

SUOMEN GEODEETTISEN LAITOKSEN JULKAISUJA
VERÖFFENTLICHUNGEN DES FINNISCHEN GEODÄTISCHEN INSTITUTES
PUBLICATIONS OF THE FINNISH GEODETIC INSTITUTE

N:o 156

**IMPROVING ACCESSIBILITY FOR PEDESTRIANS
WITH GEOGRAPHIC INFORMATION**

by

Mari Laakso



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Improving Accessibility for Pedestrians with Geographic Information

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A doctoral dissertation completed for the degree of Doctor of Science in Technology to be defended, with the permission of the Aalto University School of Engineering, at a public examination held in Auditorium M1 at the School of Science (Espoo, Finland) on the 30th of January 2015 at 12 noon.

KIRKKONUMMI 2014

Academic Dissertation in Geoinformatics

Aalto University School of Engineering

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Department of Geo-Information Processing, Netherlands

Suomen Geodeettisen laitoksen julkaisuja n:o 156

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ISBN (printed): 978-951-711-313-7

ISBN (pdf): 978-951-711-314-4

ISSN: 0085-6932

URN: <http://urn.fi/URN:ISBN:978-951-711-314-4>

Juvenes Print – Suomen Yliopistopaino Oy

Tampere 2014

Finland

Author

Mari Laakso

Title of the doctoral dissertation

Improving Accessibility for Pedestrians with Geographic Information

Unit Department of Real Estate, Planning and Geoinformatics

Publisher Finnish Geodetic Institute

Series Publications of the Finnish Geodetic Institute

Field of research Geoinformatics

Manuscript submitted 13.10.2014

Date of the defence 30.1.2015

Permission to publish granted 15.12.2014

Language English

Article dissertation (summary + original articles)

Abstract

Environments can be made more accessible by offering users information about barriers and objects that might hinder their progress, thus enabling more information about accessible routes. The study delineates the relevant geospatial information needed to describe the accessibility of an environment. Even though laws, acts and regulations give thorough building requirements for creating accessible environments, there is no holistic approach in geospatial data collection to represent the accessibility of geographical spaces. In this thesis, an information model is presented for representing the pedestrian environment. The model allows for accessibility issues and enables the use of geospatial information in pedestrian navigation applications. In addition to data contents and data modelling, this research studies how accessibility can be further increased by way of sound when communicating geospatial information. By communicating the geospatial information via sound the information content can be enhanced and usability improved. Sonic maps create remote access to nature and enhance the accessibility of a place. In this thesis, the fundamental aim was to study the information requirements in particular situations where different kinds of pedestrian users determine which route they might successfully complete.

The results of the thesis will help data providers collect and store geospatial information, while taking accessibility issues into account, and hopefully it will raise awareness about issues pertaining to universal accessibility. Albeit, the main effort should focus on building accessible environments; in certain situations, people face hindrances and geospatial information could enable users overcome them.

Keywords accessibility, pedestrian navigation, geospatial information

ISBN (printed) 978-951-711-313-7

ISBN (pdf) 978-951-711-314-4

ISSN 0085-6932

Location of publisher Kirkkonummi

Location of printing Tampere

Year 2014

Pages 129

URN <http://urn.fi/URN:ISBN:978-951-711-314-4>

Tekijä

Mari Laakso

Väitöskirjan nimi

Jalankulun esteettömyyden lisääminen paikkatietojen avulla

Yksikkö Maankäyttötieteiden laitos

Julkaisija Geodeettinen laitos

Sarja Suomen Geodeettisen laitoksen julkaisuja

Tutkimusala Geoinformatiikka

Käsikirjoituksen pvm 13.10.2014

Väitöspäivä 30.1.2015

Julkaisuluvan myöntämispäivä 15.12.2014

Kieli Englanti

Yhdistelmäväitöskirja (yhteenveto + artikkelit)

Tiivistelmä

Ympäristöistä voidaan tehdä saavutettavampia tarjoamalla käyttäjille tietoa mahdollisista esteistä tai muista kulkua vaikeuttavista kohteista. Tässä tutkimuksessa määritellään tarvittava paikkatieto, jolla jalankulkijan ympäristö ja sen esteettömyys voidaan kuvata. Esteettömien ympäristöjen luomiseksi on olemassa joukko lakeja ja asetuksia, mutta ympäristön esteettömyyden kuvaamiseksi tarvittavalle paikkatiedolle ei ole määritelty kattavaa keräys- ja esitysmuotoa. Tässä väitöskirjassa esitellään tietomalli, jolla jalankulkijan ympäristö ja sen esteettömyys voidaan kuvata. Malliin voidaan sisällyttää esteettömyyttä kuvaavia tietoja ja se mahdollistaa tämän tiedon käytön myös navigointisovelluksilla. Tietosisällön ja sen mallintamisen lisäksi tässä työssä on tutkittu kuinka ympäristön saavutettavuutta voidaan lisätä kommunikoimalla paikkatietoa myös äänen avulla. Äänen avulla voidaan paikkatiedon määrää ja laatua sekä sen käytettävyyttä lisätä. Äänikartoilla voidaan luoda eräänlainen etäyhteys kuvattuun ympäristöön ja sen avulla lisätä ympäristön saavutettavuutta. Tämän väitöskirjan tavoitteena on määrittää erilaisten käyttäjien vaatima paikkatieto tilanteissa, joissa heidän on tehtävä päätös pystyvätkö he kulkemaan valitsemaansa reitin.

Tämän työn tulokset auttavat paikkatiedon tarjoajia keräämään ja tallentamaan paikkatietoa niin, että se kuvaa myös ympäristön esteettömyyttä. Ympäristöjen esteettömäksi rakentamisen tulisi edelleen olla ensisijainen tavoite, mutta koska jotkut käyttäjät tietyissä tilanteissa edelleen kohtaavat esteettömyysongelmia, heitä voitaisiin paikkatiedon avulla auttaa väistämään ne.

Avainsanat esteettömyys, jalankulkijan navigointi, paikkatieto

ISBN (printed) 978-951-711-313-7

ISBN (pdf) 978-951-711-314-4

ISSN 0085-6932

Julkaisupaikka Kirkkonummi

Painopaikka Tampere

Vuosi 2014

Sivumäärä 129

URN <http://urn.fi/URN:ISBN:978-951-711-314-4>

Preface

This study was conducted at the Finnish Geodetic Institute (FGI) in the Department of Geoinformatics and Cartography. The FGI has provided a good research atmosphere and I am grateful to all of the directors general that I have had the pleasure of working with during my years at the FGI: Professor Juhani Kakkuri, Professor Risto Kuittinen and Professor Jarkko Koskinen.

I would like to express special thanks to Professor Kirsi Virrantaus, the supervisor of my thesis at Aalto University, for her support and guidance especially during the last phases of the project. The preliminary examiners, Professor Matt Rice and Professor Jukka Krisp, are greatly acknowledged for their valuable comments, which have improved the thesis.

At the FGI, I have had the pleasure of working in an inspirational working environment. I would like to express my sincerest gratitude to my thesis supervisor, Professor Tiina Sarjakoski, who has always been supportive and encouraging. I would like to thank the head of department, Professor Tapani Sarjakoski, for allocating to me all the time needed to write this thesis. Special thanks go out to Lassi Lehto, who helped me with the data modelling and was always there for consultation and conversation. I had the pleasure of working as part of an innovative team. I am grateful to the team members: Hanna-Marika Halkosaari, Pyry Kettunen, Mikko Rönneberg and Janne Kovanen. I will always cherish the warm memories of our ever-so-cold field studies. Special thanks go to Hanna-Marika, who has been an excellent colleague in various tasks. Likewise, I would like to thank all my colleagues at the FGI. I have been very happy to be able to work with all of you.

The most warm-hearted thanks belong to my dear family: to my beloved husband Janne and to our marvellous children, Altti, Eino, Ilmi and Oiva. Thank you for your enduring love.

I dedicate this book to my mother, who passed away in 2010. Her love has brought me to this point.

Kirkkonummi, December, 2014

Mari Laakso

Acknowledgements

The research presented in this thesis has been conducted as part of three research projects at the Finnish Geodetic Institute (FGI), Department of Geoinformatics and Cartography. I wish to thank all the sponsors, supervisors and co-workers involved in these projects:

- Haptic, Audio and Visual Interfaces for Maps and Location Based Services, HaptiMap project (FP7-ICT-224675), which was funded by the European Commission and coordinated by Lund University's Department of Design Sciences.
- The MenoMaps (I-II) project, supported by Tekes (the Finnish Funding Agency for Technology and Innovation), which was a joint venture of the Finnish Geodetic Institute, Department of Geoinformatics and Cartography, and the Aalto University of Helsinki, School of Art and Design.
- Ubiquitous Spatial Communication (UbiMap) project, funded by the Academy of Finland, Motive programme, and carried out in co-operation with the Finnish Geodetic Institute, Department of Geoinformatics and Cartography, and the University of Helsinki, Department of Cognitive Science.

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List of Publications

This thesis consists of an overview and of the following publications, which are referred to in the text by their Roman numerals.

- I** Laakso, M., Sarjakoski, T. and L. T. Sarjakoski, 2011. Improving Accessibility Information in Pedestrian Maps and Databases. *Cartographica*, 46(2): 101–108, University of Toronto. DOI:10.3138/carto.46.2.101.
- II** Sarjakoski, L. T., Kettunen, P., Flink, H.-M., Laakso, M., Rönneberg, M. and T. Sarjakoski, 2012. Analysis of Verbal Route Descriptions and Landmarks for Hiking. *Personal and Ubiquitous Computing*, 16(8): 1001-1011. DOI:10.1007/s00779-011-0460-7.
- III** Laakso, M., Sarjakoski, T., Lehto, L. and L. T. Sarjakoski, 2013. An Information Model for Pedestrian Routing and Navigation Databases Supporting Universal Accessibility. *Cartographica* 48(2): 89–99, University of Toronto. DOI: 10.3138/carto.48.2.1837.
- IV** Laakso, M. and L. T. Sarjakoski, 2010. Sonic Maps for Hiking – Use of Sound in Enhancing the Map Use Experience. *The Cartographic Journal* 47: 300–307. DOI: 10.1179/000870410X12911298276237.
- V** Laakso, M., Halkosaari, H.-M., Sarjakoski, T. and L. T. Sarjakoski, 2013. User Experiences with Voice-Based Descriptive Map Content in a Hiking Context. In Jekel, T., Car, A., Strobl, J. and G. Griesebner (eds.): *GI_Forum 2013: Creating the GISociety – Conference Proceedings*. Wichmann-Verlag, Berlin. DOI:10.1553/giscience2013.

Publications **I-IV** are peer-reviewed journal articles; Publication **V** is a peer-reviewed conference article.

In all publications, previously unreported results have been presented. The articles are reprinted with the kind permission of the publishers.

Author's contribution

In **Publication I, 'Improving Accessibility Information in Pedestrian Maps and Databases'**, the present author carried out the research, wrote the paper and had the main responsibility for planning and developing the methods. L.T. Sarjakoski and T. Sarjakoski were the supervisors in the study and participated in the planning.

In **Publication II, 'Analysis of Verbal Route Descriptions and Landmarks for Hiking'**, the present author contributed to the design and experiments of the study in cooperation with the co-authors. The analysis and preparation of the publication were done in cooperation with all the co-authors. L.T. Sarjakoski and T. Sarjakoski were supervisors and L.T. Sarjakoski devised the study.

In **Publication III, 'An Information Model for Pedestrian Routing and Navigation Databases Supporting Universal Accessibility'**, the present author carried out the research, wrote the paper and had the main responsibility for planning and developing the methods. The information model was composed together with L. Lehto. L.T. Sarjakoski and T. Sarjakoski were the supervisors of the study and participated in the planning.

In **Publication IV, 'Sonic Maps for Hiking – Use of Sound in Enhancing the Map Use Experience'**, the present author carried out the research, wrote the paper and had the main responsibility for planning and developing the methods. L.T. Sarjakoski was the supervisor in the study and participated in the planning.

In **Publication V, 'User Experiences with Voice-Based Descriptive Map Content in a Hiking Context'**, the research and writing was carried out together with H. Halkosaari. L.T. Sarjakoski and T. Sarjakoski were the supervisors in the study and participated in the planning.

1. Introduction

1.1 Accessibility for pedestrians

The term accessibility has multiple definitions depending on the context in which it is employed, and it covers a broad range of subjects ranging from barrier-free environments to the usability of services and devices to the availability of information. When applying the term to physical environments, it often denotes how accessible a particular environment is for as many different types of people as possible. This is referred to as environmental accessibility. Iwarsson and Ståhl (2003) emphasise that environmental accessibility is a relative concept with three components: a personal component, an environmental component and an analysis juxtaposing those two components. They stress that accessibility describes a person–environment relationship, where a person’s abilities come face to face with the environmental properties of a particular place. Problems in environmental accessibility have generally been perceived as concerning small groups of special users. However, for instance the number of elderly users is increasing dramatically in all Western countries. Elderly users may have certain age-related deficiencies with their sight and locomotion, which sets specific requirements for accessibility. In reality, environmental accessibility concerns a wide group of users, including children, people walking with prams or with heavy luggage, or somebody moving with leg in a cast. Ultimately, environmental accessibility is about equality.

Regarding the issue of environmental accessibility, there are several different aspects where accessibility is a concern. In modern societies, the aim is to construct physical environments according to barrier-free regulations. However, pedestrians, especially those with disabilities, still face problems while moving around. Geospatial databases play an important role in offering them help in choosing routes that they can manage. A comprehensive, true pedestrian network, one that includes detailed and accurate attribute information, increases accessibility for all users. In order to serve users with special needs, a geospatial database must contain information on features effecting environmental accessibility. Mobility-impaired users and visually-impaired users have the most explicit demands for an accessible environment. Basic requirements for accessibility are the same for all pedestrians, but for special user groups geospatial information needs to be

augmented with new features and accessibility-related attributes. Even though the requirements for barrier-free construction are well defined, there are no standards for how the accessibility of or the absence of such construction should be mapped and presented in geospatial databases.

Another aspect of environmental accessibility has to do with the availability and usability of the geographic information describing an environment. Once the relevant geographic information is stored in databases in such a way that it supports accessibility, it needs to be successfully communicated to users. The communication process is yet another aspect that concerns the issue of accessibility. Traditional map presentations are not optimal for the small displays in mobile devices often used for navigational purposes. In addition to visualisation challenges, the use context or personal abilities of the user may pose constraints (Reichenbacher, 2005; Sarjakoski and Nivala, 2005). Visual map presentations are not accessible to visually impaired users, and any user's visual channel may be occupied or limited in navigation situations. Furthermore, many users are unsure of their map-reading skills. To enhance accessibility, geographic information should be communicated using different methods and media. Voice-based information communication has proved to be an efficient method for communicating geospatial information as well (Rehr et al., 2012; Huang et al., 2012). Many of the aural applications are aimed at visually-impaired users, even though the sound used within maps could serve many different kinds of users. Sound may be used to enrich the map-use experience during the planning phase and while the user is on the move, voice-based information about the surroundings could help users with wayfinding tasks and communicate other relevant information.

If reliable and comprehensive information about pedestrian routes is made readily available, this could increase the number of pedestrians and the overall physical activity of people. Environments can be made more accessible by offering users information about barriers and objects that might hinder their progress, thus enabling more information about accessible routes. The spatial objects experienced as barriers vary between different users. With relevant geographic information, these barriers may be circumvented and users may find routes that they are able to accomplish. By communicating the information via sound, users might also become acquainted with the environment and encouraged to take more walks. In this thesis, the fundamental aim was to study the information requirements in particular

situations where different kinds of pedestrian users determine which route they might successfully complete.

A certain amount of the research was conducted as part of the Haptic, Audio and Visual Interfaces for Maps and Location Based Services (HaptiMap) project. The HaptiMap project aimed to develop multimodal, location-based services (LBS) that are also accessible for special user groups, such as elderly and visually-impaired people, and that support their use of spatial information (Magnusson et al., 2009). The project's assumption was that with better perceptualisations (making things perceivable to the senses, including senses other than visual) and interface designs, it would be possible to greatly increase both the usability and the accessibility of navigational systems, especially for special user groups.

1.2 Geographic information describing an accessible physical environment

The environments should be designed to guarantee equal access to everybody. There are numerous standards and guidelines describing the accessibility of built environments. The International Organization for Standardization (ISO) has introduced several standards for barrier-free construction, which are specified in more detail in a study by Laakso et al. (2012). Likewise, the United Nations (UN) advances the rights of persons with disabilities in society, and it has been involved in compiling a design manual for a barrier-free environment to promote accessibility for the disabled as part of the *Enable* programme (United Nations, 2008). In 2007, the European Commission created a standardisation document that aims to achieve a harmonised approach for the accessibility of buildings in Europe (European Commission, 2007). The European Commission-funded *European Concept for Accessibility* (ECA) has published a Technical Assistance Manual (Aragall, 2003) and Build-for-All Reference Manual (ECA, 2006) promoting the importance of barrier-free construction and the 'Design for All' (DfA) principle. The 'Design for All' principle advocates designing environments for a diversity of users and promotes social inclusion and equality (Aragall et al., 2013). The Design for All Foundation defines the principle as follows: 'Design for All is the intervention on environments, products and services with the aim that everyone, including future generations, regardless of age, gender, capabilities or cultural background,

can enjoy participating in the construction of our society, with equal opportunities participating in economic, social, cultural, recreational and entertainment activities while also being able to access, use and understand whatever part of the environment with as much independence as possible' (Design for All [DfA], 2014).

Accessibility is often perceived as a subject concerning just people with disabilities. However, determining which people have disabilities is not an unambiguous task. The World Health Organisation's (WHO) International Classification of Functioning, Health and Disability (ICF) uses the term 'people with activity limitations'. People may have activity limitations for a number of reasons; the limitations may be temporary and include different degrees of difficulty. It is important to emphasise, as Bednar (1977) does in the introduction to *Barrier-Free Environments*, that 'we all pass through stages in our lives with varying degrees of ability and disability'. Therefore, physical environments should also be designed to take the maximum range of users into account. Moreover, when environments, as well as products and services, are designed to serve people with specific needs, the result favours the whole population. The DfA initiative recommends that isolated accessibility solutions should be avoided, while comprehensive solutions that benefit as many people as possible should be pursued (Design for All [DfA], 2014).

In many cases, the ISO standards and commission-level guidelines are used as references for national and regional regulations. In many countries and cities, there are specific guidelines and regulations for how the building of private and public spaces should be conducted in order to respect accessibility. Existing accessibility problems may be identified by applying the guidelines and regulations for barrier-free construction to real-world situations and by recognising those instances and places where they have not been realised. Alas, real-life circumstances do not always match ideal situations (Figure 1). The concept of environmental accessibility has been recognised by high-level organisations for several decades, but it has not been integrated with geospatial databases along with technical advances in digital mapping. There are no standards or guidelines that provide methods on how information about accessibility should be stored, presented or communicated.



Figure 1. A pedestrian with a pram cannot ascend the stairs and is obliged to find alternative route to reach her destination.

1.3 Hypothesis

It is assumed that the accessibility of a physical environment can be improved with relevant geographic information and by communicating the information using sound.

1.4 Aim of the research and research questions

The research aims to define the relevant geospatial information needed to describe the accessibility of a particular environment. Once the information in the databases has been stored and modelled, while also taking pedestrian accessibility into account, it will be possible for map applications to present and communicate that information to users as required by different cases and contexts (Figure 2). The objective is to collect primary information that can be applied more broadly and that will make it possible for users to eventually decide whether or not they can successfully complete a particular route. The geospatial database should include relevant information that can be

effectively communicated to users. This research project assesses how accessibility can be further enhanced by way of sound when communicating geospatial information.

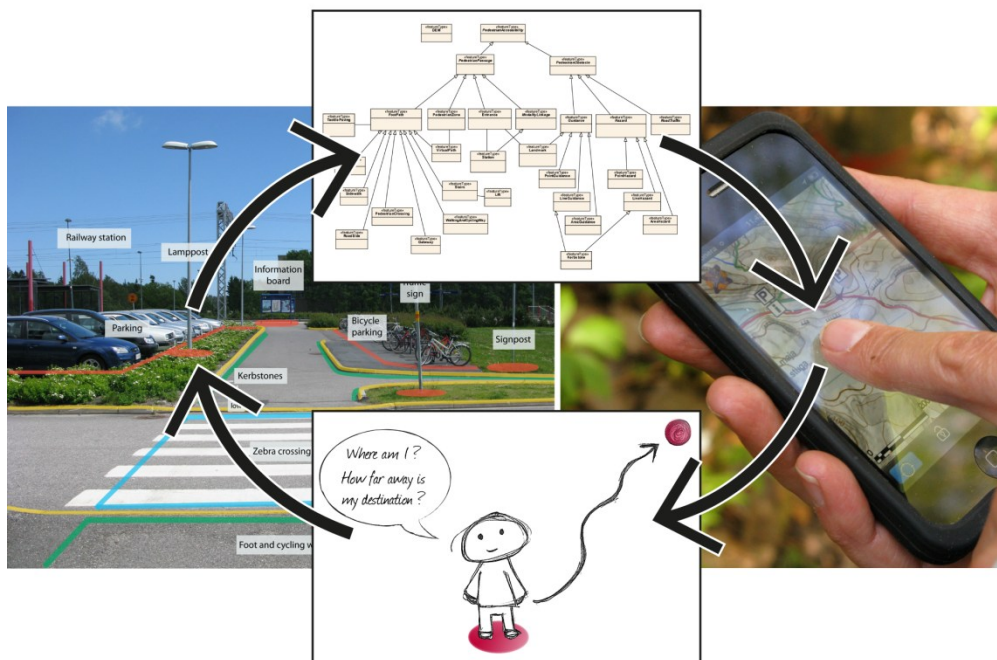


Figure 2. Geospatial information modelled while taking pedestrian accessibility into account offers users help in navigating a particular route.

The following two research questions arose from these objectives:

- 1. What kind of geospatial information is required to represent a geographical space and the accessibility of that space for pedestrians?**

The research question can be further divided into more detailed questions, which are answered in the publications presented in the thesis:

- How is the accessibility of a particular environment currently presented in various map databases, map presentations and map services, and what kinds of attributes are used? What are the geospatial features required to represent the accessibility of such an environment? (Publication I)
- What do people observe in the environment while hiking and how do they describe the routes and landmarks? (Publication II)

- What kinds of information would users like a map application to communicate while on a hike? Can the descriptive geospatial information increase the accessibility of a particular environment? (Publication V)
 - How should geospatial information be conceptualised for accessible pedestrian navigation? (Publication III)
- 2. How can sound be used to communicate geospatial information in order to increase accessibility?**

The research question can be broken down into sub-questions based on the publications presented in the thesis:

- What are the possibilities for using sound that has been integrated with maps, and how can natural sounds be used to communicate geospatial information? (Publication IV)
- What are the terms and verbal descriptions people use for their surroundings while hiking? (Publication II)
- Do audio descriptions increase the accessibility of an environment during mobile navigation use? (Publication V)

1.5 Contribution

Regarding the objectives of the study, the contribution of the original publications can be summarised as follows:

- Publication I, ‘Improving Accessibility Information in Pedestrian Maps and Databases’, provides a thorough review of Finnish pedestrian map databases, map services and different guidelines for barrier-free construction to assess how they support accessibility. Based on the review, a proposal for geospatial information content is given to fulfil the requirements of users with disabilities.
- Publication II, ‘Analysis of Verbal Route Descriptions and Landmarks for Hiking’, provides additional knowledge on human verbal descriptions of routes and landmarks. So as to better guide users in forest environments, the research focuses on the geographic objects that users rely on when navigating.

- Publication III, ‘An Information Model for Pedestrian Routing and Navigation Databases Supporting Universal Accessibility’, introduces a conceptual information model for the geospatial information required to support accessibility. The model deals with the physical environment encountered by a person moving on foot as well as those persons with disabilities. Unified Modeling Language class diagrams were used to formalise the geospatial information required for an accessible environment.
- Publication IV, ‘Sonic Maps for Hiking — Use of Sound in Enhancing the Map Use Experience’, describes new kinds of ways of communicating spatial information, even to those persons who are visually impaired, and, in general, it provides map users with a more profound use experience. Two implementation examples are presented in the study. These sonic maps can help users plan their hike in advance and. Furthermore, sonic maps provide those persons who are not able to visit a park with some sort of accessibility to nature.
- Publication V, ‘User Experiences with Voice-Based Descriptive Map Content in a Hiking Context’, describes the user requirements for informative and descriptive map content within the context of hiking. Based on these requirements, audio descriptions along a hiking path in a national park were composed. Elderly users were chosen as a target group for the field study. It was assumed that combining audio with visual information would improve overall accessibility in a hiking context by making the geospatial information more available. Based on the studies, the most important features regarding the information communicated via a mobile map application are summarised.

This thesis consists of a summary and five original publications. Following the introductory section, Chapter 2 reviews previous research on topics pertinent to the study. Chapter 3 presents the theoretical foundation of the study. The materials and methods used in the study are presented in Chapter 4. The results are presented in Chapter 5. Chapter 6 provides a discussion and the conclusions of the study as well as needs for further research.

2. Previous research

In this chapter, the first section introduces previous studies that describe the information requirements for improving accessibility with respect to navigation and wayfinding. The second section provides an overview of previous research on the role of sound in map use.

2.1. Information requirements for improving accessibility

The fundamental decision in navigation is what information should be given to navigators and how it should be communicated (Montello, 2005). Montello describes navigation as a coordinated and goal-directed movement through the environment, one which involves both planning and the execution of movements. He considers navigation to consist of two components: locomotion and wayfinding. According to Montello, wayfinding is goal-oriented and involves decision making, whereas locomotion is the planned movement of one's body around an environment in an efficient way.

For several years now, there have been navigation applications on the market for vehicle use; however, they have been lacking for pedestrian use, or else they have suffered from poor data quality (Roger, 2007). Pedestrian information requirements for navigation are different than for vehicle navigation (Elias, 2007). The study of Gartner et al. (2011) proposes a concept of human-centred pedestrian navigation systems emphasising the needs and constraints of pedestrians. A thorough study of the functional needs of pedestrians reveals both physical and social environmental features, which are important because they offer users the required information about pedestrian environments (Czogalla, 2010; Vukmirović, 2010). A comprehensive pedestrian network is the core part of navigation data (Karimi and Kasemsuppakorn, 2013). Once the network is complete, it needs to be augmented with other features describing the accessibility of the environment. What is considered as an obstacle is much related to personal abilities and thus a wide variety of users should be considered to form insight of environmental accessibility (Gray, 2003).

Several existing studies present the geographic information requirements for mobility-impaired persons in a navigation context (Beale et al., 2006; Pressl et al., 2010; Sobek et al., 2006; Völkel et al., 2007, 2008; Banovic et al., 2013). Studies by Pressl et al. (2010) and Beale et al. (2006) made use of user

questionnaires to identify the most important obstacles faced by mobility-impaired persons and other preferences for the content of geographical data for visually-impaired and wheelchair users. Wheelchair users may have very specific requirements to the environments and pathway surfaces they are able to use (Winslow, 1977; Pearlman et al., 2013). Völkel et al. (2007, 2008) gathered information requirements for mobility-impaired persons via a survey that included visually-impaired respondents. It showed how there are many environmental features that are important and even crucial to some special user groups, but which are not supported by currently available map data. Sobek et al. (2006) state that acquiring and creating data for the database are the most critical steps in the development of a successful navigation application for mobility-impaired users. Banovic et al. (2013) emphasise that the information needs of visually-impaired pedestrians are different from those of sighted people. For instance pedestrian crossings play a major role in safe locomotion of pedestrian with low-vision (Hassan and Massof, 2012).

The ease of wayfinding is one important aspect when defining accessibility in a holistic manner. If people feel unsure about the routes they should take it, hinders them from reaching their destinations and diminishes the accessibility of the routes. Landmarks play an important role in navigation and wayfinding. However, a landmark is a relative concept and successfully defining a landmark is dependent upon both the environment and the observer. Presson and Montello (1988) have emphasised the relational nature of the cognitive space when defining landmarks. Many people are not used to moving around in forest environments, and thus, they feel more uncertain when navigating in natural forest environments compared to urban areas. The reason might be the distant location, uninhabited areas where help is more difficult to find and the difficulty in recognising places and matching the perceived environment with map information. Therefore, the need to use landmarks is even more profound in forest environments so that users will remain sure that they are on the right track. Compared to wayfinding by way of paper maps the concept of location is accentuated with digital navigation devices with positioning capability. Devices tracking the user's real-time position enable navigation instructions which include location-based information on landmarks and other relevant features. However, finding salient landmarks in an unbuilt environment is not always a straightforward operation. Landmark salience has been discussed in several studies (Caduff

and Timpf, 2008; Klippel and Winter, 2005; Nothegger et al., 2004; Sorrows and Hirtle, 1999; Ishikawa and Montello, 2006). Caduff and Timpf (2008) claim that the salience of a landmark is not an inherent property of the feature, but a product of the relationship between the feature itself, the surrounding environment and the observer's cognitive and physical point of view. Sorrows and Hirtle (1999) place landmarks in three categories: visual, cognitive and structural. With respect to the salience of the landmark, they point out that the strongest landmarks contain all three elements. In a study by Pick et al. (1995), in which map readers were dropped off in the wild and had to localise themselves with a plain topographic map, landforms proved to be adequate features for localising oneself. According to Snowdon and Kray (2009), the most frequently used landmarks are peaks and watercourses; paths, the types of trees or particular features of the landscape may also be considered landmarks that support navigational decisions when hiking. Apart from visual landmarks, various environmental sound sources may be used as sonic landmarks. In a study by Baus et al. (2007), users found auditory landmarks to be effective in a navigation context. Sonic landmarks stand to be beneficial especially visually-impaired users.

Previous research on integrating landmarks with wayfinding descriptions mostly covers studies in urban environments. The landmarks act as organising markers for perceiving spatial information and wayfinding (Golledge, 1999). When giving pedestrian route instructions, landmark-based instructions have proved to be more efficient than metric instructions (Rehrl et al., 2012; Ross et al., 2004). Studies show that enriching routing directions with landmarks is an efficient way to communicate navigational instructions (Raubal and Winter, 2002; Elias et al., 2009). In navigation and wayfinding, landmarks play a special role that is even more pronounced when moving in a forest environment (Brosset et al., 2008). Especially in unbuilt environments, some landmarks are ambiguous or sometimes create different impressions among different users. To be able to communicate geographic information and guide users verbally, additional knowledge about human verbal descriptions and vocabulary on routes and landmarks need to be acquired in nature environments.

2.2. Communicating geographic information by way of sound

Maps have always been a means to communicate geographic information by abstracting and modelling real-world phenomena. Different models of

communication have been applied to cartographic information. Information communication with maps may be seen in the framework of classical information theory, which was first introduced by Shannon (1948) and further elaborated upon with respect to cartographic information by Board (1967), Kolacny (1969) and Robinson (1975), among others. In Goodchild's (2000) interpretation of Shannon's theory, the successful communication of geographic information reduces the receiver's uncertainty about the geographic world. Hopfstock (2010) has summarised the changing paradigm in cartography from the communication era to the digital and geovisualisation era. With digital maps, the variety of expressions has been broadened beyond that of a traditional visual medium only. Since hearing is our second most important sense after sight, attaching sound to a map is worth studying. As stated by Brauen and Taylor (2007), cartography cannot afford to continue undervaluing the use of sound as well as the other non-visual senses.

While geographic information is used via digital maps in navigation applications and other location-based services, it is possible to communicate information in audio format as well. Attaching sound to a map or navigation application makes it possible to communicate more information to many user groups. The prospect of integrating sound with navigation and other map applications has been recognised in many studies. Already before digital maps, the use of sound in making geographic information perceivable was being studied. As cited by Cartwright (2009) and Porteous and Mastin (1985), there is, for instance, an early example in which Granö (1927) did pioneering work on creating an agricultural soundscape that illustrated cartographic representations with acoustic sensations of human activity, birdsong and grazing cattle on the island of Valosaari in Finland. The concept of soundscape was first introduced by Schafer (1977, 1994). The potential of soundscapes in cartography has also been discussed by Théberge (2005). He recognises the figure-ground relationship in environmental sound and its possibilities for maps. Théberge has also focused on the concept of cyperc cartography, which Taylor (1997) originally discussed. The use of soundscapes in enriching our multisensorial reading of space, as well as the role of sound in cartography, has been extensively discussed by Caquard et al. (2008). Also, Brauen and Taylor (2007) have discussed the motivation for introducing multisensory information into mapping projects. They presented an atlas project with incorporated sounds as an example.

Krygier (1994) has also presented a variety of sound forms and a wide range of possibilities for using them in geographic applications. Rice et al. (2005) have presented the design of map interfaces within the context of visually-impaired users in a research project entitled the 'Haptic Soundscapes Project'. They used special interfaces with haptic and auditory feedback. The sounds in use were different kinds of auditory cues, speech and tones with varying frequencies. Research on computer technology, particularly in the field of auditory displays, has focused on how to transform visual information into aural information. MacVeigh et al. (2007) presented a study on auditory display in GIS. They used a simplified raster image in which three different sounds were integrated into a layer, and a value was calculated and played for each sound at each point. This is a good example of a sound-covered map and could help visually-impaired users hear which objects are within a particular hearing range. Another example of auditory displays comes from Dingler et al. (2008), who studied the learnability of sound cues for environmental features. Likewise, Sarjakoski et al. (2009) have discussed the importance of sound for map use experience on ubiquitous maps. The augmented sound elements may support aesthetic and entertaining aspects of interactive maps. As stated by Peterson (2007), multimedia cartography may contribute to the joy of discovering something new about the world.

To introduce new routes and surroundings for people with visual impairments, verbal descriptions of an environment, so-called verbal maps, are commonly used. Verbal maps are not as effective a means of spatial learning as tactile maps (Espinosa et al., 1998), but the benefits of verbal maps are that users can make their own maps with some help. Verbal maps can combine different modalities of transportation, e.g. walking and taking public transport, and also attributed features can be included, such as street names, the flow of traffic, high or low kerbstones, landmarks (also auditory and olfactory), information about safe crossings, inclinations and declinations, tactile paving and other surface information (Banovic et al., 2013).

In a mobile context, speech has been used since the very beginning in navigation devices to provide users with visual channels to observe the environment. Voice-based turning instructions are commonly used and are an efficient way of delivering information in navigation devices. Information associated with geographic locations, which can be communicated in text-based and voice-based formats, are manifold, ranging from simple route

guidance to descriptive information (Kovanen, 2013) or even to narrative stories associated with places (Caquard, 2013). Human navigation and wayfinding are different in nature and in urban environments (Brosset et al., 2008). The scarcity of salient and distinguishable objects in natural environments makes navigation more challenging than in built environments (Whitaker et al., 1992). This calls for further research on the vocabulary and verbal descriptions in pedestrian navigation in natural environments.

3. Theoretical foundations

This chapter briefly describes the theoretical framework of the subjects covered in the thesis. Concepts from the fields of user-centred design and data modelling are presented in order to build a frame of reference for the methods used in the research conducted for the thesis.

3.2. User-centred design

In the user-centred design (UCD) approach, users' desires, needs, motivations and context are taken into account when creating products and services (Cooper et al., 2007). Studies on users' requirements have played a key role when gaining knowledge about what kinds of objects are important in pedestrian navigation and wayfinding, and furthermore, what kinds of information people need in order to feel comfortable and safe when going out. In the context of geospatial information and map use, the UCD approach has been successfully applied, for instance, when designing a multichannel map service concept (Halkosaari et al., 2013).

Commonly used design tools in the UCD process include scenarios and personas. Personas provide a means to model users for design purposes. A persona description typically contains an overview of a particular persona, such as name, age and profession, together with personal goals, fears and typical activities (Pruitt and Grudin, 2003). Personas are not representations of real people as such, but are based on the real behaviours and motivations of the studied users (Cooper et al., 2007). Scenarios are used to express typical situations that users encounter and demonstrate their needs in such situations (Rosson and Carroll, 2002). Persona descriptions and scenarios highlight the data requirements at a conceptual level from the user's point of view.

When collecting data, the think-aloud method has been effectively used to access the thoughts of users as they are performing a task (Boren and Ramey, 2000). The method has its roots in psychological research (Van Someren et al., 1994). The think-aloud method avoids interpretation by the subject and only assumes a very simple verbalisation process. It creates a relatively objective method using verbal protocols as data, albeit the task assignments strongly influence the resulting protocols.

For analysing user-generated issues, the affinity diagramming technique is widely used. Affinity diagramming is a simple and effective technique for grouping and understanding even a large amount of information (Beyer and Holtzblatt, 1998, pp.154–163). With the affinity diagramming method, individual observations are written down on slips of paper, then the related items are placed together to form groups of broader themes. The affinity diagramming method is a bottom-up process, which reveals common issues and themes based on individual observations.

3.2. Data modelling for spatial representation

Models are commonly used to simplify complex phenomena via an abstraction. Board (1967) emphasised that maps should be seen as models of the real world and they should be employed as conceptual models in order to better understand the real world. A modelling process can be seen as a generalisation process to model the space in order to form a cognitive map (Sarjakoski, 2007). The International Organization for Standardization's (ISO) Technical Committee (TC) 211 for Geographic information / Geomatics defines a model as an abstraction of some aspects of reality. Conceptual modelling provides a formal structure for understanding and using data about entities in the real world (Roswell, 2012). Roswell considers data modelling a critical tool for developing a common understanding of the meaning of geographic information. Goodchild (1992) describes data modelling as the process of discretising spatial variation and emphasises that it should be an accurate representation of geographical reality. Worboys (1995) explains the models of spatial information as a process where parts of the source domain are represented by a modelling function in the target domain to simplify and abstract phenomena of interest. Molenaar (1998) has devised an illustration consisting of several levels for data modelling (Figure 3), where conceptual modelling is located between spatial and logical data modelling, thereby serving the needs of geo-information theory and application disciplines. Before making conceptual models, it is important to identify the real-world phenomena to be modelled via context mapping and spatial modelling. Spatial modelling can be seen as a sub-set of a conceptual model for a particular mapping discipline.

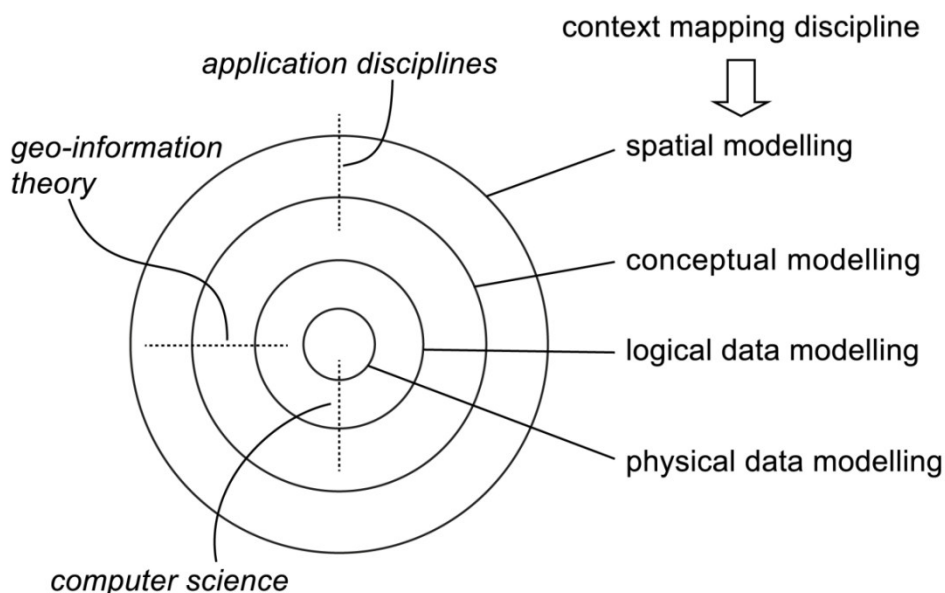


Figure 3. The levels for data modelling (redrawn from Molenaar, 1998). Reprinted by kind permission of M. Molenaar.

An object-oriented approach is commonly used to model geographic information. To describe a conceptual model, various modelling languages may be used. In this thesis, the Unified Modeling Language (UML) class diagram is applied to formalise the information model for a geospatial pedestrian database that also supports an accessibility aspect. UML is an expressive language used to visualise, specify and document software-intensive systems as well as workflows, structures and behaviours (Booch et al., 1999). A class diagram consists of object classes and the relationships between the object classes. In geographic information processing, we are primarily interested in inheritance relationships and associations. A class diagram shows the properties and operations of a class and the term feature is used as a general term to cover the entity (Fowler, 2004).

When compiling the information model presented in this thesis, previous research in the field of modelling geographic information was studied, namely research by Borges et al. (2001) on the creation of an OMT-G data model for geographic applications in UML, and the further development of Borges' work by Lisboa-Filho et al. (2010) and Nalon et al. (2011) with

GeoProfile, as well as a study by Friis-Christensen (2001). Fang et al. (2012) presented a data model for landmark-based pedestrian navigation that stresses the importance of landmarks promoted during the data modelling phase to enable efficient and reliable navigation.

4. Research methods and materials

To increase the accessibility of the physical environment by describing the relevant information for pedestrian users, two principal aims were set for this work:

- A) To compile the geospatial information needed to represent the geographical space and the accessibility of that space.
- B) To study how sound can be used in communicating spatial information in order to increase accessibility.

Users had a strong role in establishing the information requirements for describing an accessible environment. In the data collection phase, users were involved during several stages of the study in terms of defining user requirements and evaluating the findings. During the HaptiMap project, different project partners performed dozens of user tests; they involved, in total, hundreds of users (Magnusson et al. 2009b; Carmien and Rasmussen-Gröhn, 2011, 2012). The results obtained from these tests have been included in the study to describe an accessible environment and study the use of sound in communicating geospatial information. Table 1 presents the objectives and methods used in the different papers.

Table 1. Research objectives and methods applied in the study

Aim	Paper	Objective	Method	Materials
A	I	To identify how the accessibility of the environment is presented in different map databases and presentations and what kinds of attributes are used. To define important features and attributes describing accessibility.	Feasibility study via a literature review, review of various maps, map sites and databases.	Literature. Compilation of maps.
A	II	To study how people observe their surroundings while	Explorative user testing using the thinking-aloud	Recordings from the field tests.

		hiking and what are the landmarks they rely on when navigating and the vocabulary used in descriptions.	method and analyses of landmarks.	
A	III	To conceptualise the geographic information needed for accessible pedestrian navigation.	Constructive research to model the geospatial information with UML.	Collection of geospatial features.
B	IV	To investigate the possibilities of using sound that has been integrated with maps. To identify how audio can be used to communicate information about the environment to map users.	Explorative research via a literature review, empirical sound collection in a hiking context and embedding sound in maps to enhance accessibility.	Literature. Recordings from the field studies.
A,B	V	To study the kind of information users would like a map application to communicate while on a hike. To evaluate the audio descriptions communicated by the navigator.	Workshop for user requirement collection. Collection of user experiences via interviews and observations of descriptive and informative audio descriptions along a hiking path.	Observations from the workshop and from the field tests.

4.1. Methods for compiling the data content of a geospatial database for accessible pedestrian navigation

Pedestrians observe the environment from a very different level of detail than a car driver. The creation of a walkable base network is in core role to enable successful navigation and routing for pedestrians. In most cases, the pedestrian network is totally different than a vehicle network. Furthermore, the identification of accessibility-related features and attributes of a particular environment is an important stage in the data collection process.

Collecting information requirements

To identify how the accessibility of an environment is presented in different geospatial databases, map presentations and map services, an explorative study was conducted that included reviewing various maps, map sites and database descriptions (Publication I). The data features and attributes in use at the time were collected. Additionally, a literature review was conducted that included material regarding guidelines and instructions for constructing barrier-free and accessible environments. To cover the physical environment extensively and to take all the accessibility issues into account, a wide range of guidelines and standards in the field of barrier-free construction and accessibility were studied (Publications I and III; Laakso et al., 2012).

Persona descriptions and scenarios were used to demonstrate the requirements for data content (Table 2). The contents of the required data are easier to conceive by illustrating the user's situation and the information s/he requires to be able to accomplish a chosen route. Scenarios don't pursue to cover all possible use case but to highlight the data requirements from the user's point of view.

Table 2. To demonstrate the user requirements, personas and scenarios were created for different kinds of profiles

Profile	Persona description	Scenario
A person with visual impairment	Leena, aged 43, is almost blind. In good conditions, she is still able to see shapes. She has a guide dog. She feels unsafe and uncomfortable	Leena wants to find a nice walking route near her home where she could go on a daily walk with her dog. The route should go through green areas

	walking on routes with which she is not familiar.	and avoid crossings. She would like to learn beforehand all the sonic landmarks on the route to confirm that she is on the right track.
A person using a wheelchair	Martin, aged 56, needs a wheelchair to move. He has an electric wheelchair, he prefers asphalt surfaces, and he needs to avoid steps, steep hills and high kerbs. In addition, the wheelchair takes more space than a standard pedestrian wherever he goes.	Martin wants to go to the national park outside town by bus. He needs to know what kinds of paths are available in the park and whether or not the busses are accessible with a wheelchair. He also needs information about the accessibility of toilets and cooking shelters along the paths.
An elderly woman with mobility restrictions	Sonja, aged 80, has recently moved to a city close to her children. She has limited vision, so she is a bit unsure about moving around. In addition, she has some mobility restrictions, and while on a walk, she needs to sit down every now and then.	Sonja would like to familiarise herself with the surroundings and go visit her daughter's home, which is one kilometre away from her home. If the weather is good and she feels like it, she would like to walk there and test different routes. If she feels tired, she prefers the bus.
A roller skater	Markus, aged 25, has lately started to roller skate. He wants to roll on smooth, paved routes. He wants to avoid steep hills, both up and down.	Markus plans his workout route beforehand. He wants to know the total length of the route, the height profile and all the crossings on the route. The road surface material and existence of road construction are important information for him.

Since forest environments are quite different than built environments, it was important to study what kinds of terms and concepts people use when hiking in natural environments. To study how people observe their surroundings while hiking and what are the landmarks they rely on, an empirical thinking-aloud study was carried out in a national park (Publication II). The study was repeated in wintertime when the ground was covered with snow. Users were asked to describe all the remarkable features they encountered and, in decision points, describe their route options. All of the users' descriptions were recorded in audio and video. After the field tests, the recordings were transcribed and divided up into propositions. The propositions were classified into categories and then analysed.

To broaden the scope of available information on a map service beyond that of traditional topographic and navigational information, a workshop was organised to evoke ideas on new kinds of information that users would like to have available when on a hike (Publication V). After a motivational component, each participant in the workshop gave ten proposals for additional information that the map services could offer. In another exercise, participants formed groups and generated hiking-related scenarios to reveal new types of information that had not yet been presented in existing visual map presentations. Proposals were organised into groups of a few common topics.

The conceptual modelling of the data

To formally present in geospatial databases the geographical space that pedestrians encounter information modelling was performed. Geometric data describe the location and extension of features, whereas additional attribute data describe other properties of the geometric features. An information model, expressed in a graphical manner using Unified Modelling Language (UML) class diagrams, was chosen to present the conceptual model of the environment and its accessibility (Publication III). The information model contains information about object classes, attributes and the relationships between the classes used in the database. In geographic information processing, the inheritance relationships and associations are important in order to provide users with comprehensive information about their routes and walking environments.

The applicable requirements and recommendations set by the INSPIRE Data Specification on Transport Networks – Guidelines (INSPIRE, 2010) were

employed during the modelling phase. The content of the information model was composed using various information sources. One important repository was a data catalogue description, which was collected and used by one of the HaptiMap partners, the federation of municipalities called Kreis-Soest in Germany. Their object catalogue was used as a starting point to compose the feature list describing an accessible environment. In Soest, a city-wide mapping exercise was performed at a high level of detail. The mapping was performed to enable blind pedestrians safe navigation in the city. As part of the HaptiMap project, a considerable amount of user requirements were collected from studies on elderly and the visually-impaired users as well as hands-on experiences from numerous user tests and demonstrator developments (Carmien and Rasmus-Gröhn, 2011, 2012; Magnusson et al., 2012). The contents of the Kreis-Soest data were augmented with data resulting from research done at the Finnish Geodetic Institute (Publication I) and from other HaptiMap partners from the municipality of Lund (Sweden) and the Lund university (Sweden), ONCE (Spain), Technalia (Spain), as well as from other repositories, such as the standards, guidelines and regulations in the field of barrier-free construction and accessibility. The background and references are explained in more detail in HaptiMap deliverable D4.4 ‘Accessible map and LBS content guidelines’ (Laakso et al., 2012).

4.2. How accessibility can be enhanced by using sound when communicating geographic information

The aim of the study was to identify how sound can be used to communicate geospatial information in order to improve accessibility to the environment. To investigate the possibilities of using sound integrated with maps, a review study was performed (Publication IV). A literature review was carried out to explore how sound has been exploited in cartographic communication to date. To explore the possibilities of using natural sounds and soundscapes, an empirical sound assessment was carried out in a hiking context. A few spots along a popular hiking path were chosen; a number of soundscapes were recorded at such spots. A soundscape can be perceived as a sonic window into nature. The soundscapes were embedded in a desktop map service to give users an opportunity to sense the environment when exploring the area with a computer. User experiences with the soundscapes were collected in a laboratory test where potential hikers used the web map application to plan their hikes in advance (Flink et al., 2011).

Another experiment with natural sounds combined with a hiking map was aimed at users with poor vision (Publication IV). A special, intensively generalised map was used. A few map elements were accentuated. The walking routes were emphasised with thick, simplified lines. Other highlighted objects on the map included bodies of water, roads and map symbols for outdoor information. After making the visual generalisations, sound was added. Each map element was attached to an in situ recorded natural sound. With the help of a mouse-over function, users could explore the map of varying sounds.

In addition to using the natural and authentic sounds of the environment, descriptions and instructions are an effective way of using sound to communicate geospatial information. To study the kind of information that users would like a map application to communicate while on a hike, a workshop for was organised to collect a series of user requirements (Publication V). Using these requirements, we selected content topics that are relevant to users while on a hike. The aim was to communicate information that is not necessarily visible in the natural environment, such as instructions and information on available services (such as availability of drinking water, guide service, toilets). Additional information on natural and geological themes was also identified as interesting subject. One purpose of the audio descriptions is to read out some textual information marked on the map, such as the names of lakes and buildings. At the route crossings, audio descriptions offer the route options and descriptions of the different route destinations. Additionally, timely information on route conditions and changing circumstances were recognised as one of the topics to be used in audio descriptions.

Informative audio descriptions were composed for nine spots along a popular hiking route in a national park. The geo-referenced audio descriptions were embedded in a mobile map application. It was assumed that combining audio and visual information would improve the overall accessibility of the information and, in this way, of the natural environment as well. Elderly users were chosen as a subject group for the field study. Elderly users may have certain age-related deficiencies in their sight and locomotion, which sets specific requirements for a map application. They have stronger demands on accessibility of the physical environment as well as on reliable information. To observe and evaluate user reactions, the field tests were video recorded and users' suggestions and comments were collected during the test. Notes

were completed afterwards based on the video recordings. Each suggestion and comment was transcribed onto a separate slip of paper. There were altogether 254 paper slips with a comment or suggestion concerning the use of the map application and the information the application provided. To organise and classify the findings, we utilised the affinity diagramming method (Beyer and Holtzblatt, 1998, pp. 154–163) (Figure 4).



Figure 4. Observations from the field studies were transcribed onto stickers and organised using the affinity diagramming method.

5. Results

The results are divided in two sections, each of which answers one of the main research questions. The results are presented in more detail in the original publications referred in the text.

5.1. Representing an environment that supports pedestrian accessibility

The aim of this study was to collect knowledge about the kinds of geographic information that currently exist and what is required to adequately represent a pedestrian environment and its accessibility (Publication I). The accessibility attributes were extracted from the various barrier-free building guidelines and regulations, as well as existing maps and map services for special user groups. For instance, for a wheelchair-accessible route the minimum width of the sidewalk is 2 metres, resulting in an attribute indicating the width of the walkway. The attribute should be given at least when the sidewalk is less than 2 m, which is the limiting width for wheelchair users.

The objective was to collect primary information, preferably numeric values representing the absolute information that will be stored as attribute values. As stated by Iwarsson (2003), accessibility is not an absolute concept; rather, it relies on personal capacities. Therefore, derived statements such as ‘*accessible*’ or ‘*inaccessible*’ are not informative if the reasons are not given. Instead, the information behind the statement ‘*inaccessible*’ should be provided, such as information about the presence of stairs or, even more specifically, the number of steps and the height of each step. A user may be able to manage a few wide and low steps, but not long steps and big level differences. With numeric values representing the absolute information it is possible to offer relevant information for different cases. With exact information, we can enable users to decide for themselves whether or not they can take the route. When the information model supports accessibility, it enables routing that takes different user preferences into account and increases the overall accessibility of the route.

This research (Publication III) introduced an information model for pedestrian accessibility. The model is termed *AccessibilityMap* and the focus has been on a pedestrian environment and its accessibility. All real-world objects that may have an effect on a pedestrian user have been included in the model. These objects are either parts of the passable route network or other

elements that guide or hinder pedestrians. This information model is a conceptual model, which may be considered to be at a metamodel level of abstraction (Roswell, 2012).

The features of the physical environment are divided into two abstract top-level classes: in 'PedestrianPassage' class are the features offering the access, while the obstacles hindering the access are the in the 'PedestrianObstacle' class. The primary elements modelled for the *AccessibilityMap* were spatial geometric elements: point, line and area representations of elements that are part of a pedestrian environment. Child classes inherit the attributes of the top-level class, if applicable. All elements may have temporal validity (i.e. a time description of the element's existence in the real world), and furthermore, information about when the data were entered into, modified in or deleted from the data set. Temporal validity is not expressed in the UML model. Figure 5 shows the generalised UML model together with relationships and associations. The main feature classes forming the passable network and the grouping of obstacle classes are presented. The importance of landmarks shows in the model. *Landmark* feature class is associated with *Entrance* feature class as many buildings and stations serve as landmarks. *Landmark* feature class has a relation to the *Guidance* feature class belonging to the 'PedestrianObstacle' class' as features may be classified as physical obstacles but also serve as guiding objects.

The 'Footpath' feature class constructs the topological pedestrian network. All sub-classes will inherit the attributes of the 'Footpath' class. The network includes all pedestrian routes, including virtual paths through open areas where no actual paths exist. The geometry of pedestrian zones may be stored as area and passable links can be calculated inside the area with various shortest path algorithms, such as visibility graph or convex path approach (Hong et al., 2013). The network is connected to the road traffic network to enable the use of roadsides where no designated pedestrian routes are available. Network links should have attributes such as street names, surface material and condition status information, if applicable. Pedestrian crossings play a major role in safe locomotion and thus the information should be enhanced with attributes like information about divisional islands and traffic lights and their acoustic signals.

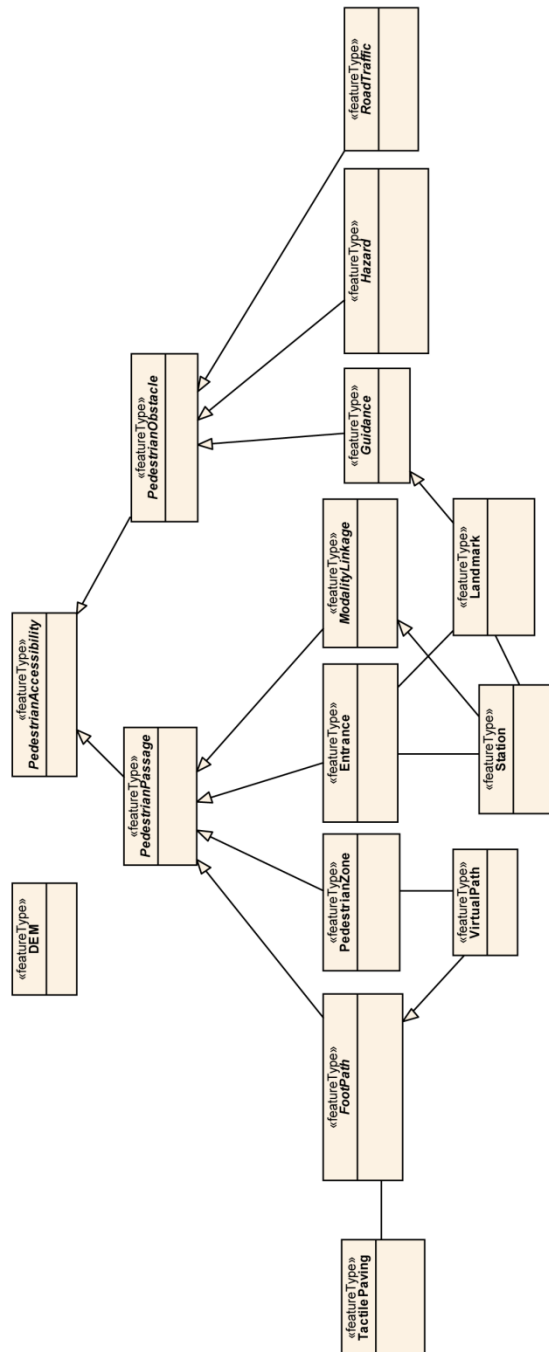


Figure 5. The generalised view to the database content. The model is presented in more detail in Publication III.

Landmarks and points of interest also play an important role in navigation, in wayfinding and in assuring that users are on the right track (Publication II). In forest environments, natural features may be used as landmarks, such as hydrological elements or landforms. Such features, which cannot be modelled as landmarks even serving as one, can be given a special landmark attribute which enables their use for navigation purposes. It has to be noted that seasons affect the observation of particular landmarks: different sets of landmarks can be observed in wintertime and in summertime. Important attributes for Landmark feature are addresses, building names, place names and street names; additional information on auditory and olfactory attributes can also be given. Building entrances should be mapped according to their actual location and addresses should indicate this location. The actual location of an entrance is especially important for people with visual impairments. The attributes for entrances include the name, address and information about wheelchair access.

Real-world objects that are considered as obstacles for pedestrians can be divided into two groups: guiding and hindering objects. Objects connected to the pedestrian environment, either physically or logically, should be included. These objects are categorised by their geometry. The itemisation of different objects is important in order to search for certain types of objects (e.g. mailboxes, parking meters, benches), when necessary. Figure 6 presents the suggestive enumerations for the feature types. Enumerations are to be formulated according to different environments.

There are two attributes with derived enumerations; the *DifficultyLevel* and *DangerLevel*. While the objective is kept to collect primary information, as stated before, these attributes have been added to generalise the information for better accessibility. The difficulty level refers for the classification often given to hiking paths by an outdoor authority. The level of difficulty is influenced by factors such as elevation changes and type of terrain. Features associated with a danger potential for pedestrians may be marked with a danger-level attribute. Danger level may arise because of mixed traffic (bicycles and pedestrians on the same lane), crossings with simultaneous green light for pedestrians and for turning vehicles, or other reasons that increase the potential for danger. The danger level can be assigned according to the severity of the danger potential. These attribute values can be used for weighted route calculations. However, the actual data behind the increased

danger level should be additionally stored as a separate attribute when possible.

A digital elevation model (DEM) is the basis for deriving height and slope inclination information for geographic features. Topographic information and landforms may be used as landmarks, especially in forest areas where few other significant objects are available; for example, the top of the hill or the highest point of the track may serve as landmarks in a hiking context.

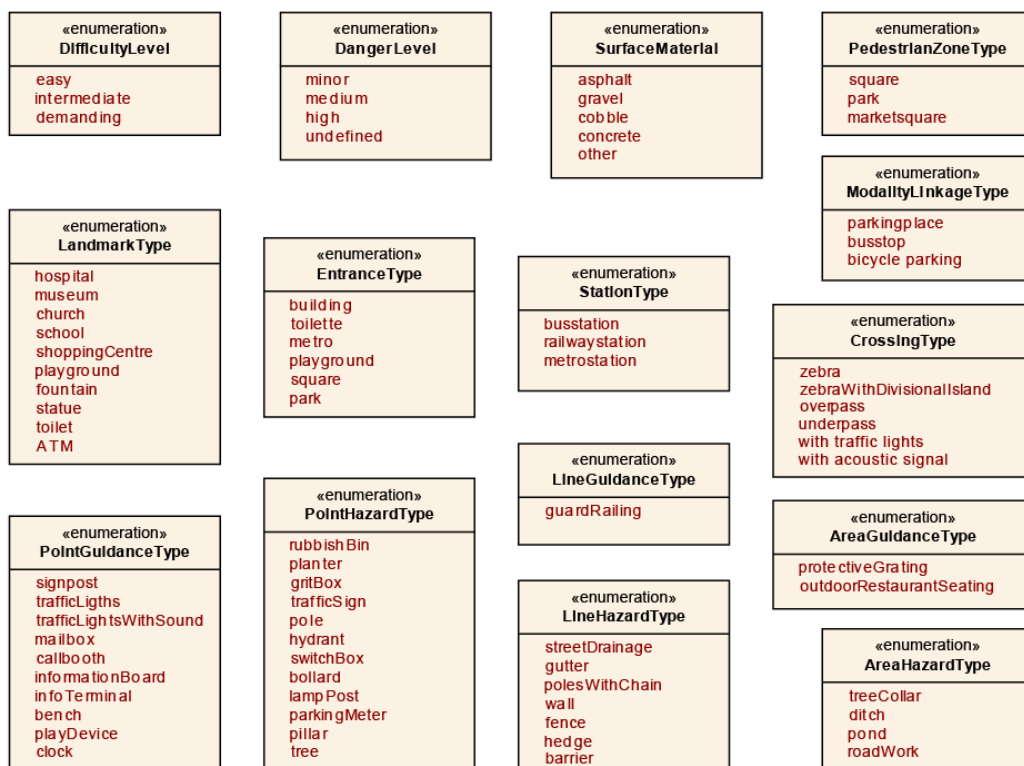


Figure 6. Enumerations for the feature types.

The *AccessibilityMap* information model presented here is comprehensive and has been designed according to the ‘Design for All’ principle, while trying to serve as broad an audience as possible. However, it is important that the amount of information is relevant to the user and to the situation at hand. In practice, it may be necessary to reduce the amount of information presented and to prioritise items. In terms of safety and degree of difficulty, the important features for various groups have been identified (Table 3). The prioritisation depends on the user group and is somewhat different for each group. Several user groups can be identified within any particular group of

pedestrians; such groups may have different priorities concerning the information needs of the user. When dividing users into different groups and sub-groups, careful user studies should be undertaken. Laakso et al. (2012) has suggested various situations and related geographic features that cause difficulties and present risks to persons with different kinds of visual impairments. In the study, four different categories of people with visual impairments were identified (totally blind with a dog, totally blind with a cane, partially sighted without aids and partially sighted with aids). People with mobility restrictions comprise another user group with several sub-categories (wheelchair users (manual/electric), people with walkers and people with baby prams or a heavy burden). Furthermore, small children and elderly persons may be seen as groups with special user needs. However, it should be noted that a group is always heterogeneous and variations in user requirements exist; therefore, the data structure should allow for these differences.

Table 3. Prioritisation of the features by user group

User group with special requirements	Prioritised features	Essential attributes
Users with visual impairments	PedestrianCrossing	CrossingType
	Entrance	
	TactilePaving	
	Kerbstone	Missing
	Stairs	missingTactile
Users with mobility impairments FootPath attributes: - SurfaceMaterial - Inclination - width	PedestrianCrossing	CrossingType
	Entrance	wheelchairAccessible
	Lift	wheelchairAccessible
	Kerbstone	Height
	Stairs	withEscalator withRamp rampDeclination numberOfSteps withHandRail

In general, accurate and complete information on pedestrian network is essential for all users. A comprehensive pedestrian network is a vital part of the data. Compared to a road network, a pedestrian network is more complex and contains, for example, sidewalks, often for both sides of the street, and created virtual paths through open areas, such as squares. In a pedestrian network, the crossings are the most dangerous spots, and therefore, it is vital to properly attribute the pedestrian crossings. Crossings have a type attribute, and for weighted route calculation, a crossing can be tagged with a danger-level attribute. A pedestrian crossing can be regarded as dangerous if it, for example, has a simultaneous green light for pedestrians and for turning vehicles or has only a short green light.

Another significant environmental characteristic causing challenges has to do with differences in the surface level. Level changes cause problems, especially for people with mobility restrictions. Information that is a high priority for them is information about stairs (with a ramp, with an escalator, a number of steps, ramp declination), information about the existence of kerbstones (high/lowered) and the exact locations of accessible entrances. In addition, all obstacles in the walking area that pose a danger or could be insurmountable are of a first priority; they need to be mapped and presented to users. These features are listed as hazardous points, lines or areas, and they encompass features such as construction works, scaffolding, bollards, bars, and similar obstacles.

Based on the user study done in the field (Publication V), the most important characteristics of the navigation application have to do with information that can be summarised as reliability, content and communication. As already demonstrated by earlier studies, safety is one of the main issues for all users in a forest environment (Nivala et al., 2009). The map application has to be reliable and consistent so as to create a feeling of confidence. This was also confirmed in this study and emphasised by the elderly users. The information content is also important. The elderly users involved in the field test wished for the same topics as had been identified in the user requirement workshop with project workers earlier. One of the most important topics was detailed information about the trails: their current condition and degree of difficulty in general as well as an estimate of how long it would take them to complete the trail in terms of distance and time. All the decision points where users need to choose which way to take are clearly spots where additional information is needed. The users were expecting information at each route crossing, such as

what path to choose and where the intersecting paths led to. They also wished for further details about their surroundings, such as information on local geology, flora and fauna.

5.2. Use of sound to enhance accessibility

For people with disabilities, going to unfamiliar places is always a challenge. However, many people, despite their physical or mental abilities, feel insecure visiting strange places. For some people, forest environments in particular are a potential place where they can lose their way and become lost. People may feel uncertain about their map-reading abilities, their physical conditioning or other factors related to their own competence or to the environment. When relevant information about the environment is available, and it is communicated in an easy and accessible way, users feel more secure and confident to go out into new places. This research discovered how accessibility can be enhanced by using sound to communicate geographic information. This is one dimension in the concept of accessibility.

In Publication IV, we presented examples of successful implementations of sonic maps designed to help users explore the hiking area and plan their hikes in advance. It was expected that the possibility of exploring the area via sounds beforehand would lower the threshold of concern with respect to actually visiting the place. Furthermore, sonic maps with natural, original sounds from the area provide those who are not able to visit the park with virtual access to nature. The preliminary user tests showed that people are fond of having the possibility to obtain in advance an idea about the environment and its qualities. Users wanted to have current sonic information about the environment, for example information about a particular season of the year. Sonic maps create remote access to nature and enhance the accessibility of a place. The real-world sounds of a certain location are something we rarely can learn about without actually being there ourselves.

Landmarks are a natural way to communicate spatial descriptions (Publication II). In a natural environment, landmarks are less easy to identify than in urban environments and more landmark description is needed. Thus, in natural environments less prominent features may be used as landmarks to assure users about their location, such as landforms and forest types. Landmarks should be used in route guidance instructions. In audio

descriptions, the terms and verbal descriptions should be in conjunction with the ones used by the users. The importance and specific character of landmarks in forest environment has been further studied in Sarjakoski et al., 2013.

Publication V describes the user requirements for informative and descriptive map content within the context of hiking. It was expected that combining audio with visual information would improve the overall accessibility of particular routes in a hiking context. To compensate for the small display screens in mobile devices, sound has proven to be an essential medium in navigation applications. It supports users who are unable to follow visual guidance because of impairments or for other context-related reasons. The primary aim of the audio descriptions was to offer users additional information in a convenient and effortless manner. Quite surprisingly, however, the mobile map application with location-based audio descriptions increased feelings of safety among elderly hikers by ensuring them that they were on the right track while hiking in the national park.

Audio descriptions were well accepted among users and they can potentially be studied further as a successful means of communicating map information to users on the move. Audio descriptions have the potential to be especially efficient at providing orientation help when users are unsure of which direction to take. Users may be aware of their location, but unsure of the direction to take in order to proceed on the chosen route. The descriptions of the environment offer them help in understanding the directions. Users may have difficulties reading small text or they may otherwise find map reading difficult. The elderly users preferred audio information over text because they did not want to wear their reading glasses while on the hike. For instance, when passing by a lake the users were delighted to hear the name of the lake from the navigation device, but they would not have made the effort to read it from the map. Especially in forest environments, where the routes are not labelled or signposted, users readily welcomed information confirming their location. With audio descriptions, the environment can be 'labelled' with linguistic cues by expressing the names of lakes and landforms when users are approaching or passing by them. A combination of visual, textual and audio communication would make the most efficient medium.

This study confirms the fact that elderly users are a particular user group for pedestrian navigation systems, and the voice-based descriptive information

embedded in a map application proved to be attractive and useful. Visually hidden audio descriptions communicated reactively in certain locations or activated by a user's gestures are an efficient way to add information to a navigation application.

5.3. Geospatial data quality aspects

The quality of the data is one of the major issues that impedes personal navigation by pedestrians, especially those with disabilities (Roentgen et al., 2011; Sobek et al., 2006). Quality aspects are closely associated with the topic of accessibility of the environment and are extremely important in terms of safe pedestrian navigation. According to the quality principles of ISO 19113, the following quality components should be considered in geospatial data: completeness, logical consistency and positional, temporal and thematic accuracy of the data (International Organisation for Standardisation [ISO], 2002). In particular, the completeness and positional and temporal accuracy of the data are all crucial for accessibility. It is essential for the user that the whole route, from the starting point to the ultimate destination, is accessible and that accessibility information is made available for the user.

The requirements for positional accuracy depend on use cases in which the data are utilised. The most stringent requirements are set when guiding visually-impaired pedestrians. For those applications, the positional accuracy of the data should be in the range of 0.5 m, which is the reach of a white cane. In other pedestrian navigation applications, the requirements for positional accuracy are much less stringent and an accuracy level of about 5 m is sufficient. It should be noted, however, that the level of detail in pedestrian navigation databases is high. The data must be logically consistent, and therefore data with a high level of detail must also have a high degree of positional accuracy. In practice, with mobile mapping systems a positional accuracy of 0.1 m can be reached for the detailed map feature collection. With city-based maps, the positional accuracy is typically in the range of 0.1 m. It is more likely that the problems concerning positional accuracy are the result of the navigation device. In particular, this is the case in covered remote areas in a forest environment. If certain areas or spots are known to be located in positioning blind points, the uncertainty of the positioning signal can be expressed in the geospatial database. This will help

users be more alert if they know that the positioning is not necessarily working properly in certain spots.

The temporal quality of the data has many different aspects in a database context. There is the internal lifespan of the spatial object in the database, the temporal validity of the real-world features as well as the data being up to date. The INSPIRE data specification recommends using the derived attributes to record the lifespan of a spatial object. These attributes specify the date and time at which this version of the spatial object was entered into, modified or deleted from the data set. The attributes specify the beginning of the lifespan for the version being used in the spatial data set itself, which is different from the temporal characteristics of the real-world phenomena described by the spatial object. There should be separate attributes that represent the temporal validity of the real-world phenomena. These attributes specify the date and time at which the real-world phenomena started to exist in the real world, as well as the date and time from which these particular phenomena will no longer exist. This information should be communicated to the end user, e.g. in cases involving construction work detours and the opening hours of gates. In order to guarantee that the data are up to date, an update plan and process for collecting changes should exist and be put into operation. Changes in the environment and corresponding corrections in map data should come into effect with a minimum amount of delay, especially for hazardous objects. Construction sites and similar hazards that affect the pedestrian environment and may cause users harm should be inserted into databases beforehand when possible and with relevant time stamps.

6. Discussion and conclusions

The ultimate goal of this study was to improve the accessibility of pedestrian environments by describing the geospatial information representing the space and by also communicating the information by way of sound. In order to meet this goal, the relevant geospatial information representing the geographical space and objects affecting accessibility were defined. Even though laws, acts and regulations provide precise building requirements for creating accessible environments, there is no holistic approach in geospatial data collection to representing the accessibility of geographical spaces. To answer the two research questions posed at the beginning of the thesis, a discussion and conclusions are given in corresponding sections below.

What kind of geospatial information is required to represent a geographical space and the accessibility of that space for pedestrians?

To specify the required geospatial information in order to represent the accessibility of a particular geographical space, a thorough feasibility study was conducted. By applying the guidelines and regulations for barrier-free construction to real-world situations, the framework for data specification was created. There are a large number of map databases, map presentations and map services aimed at pedestrians for different purposes. While some of them include certain accessibility issues, in many cases only one special user group has been considered, for instance wheelchair users. The information represented in the database might just read 'inaccessible' without any further details. In order to enable as broad-based an application as possible, the exact information behind the statement 'inaccessible' should be introduced, such as information about stairs, or even more specifically, the number of steps and height of each step. With exact information, the possibility is left to users to decide whether or not they can take a particular route.

To formally present the geospatial information representing a particular environment, an information model was compiled. The information model presented in this thesis provides frameworks for data collection in geospatial databases. Rich and categorised data content facilitates the use of data in map and navigation applications. Furthermore, it is more profitable when a single geospatial database serves as many people as possible. When the information model supports accessibility, it enables routing that takes different user preferences into account and increases overall accessibility.

But environmental accessibility is not just about physical obstacles. Some users may not take a walk or go for a hike because they feel unsure about their map-reading abilities, their physical condition or other factors related to their own competence or to the environment. Because users feel that forest environments in particular are more difficult to navigate, the study focused on observations and descriptions of routes and landmarks in a hiking context. Landmarks should be used in navigation instructions and in assuring that users are on the right track. Landmark features may be stored in databases as landmarks, or if belonging to another feature type, given a landmark attribute. With digital devices, more detailed information about the surroundings can be introduced and, in this way, enhance accessibility to the environment.

The results of the thesis will help data providers collect and store geospatial information while taking accessibility issues into account, and hopefully it will raise awareness about issues pertaining to universal accessibility. In terms of safety and serving users who have the most stringent needs for accessibility information, the most important features for various groups have been identified. When implementing the model, some modifications are possibly required to adapt the contents to local needs. However, for purposes of data re-use and data sharing, there is a need to harmonise the data model used for pedestrian navigation so that it also covers accessibility issues. The information model provided in this thesis could serve as a starting point for this kind of harmonisation work.

With better satellite receivers, new positioning satellites and advanced positioning services, the positioning accuracy of common mobile devices is improving and will reach a decimetre level of accuracy in the near future. With such a high degree of positioning accuracy, it will be possible to guide users more precisely if the underlying geospatial data contents support this process. Mapping the environment in detail, where even the smallest of accessibility issues is taken into account, is not easy to achieve. However, with modern data collection techniques, such as mobile laser scanning (Kukko et al., 2012) and mobile photo-based mapping, as well as with the aid of volunteered geographic information, it is possible to map the environment at a high level of detail.

How can sound be used to communicate geospatial information in order to increase accessibility?

This study assessed how accessibility can be enhanced by using sound to communicate geospatial information. Collecting real-world sounds and presenting them as soundscapes will help users explore particular hiking areas and plan their hikes in advance. Soundscapes embedded in a hiking map provide those who are not able to visit the park with virtual access to nature. The benefit of natural sounds is that they can be understood without the need to specify them. For instance, a soundscape with a gurgling brook speaks for itself and serves even as a sonic landmark. Integrating voice-based descriptive information in a hiking environment with a map application proved to be attractive and useful for users. With relevant information about an environment communicated in an easy and accessible way, users felt more secure and confident to go out and visit new places. Audio descriptions communicated reactively in certain locations are an efficient way to add information to a map and navigation application.

The results of the thesis prove the a priori hypothesis '*It is assumed that the accessibility of a physical environment can be improved with relevant geographic information and by communicating the information using sound.*' to be true. With relevant geospatial information and a comprehensive and complete pedestrian network, together with environmental features affecting accessibility, users with different needs and preferences are able to decide which route they can successfully complete. Using sound to communicate geospatial information makes the information and thus the environment itself more accessible. Albeit, the main effort should still focus on building accessible environments; in certain situations people face hindrances, and geospatial information could enable users to more easily overcome them.

6.1. Future research

In this study, the focus has been on the geospatial information requirements that facilitate accessibility and on how the use of sound enhances the accessibility of information. Visualisation is a major aspect to consider when dealing with geographic information and maps. The visualisation of geographic information on small screens in different contexts and circumstances is a broad research subject, one which will eventually need to

be addressed before even the most comprehensive database content can be delivered successfully to sighted end users.

In many cases, the reason for why users face problems while navigating has to do with the content of the data (Kammoun et al., 2012). The required data may be missing, or else available data might be incorrect, incomplete, neither accurate nor consistent enough, or out of date or incorrectly classified. Data collection is a burdensome task, and therefore the best solution would be if all geospatial data content responds to the majority of requirements for different use cases.

Crowdsourcing, social media and volunteered geographic information (VGI) are emerging trends that offer great potential for pedestrian-level data collection. The power and value of VGI rests in its ability to profit from local knowledge and, at its best, to be temporally relevant. OpenStreetMap (OSM) is an online map created by volunteers; it is one of the best examples of geographic information that has been voluntarily collected (Goodchild, 2007; Neis and Zielstra, 2014)). Many different OSM-based maps have been created in recent years and tailored to different purposes, such for as skiing, hiking or public transportation. Projects such as OpenRouteService and Open TripPlanner as well as other routing applications (Luxen et al., 2011) have demonstrated that volunteered geographic information has the potential to be a reliable data source for pedestrian routing and navigation applications involving users with disabilities (Neis and Zielstra, 2014; Kaklanis et al., 2013). Rice et al. (2012, 2013) report encouraging research experiences when collecting information on temporary barriers and obstacles with VGI in order to update the geospatial databases used in navigation by users with visual impairments. In a study by Hara et al. (2013), crowdsourcing was used to identify street-level accessibility problems. They used crowd workers from Amazon Mechanical Turk to assess the accessibility of sidewalks using Google street view imagery.

Volunteered geographic information opens up new possibilities, but at the same time it also raises questions regarding data quality and reliability. With OpenStreetMap, this problem has largely been solved via a tight, broad-based, reliable and trustworthy community (Haklay, 2010). But when a high level of quality is required from the standpoint of safety, often a responsible authority is also required. One way to handle the uncertainty with respect to

data validity is to notify users about the original data source and leave the decision of trust to them.

This research project, along with many studies already before it, has confirmed the importance of landmarks in wayfinding and navigation. However, traditional topographic databases do not recognise such features in their object lists. The collection and classification of landmarks used in topographic databases is an important and interesting topic for further research.

The information model presented in this thesis was designed to comprise various outdoor environments. In urban areas, however, large indoor spaces at stations, in shopping malls and in other public buildings are connected to the pedestrian environment. Extending the model to cover indoor networks is the next step in the effort to enable seamless navigation in cities and in connection with public transport.

Users are expecting more and more intuitiveness, ease of use and adaptability from the devices and applications they are using. Applications and services that require a great deal of user interaction are not likely to gain in popularity among users (Raubal and Panov, 2009). Thus, context awareness and adaptation are also important issues in the area of mobile map use. A major goal is to minimise user interaction through service adaptation and to provide context-sensitive and personalised information to users (Sarjakoski et al., 2008). Predefined profiles are one way to ease and expedite the use of mobile maps, but they seldom match precisely the actual preferences and competence of users. Further techniques may provide portable profiles where users can define their personal capabilities and preferences and where the profile may be inserted into different applications and services. User-centred map design is an important area of research in terms of improved accessibility (Karimi et al., 2014). People are keen to obtain the information that they are personally interested in with respect to various map-use scenarios. With profiles and other preference settings, users may harvest the information they require in different situations. Environmental accessibility may be augmented by cost calculations for walkability, which will take into account various attributes concerning infrastructure and safety (Guhathakurta et al., 2013). Weighted routing based on personal preferences is something that is worthy of further study. Route maps are already in wide use, and even

more tailored route choices may be given when the data contents are rich enough.

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