestrian navigation in forest, driving). Make sure the user interface is scalable for different screen sizes. Let the user adjust the power saving options to lengthen the device's battery life.
11. **Follow balanced and simplistic visual design.** Use clear contrast between visual elements, balanced layout and informative colors (map: forests as green etc., user interface: alarms as red). Visual elements should guide users gaze to important elements. Avoid visual clutter.
12. **Offer help.** Even though it is better if the system can be used without documentation, it is necessary to provide help and documentation. Provide fast guidance focused on user's task and more detailed documentation with search functions. Pay attention to the understandability of the help.

CONCLUSIONS

As a result, it is shown that the previously presented heuristics were suitable for the evaluation of mobile map applications. The analysis of the understandability of the previous heuristics pointed out the need to clarify them. The new, validated and extended usability heuristics introduced in this paper are supposed to be widely usable in the development of mobile map applications.

The collected data set is very large and it would give possibilities for more detailed analysis, especially with the qualitative aspects of usability evaluation reports but also with the quantitative data. For example, the analysis of the amount of a certain problem found by different evaluators could strengthen or weaken the validity of a certain heuristic.

It was though not possible to analyze the data for this paper in more detail but the data still gives possibilities for further analyses.

A good next step for the research in the field of the usability heuristics of mobile map applications is to complete analyses of different mobile map applications with these updated heuristics. Also a comparative study of these domain-specific heuristics and general heuristics would further test the efficiency of these heuristics. Besides the steps related to usability heuristics, more usability research overall is needed to further develop the user experience of mobile map applications with the expanding use cases of them.

ACKNOWLEDGEMENTS

I want to thank the students of the university course User-Centered Software Development for taking part in the research by using the previous heuristics in the usability testing and for giving valuable feedback of the understandability of the previous heuristics. I also thank Hannakaisa Isomäki and Johanna Silvennoinen for the help in the design of the data collection. My gratitude also belongs to Nokia Foundation, the doctoral program UCIT and my home university department that have supported this work. At last I want to thank Emil Aaltonen funding for admitting a grant for the conference travel costs.

REFERENCES

Bertini, E., Gabrielli, S., & Kimani, S. (2006). Appropriating and assessing heuristics for mobile computing (p. 119). ACM Press. http://doi.org/10.1145/1133265.1133291

Fonecta. (2013). Fonecta Maps. Retrieved November 21, 2014, from http://www.fonecta.fi/kartat

Forsell, C., & Johansson, J. (2010). An heuristic set for evaluation in information visualization. In Proceedings of the International Conference on Advanced Visual Interfaces (pp. 199–206). New York, NY, USA: ACM. http://doi.org/10.1145/1842993.1843029

Hermawati, S., & Lawson, G. (2016). Establishing usability heuristics for heuristics evaluation in a specific domain: Is there a consensus? Applied Ergonomics, 56, 34–51. http://doi.org/10.1016/j.apergo.2015.11.016

Komarkova, J., Visek, O., & Novak, M. (2007). Heuristic Evaluation of Usability of GeoWeb Sites. In J. M. Ware & G. E. Taylor (Eds.), Web and Wireless Geographical Information Systems (Vol. 4857, pp. 264–278). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-540-76925-5_20

Kuparinen, L., Silvennoinen, J., & Isomäki, H. (2013). Introducing usability heuristics for mobile map applications. In Proceedings of the 26th International Cartographic Conference. Dresden, Germany: International Cartographic Association. Retrieved from http://icaci.org/files/documents/ICC_proceedings/ICC2013/_extendedAbstract/424_proceeding.pdf

Machado Neto, O., & Pimentel, M. da G. (2013). Heuristics for the assessment of interfaces of mobile devices (pp. 93–96). ACM Press. http://doi.org/10.1145/2526188.2526237

MapFactor. (2013). MapFactor Navigator Free [Android]. Retrieved from http://navigatorfree.mapfactor.com/en/

Navmii. (2013). NavFree.

Nielsen, J. (1992). Finding usability problems through heuristic evaluation. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 373–380). New York, NY, USA: ACM. http://doi.org/10.1145/142750.142834

Nielsen, J. (1994). Heuristic evaluation. In J. Nielsen & R. L. Mack, Usability Inspection Methods. New York, NY: John Wiley & Sons.

Nokia. (2013). Nokia Maps [Windows Phone].

Wiener, J. M., Büchner, S. J., & Hölscher, C. (2009). Taxonomy of Human Wayfinding Tasks: A Knowledge-Based Approach. Spatial Cognition & Computation, 9(2), 152–165. http://doi.org/10.1080/13875860902906496

Zuk, T., Schlesier, L., Neumann, P., Hancock, M. S., & Carpendale, S. (2006). Heuristics for information visualization evaluation (p. 1). ACM Press. http://doi.org/10.1145/1168149.1168162

BIOGRAPHY

Doctoral student, Liisa, Kuparinen;
Department of Computer Science and Information Systems,
University of Jyväskylä, Finland;
+358 44 3737425
liisa.kuparinen@jyu.fi

Master of Economics, doctoral student of Information Systems Science, Liisa Kuparinen is finishing her PhD titled “Designing and Evaluating Mobile Map Services: the Viewpoint of Spatial Cognition in Navigation”. Previously Kuparinen has published studies related to this topic about using eye-tracking as a research method for decision of which landmarks to emphasize on mobile map applications; depth perception in tablet-based Augmented Reality and the first paper introducing usability heuristics for mobile map applications.

Besides the usability aspects of development of mobile map applications, Kuparinen is experienced in Human-Technology Interaction (HTI) related research and practice overall. Her interests also include Animal-Technology Interaction; how to support the wellbeing and research of animals, especially pets, with technical solutions.

Kuparinen is part-time entrepreneur in IT business and a board member in many regional and national organizations and associations.