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Schematisation in Hard-copy Tactile Orientation Maps

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Zusammenfassung

Diese Dissertation beschäftigt sich mit der Schematisierung computer-generierter taktiler Orientierungskarten, die dabei helfen sollen, räumliches Wissen über unbekannte städtische Umgebungen zu vermitteln. Computer-generierte taktile Orientierungskarten sind Überblickskarten für Blinde, deren Details als erhabenen Elemente mittels eines Prägedruckers erfühlbar gemacht werden.

Anfangs wird festgestellt, dass nur sehr wenige Informationen durch eine taktile Karte vermittelbar sind. Dies ist bedingt durch die grobe Auflösung des Tastsinns und den kognitiven Aufwand der seriellen Exploration einer taktilen Karte. Dabei unterscheiden sich computer-generierte, geprägte taktile Karten allerdings sehr von den handgefertigten tiefgezogenen taktilen Karten. Daher sind die Möglichkeiten und Grenzen der Informationsvermittlung mittels taktiler Karten aus einem Prägedrucker ein erstes Forschungsfeld. In der Arbeit konnte gezeigt werden, dass Prägedrucke qualitativ eine nahezu gleichwertige Alternative zu traditionell gefertigten Tiefziehkarten sind. Ihr großer Vorteil ist, dass sie schnell und individuell anzufertigen sind und (abgesehen vom einmaligen Anschaffungspreis für den Drucker) überaus preisgünstig, für jeden zu beschaffen und ohne langes Training zu verstehen sind.

Noch mehr als in anderen Karten muss bei taktilen Karten eine Vereinfachung stattfinden. Vereinfachung kann erstens durch die Auswahl einer begrenzten Zahl Kartenelemente aus allen vorhandenen erreicht werden. Neben dieser quantitativen Vereinfachung durch Selektion ist zweitens auch die qualitative Vereinfachung durch Schematisierung denkbar. Unter Schematisierung wird in dieser Arbeit die kognitiv motivierte Vereinfachung von Kreuzungen, Linien und Formen verstanden. Anstatt die Anzahl der darzustellenden Objekte weiter zu reduzieren wird untersucht, welchen Einfluss die Art und Weise der Darstellung der ausgewählten Elemente auf die Wissensvermittlung hat. Als zweites Forschungsfeld wird die These aufgestellt, dass Schematisierung als qualitative Vereinfachung von taktilen Orientierungskarten dazu beitragen kann, die Karten handhabbarer zu machen und sie besser zu verstehen als nicht schematisierte Karten. In der Arbeit wird gezeigt, dass die Vereinfachung der Straßenform und die Begrenzung auf prototypische Kreuzungsformen nicht nur die Exploration der Karte beschleunigte, sondern auch die Merkleistung positiv beeinflusste und subjektiv von den meisten Studienteilnehmern als bevorzugte Darstellungsart gewählt wurde.

Taktile Karten, die erst mühsam Detail für Detail ertastet werden müssen, machen das Verschaffen eines ersten Eindrucks oder Überblicks schwer. Als drittes Forschungsfeld wird un-

tersucht, mit welchen Mitteln es dem Kartenleser erleichtert werden kann, auch ohne Überblick bestimmte Objekte in der Karte schnell ausfindig zu machen. Es werden drei Hilfsmittel untersucht: Führungslinien vom Kartenrand zum Objekt, die Positionsindikation durch Positionsmarken am Blattrand und Spezifikation mittels Koordinaten und ein über in der Karte befindliches Raster. In der Arbeit wird gezeigt, dass alle drei Varianten mit Prägedruckern umzusetzen sind und dass für taktile Karten der Größe A4 mit nur einem Zielobjekt und wenigen Distraktorobjekten die Führungslinie zwar am schnellsten ist, diese aber (wie das Raster auch) die weitere Exploration der Karte behindert. Daraufhin werden Vor- und Nachteile der verschiedenen Hilfsmittel in diesem und in anderen Anwendungsfällen diskutiert.

Abschließend werden Berührungspunkte zwischen den drei Untersuchungen diskutiert. Sie werden in einen Zusammenhang gestellt und es wird argumentiert, dass die kognitiv motivierte Vereinfachung ein Konstruktionsprinzip für geprägte taktile Orientierungskarten sein sollte, um die Kartennutzung und das -verständnis zu unterstützen. Es wird zusammengefasst, welche Empfehlungen für die Konstruktion von taktilen Orientierungskarten vor dem Hintergrund der Einschränkungen des Prägedrucks aus dieser Arbeit gewonnen werden können. Dann wird diskutiert, wie die Schematisierung anderer Karten in Abhängigkeit von Nutzungsziel, Vorwissen des Kartenlesers und Verhältnis zwischen dem Zeitpunkt der Wissensaneignung und dem Zeitpunkt des Wissensgebrauchs adaptiert werden sollte. Am Ende wird ein Einblick in die Grenzen der Arbeit und ihrer Schlussfolgerungen gegeben, um dann mit einem Ausblick auf mögliche Transfers der Erkenntnissen auf andere Anwendungen, z. B. multimodale oder interaktive Karten auf taktilen Flächendisplays/Stiftplatten, zu schließen.

Abstract

This dissertation investigates schematisation of computer-generated tactile orientation maps that support mediation of spatial knowledge of unknown urban environments. Computer-generated tactile orientation maps are designed to provide the blind with an overall impression of their surroundings. Their details are displayed by means of elevated features that are created by embossers and can be distinguished by touch.

The initial observation of this dissertation states that only very little information is actually transported through tactile maps owing to the coarse resolution of tactual senses and the cognitive effort involved in the serial exploration of tactile maps. However, the differences between computer-generated, embossed tactile maps and manufactured, deep-drawn tactile maps are significant. Therefore the possibilities and confines of communicating information through tactile maps produced with embossers is a primary area of research. This dissertation has been able to demonstrate that the quality of embossed prints is an almost equal alternative to traditionally manufactured deep-drawn maps. Their great advantage is fast and individual production and (apart from the initial procurement costs for the printer) low price, accessibility and easy understanding without the need of prior time-consuming training.

Simplification of tactile maps is essential, even more so than in other maps. It can be achieved by selecting a limited number from all map elements available. Qualitative simplification through schematisation may present an additional option to simplification through quantitative selection. In this context schematisation is understood as cognitively motivated simplification of geometry and synchronised maintenance of topology. Rather than further reducing the number of displayed objects, the investigation concentrates on how the presentation of different forms of streets (natural vs. straightened) and junctions (natural vs. prototypical) affects the transfer of knowledge. In a second area of research, a thesis establishes that qualitative simplification of tactile orientation maps through schematisation can enhance their usability and make them easier to understand than maps that have not been schematised. The dissertation shows that simplifying street forms and limiting them to prototypical junctions does not only accelerate map exploration but also has a beneficial influence on retention performance. The majority of participants that took part in the investigation selected a combination of both as their preferred display option.

Tactile maps that have to be tediously explored through touch, uncovering every detail, complicate attaining a first impression or an overall perception. A third area of research is examined, establishing which means could facilitate map readers' options to discover certain objects on the map quickly and without possessing a complete overview. Three types of aids are examined: guiding lines leading from the frame of the map to the object, position indicators represented by position markers at the frame of the map and coordinate specifications found within a grid on the map. The dissertation shows that all three varieties can be realised by embossers. Although a guiding line proves to be fast in size A4 tactile maps containing only one target object and few distracting objects, it also impedes further exploration of the map (similar to the grid). In the following, advantages and drawbacks of the various aids in this and other applications are discussed.

In conclusion the dissertation elaborates on the linking points of all three examinations. They connect and it is argued that cognitively motivated simplification should be a principle of construction for embossed tactile orientation maps in order to support their use and comprehension. A summary establishes the recommendations that result from this dissertation regarding construction of tactile orientation maps considering the limitations through embosser constraints. Then I deliberate how to adapt schematisation of other maps contingent to intended function, previous knowledge of the map reader, and the relation between the time in which knowledge is acquired and the time it is employed. Closing the dissertation, I provide an insight into its confines and deductions and finish with a prospective view to possible transfers of the findings to other applications, e.g. multimedia or interactive maps on pin-matrix displays and devices.

Declaration of Authorship

The thesis I am submitting is entirely my own work except where otherwise indicated. It has not been submitted, wholly or in part, for another degree of this University or at any other institution. I have clearly signalled the presence of quoted or paraphrased material and referenced all sources. I have acknowledged appropriately any assistance I have received in addition to that provided by my supervisor. I have not sought assistance from any professional agency except for English proofreading.

Christian Graf (Author) Hamburg, July 2013

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Last, I wholeheartedly thank my parents Ulrike and Dieter Graf for having raised me as an interested intellectual being and for having carried me through dire straits that ruled our lives for a few years. May the joy and pride about the result satisfy them after all. All my love and kisses go to my wife Daniela and my son Johan. Both are the pillars in my life now. They supported me unconditionally and with abundance of patience such that I could cope with the challenges.

Contents

Part I.

Cognitive Aspects of Spatial Reasoning with Tactile Orientation Maps

Chapter 1.

Introduction to Hardcopy Tactile Orientation Maps

In the world of today, maps are present everywhere. They provide spatial knowledge about parts of the world easily and instantly – without having to travel or having to be there physically. Orientation maps, for example, provide an overview of certain geographic environment. Map-users learn about objects in the environment, for example, which objects exist, how they are spatially distributed in the area, and though which paths they are connected.

About 39 million people are currently blind globally (WHO Media Centre, 2012). This large number of blind people that cannot make use of visual maps are reason enough to think about alternatives. One alternative could be to use computer-generated tactile maps that can be produced swiftly and distributed easily.

In order to develop an understanding of what a tactile map actually is, how it is used, and which specific problems result from its use, exploration and knowledge extraction of tactile maps is explained (see section 1.1). Modern printer technologies offer possibilities to swiftly produce individual tactile maps (see section 1.2). However, there is still a lack of research regarding the construction principles of how to generate tactile maps that are easy to understand once they have been produced with today's tactile printers. In section 1.3, I will focus the discussion of this thesis, then present a research goal, several scientific theses, and related research questions. The chapter ends with section 1.4 that provides an overview of how this thesis is structured with regard to achieving the research goals.

1.1. Survey Knowledge Acquisition with Tactile Maps

When planning to visit an unknown environment, it is recommendable to acquire knowledge about spatial relations prior to the actual journey. This is especially true if possible specific wayfinding problems cannot be anticipated.

The strength of maps is their ability to convey survey knowledge as they allow to form a cognitive map. Such cognitive maps can be used to construct solutions to wayfinding problems when necessary, instead of making a huge effort to learn individual solutions for each potential wayfinding problem (i.e. acquire route knowledge). This type of structured knowledge is not just about solving problems dynamically. It also provides a better environmental awareness of spatial entities and supports for various inferential and wayfinding problems. Consulting maps and using their encoded knowledge allows the user to develop a versatile representation. The survey knowledge acquired during small-scale map exploration can be helpful for navigation on a geographic scale. Thus, survey maps are effective support tools for human navigation (details and references see section 2.1).

Most people are used to visual maps that are often printed on paper or are displayed as digital graphics on computer screens. To illustrate what maps could mean for people who have lost their eyesight, let us image the following scenario:

Hannah is a independent woman in her fifties. Over the past ten years she has been gradually losing her eyesight through macular degeneration. She was always independent before this happened and still wants to carry on exploring the world. She is adventurous. She likes discovering unknown parks and zoos and her favourite shopping areas. When she visits a park, she wants to stroll and walk around independently, i.e. without determining her route in advance. Often, the position provided by her GPS navigation system does not provide her with much information as she is not familiar with the surroundings habitually. When she is in a zoo, she likes to choose one or another direction spontaneously and spend time with her favourite animals. When she is in a shopping area she wants to be flexible and go back and forth between her most favourite shops without relying on a predefined route.

As a result of her mobility training and by using a long cane, she has no problems making her way independently through most environments. She is able to avoid obstructions in her path, detect curbs, or cross intersections. For finding routes and moving from one point to another, she uses a GPS-based navigation system with artificial language that tells her when to turn left or right. However, her experience with this route-oriented system is not altogether positive. She has accidentally been lead into blind alleys, for example, into a blocked road. Without having an idea of how the environment is structured she feels lost. This is why Hannah wishes to be prepared. She wants to get an impression of the area with its network of streets and all important landmarks before she sets off. Knowing the global structure of a route allows her to make detours easily, choose short-cuts, and understand inter-object relations between landmarks on the route she has not yet experienced herself. A navigation system that only provides route information does not allow such flexible spatial behaviour. As she does not have any access to visual information while moving, she is convinced that travel preparation with an overview of the environment including her favourite point-of-interests and major landmarks highlighted will help her once she sets off – both through self-localisation and flexibly finding her way. This kind of global knowledge from maps could help Hannah to prepare for her travels.

To acquire the necessary spatial knowledge about the structure of the environment, she uses a hardcopy tactile orientation map (TOM) with raised lines before she starts to travel. These maps are constructions that are printed with a computer-controlled embosser. It displays the structure of the area including streets, principal landmarks, and a choice of personally relevant points-of-interest from a birds-eye perspective, for example, the entrance of the zoo, the paths in the zoo, and the locations of her favourite animals. By exploring the raised lines of the tactile orientation map with her fingers, Hannah has the chance to acquire an overview of the area helping her to navigate independently during later locomotion. She feels more confident and powerful consulting a customised tactile orientation map before her tour. Nevertheless she still uses her GPS-based navigation system while she is travelling as it provides detailed real-time information of the route. The combination of both—tactile maps when learning offline and the option of an online navigation system—enables Hannah to maintain her independence on her tours.

Hannah is only one single person, but she shares the fate of 39 million others. Some blind people are congenitally blind (blind from birth), but the huge majority have suffered eye-related diseases or accidents in the course of their lives, just like Hannah. They could just as well be in Hannah's situation – therefore Hannah represents a large portion of blind persons who lost their eyesight in adult life. Nevertheless, she has not lost the will to explore unknown places. She knows how to read maps and has used visual maps before. Therefore she has learned important map standards, such as scale, to make her map-reading successful. Now, she looks forward to using computer-generated tactile maps to learn about the spatial structure of the environments she likes to visit.

This thesis investigates ways to support late-blind human navigators to effectively learn about a geographic environment from simplified tactile orientation maps produced with commercially available tactile printers (aka embosser). In this thesis, simplifying means abstracting metrical details while preserving the environmental structure of the geographic environment. Here, environmental structure refers to the qualitative characteristics of the spatial environment, specifically to existing entities, such as streets, buildings, and spatially extended compounds (parks, sport areas), and the qualitative relations among these entities, for example, cardinal and relative directions or categories of distance (near vs. far). Metrical details, such as length of street segments and intersection angles, are deliberately neglected to mimic the schematisation ensued when (blind) humans learn maps. This intends to support the human map reader to learn essential qualitative details while emitting specific metric details. Reducing the geographic complexity is essential in order to enable acquisition of spatial knowledge about that particular reality. Otherwise the tactile map is too cluttered and eventually becomes meaningless. The acquired spatial knowledge supports tasks of unaided wayfinding, i.e. wayfinding without navigation aids at hand. Consequently, the travellers' independence is maintained.

Without vision, navigating the world is not easy. Most blind people can directly sense what is around them with their hands or with the tools they use like the white cane. This may be sufficient regarding locomotion as obstacles in their way can be felt and avoided. However, blind people do not have the ability to sense things that are away several meters or hundreds of meters, for example, distant landmarks. There are certain effects that have proven to aid blind people navigating through spaces, for example, verbal descriptions. However, constructing a spatial model from such serial propositional input takes a lot of cognitive effort. The serial input flow has to be interpreted, then has to be combined with previous information, and finally, a mental representation has to be formed. Direct exploration of the environment, i.e. environmental learning, becomes a great challenge. Locomotion, particularly avoiding obstacles, and building up a mental representation of the environment are necessary simultaneously. This takes a lot of cognitive effort. Without vision, it is much harder to understand the structure of the spatial environment if the extensive sense of sight is unavailable.

Beside describing language and environmental learning, some external spatial representations that communicate the structure of the geographic world in an accessible and understandable way could be a further option. *Tactile maps* (also named tactual maps) displaying tactually prominent entities could be possible options. They provide functions similar to visual maps in a non-visual form. For a photograph of a tactile map see Figure 1.1; an enlargement is shown in Figure 1.2.

In tactile maps, map entities physically raise above the base material of the map so that map readers can feel them by reading the map with their tactile senses. This is how spatial knowledge is conveyed non-visually to support navigation through spaces. Additionally, a map represents reality in an analogue form: the structure displayed on maps resembles the structure you find in reality. The mapping corresponds to the actual geographic environment, no further cognitive transformation is needed, and cognitive capacity is available for other tasks.

A tactile orientation map can hardly be a full substitute for a visual orientation map. Tactile maps are only able to show very limited details because the entities that represent spatial objects and concepts are spacious. They have to be this big as the tactile resolution is lower than the visual. All tactile entities compete for the limited space available and usually do not represent all knowledge that might be beneficial to a task (for details, see chapter 2 for sensory and cognitive limitations in tactile map-reading). Therefore, a selection of entities has to be made. Landmarks with the purpose of giving orientation cues to navigators, for example, should be displayed. Theoretically, this could be compensated by larger tactile maps that display particular content over a larger surface. For the sake of good usability however, the size of any tactile map is limited to the size of an arm's reach, often called the manipulatory space. Therefore only the most relevant information is selected to be represented on the map. Otherwise the map would clutter quickly and would be hard to understand – simply for the

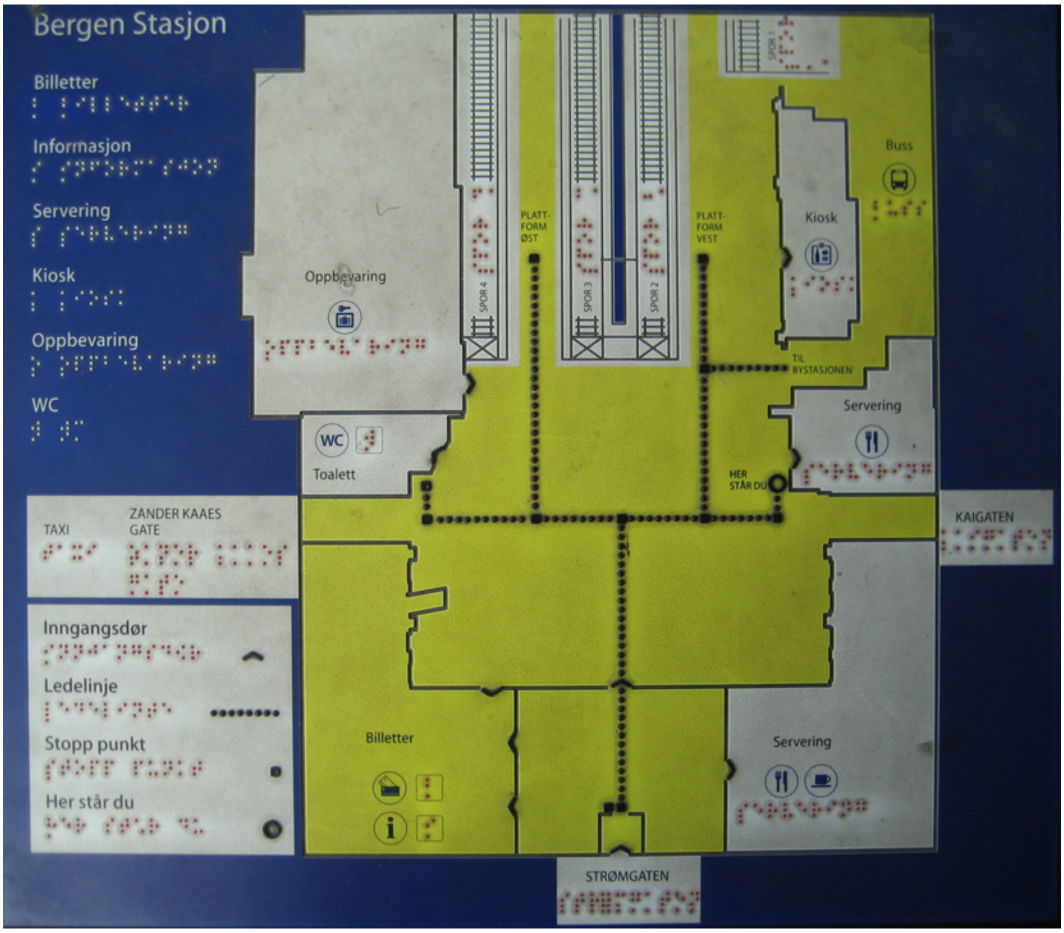

Figure 1.1.: A tactile map representing the Bergen railway station produced with conventional techniques: The final product is a metal plate with raised lines (for an enlargement of a section of this map see Figure 1.2).

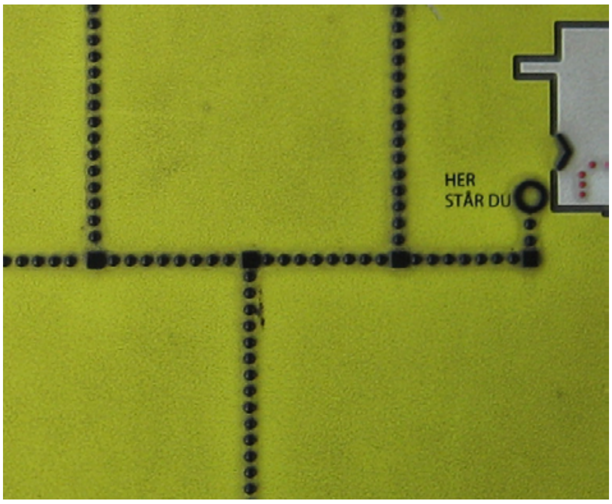

Figure 1.2.: An enlargement of the central part of a tactile map shown in Figure 1.1. The broken lines signify the safe paths from the you-are-here position to the platforms and the exit (not visible).

amount of entities displayed.

Another approach could be to schematise the map. Schematisation, in this context, means to cognitively motivate the process of map simplification with the goal to ease map comprehension. A first approach to schematisation is to abstract the representation of streets beyond the size they would usually have when displayed on a scale. The effect is know from every street map: if the representation of a street was rendered with the scaled-down version of the width of the street, it would be too narrow to make the map easily readable. Therefore, the streets are displayed on a larger scale.

Schematisation would not have any effect on map comprehension if there were too many objects on the map. Thus, this second approach is not a substitute for the first one, i.e. selecting the information to be displayed, but complements the map to make it more comprehensible. It could be said that selection prevails, schematisation refines – and both contribute to map comprehension.

This thesis proposes how computer-generated tactile-orientation maps should be abstracted to enable the map-reader to understand the schematic environmental structure easily.

1.2. Principles for the Automatic Production of Tactile Orientations Maps

Map making was a handicraft in former centuries, often considered an art, but the advent of computer technology has brought new possibilities, new products, and new ways of making, producing and disseminating maps. Nowadays, people can enjoy both the commodities of traditional maps made of paper and the convenience of dynamic, real-time, digital maps, as for instance in car-navigation systems. The principles of good map making that were part of the implicit knowledge of experienced map makers in former times have been partly encoded in computer technology. Today, visual maps are often the result of computer-supported map making. The process of making maps has become more and more efficient, and map makers have adopted computer technology for such central strategies as cartographic generalization (see, for example, the review by Brassel & Weibel 1988). Accordingly, one may ask for similar development in the area of tactile maps. Indeed computers are used in the process of making tactile maps, but they are mere tools expressing some ideas of map makers. Explicit principles and procedures of how to construct tactile maps the best possible ways—so that they are interpreted correctly and prevent wrong conceptualisations —are still not available or well-established.

I distinguish two consecutive processes in the production of tactile maps: map design and map production. *Map design* is largely done manually today and supported by certain graphic software. It covers two main parts: map entity selection and map entity placement. In the first step, the selection of entities depends on the tasks a map should complete. In the second step, the selected entities are abstracted, placed, and optionally labelled. Similar to visual maps but more pronounced, the main restricting factor to placing entities in tactile maps is the limited space. In traditional tactile map making, the constraint satisfaction problems that arise when spacious tactile symbols have to be placed within the available space, are solved on a highly individual basis – individual to the map and by the individual map maker. Today's experience is founded on heuristics that inform about practical solutions for this challenge. How and why some maps are abstracted in certain ways is tacit knowledge of their designers. In some cases this knowledge is gathered in guidelines that explain how to apply tactile map design – but on a rather high level and inaccessible for automation. The second step *map production* concerns the presentation of a map design to a map-reader, either as a physical map that can actually be touched or as a virtual map where touch is mediated by some computer-driven device.

The traditional heuristic approach to map design could serve as a starting point for procedural support, i.e. formalising the procedure to simplify geographic information for tactile orientation maps. When investigating such procedural support the context of use should be considered. This includes the map-user who should be able to understand the map in a specific context given a specific wayfinding task. This task may be highly specific, for example, getting acquainted with the spatial structure of zoos or malls, like Hannah wants to do in the scenario described above (see section 1.1). Tactile survey maps that communicate the overview of an environment to ease orientation are *tactile orientation maps* (TOM).

From a cognitive point of view, usable tactile maps are desirable as they make the knowledge acquisition easier. In this thesis, good usability of a tactile map is meant as depending on the efficiency and the efficacy of knowledge transfer between map and map-user. The focus is on the properties of tactile orientation maps and the cognitive strategies of knowledge acquisition they afford. A result of good usability is an effective understanding of the street network with its embedded landmarks, the efficient use of the map, and the (subjective) satisfying experience using the map. Presumably, using such tactile maps will lead to safer, more efficient, and confident navigation and spatial behaviour. Increased spatial awareness and wayfinding ability may also have an important effect on greater independence of blind people. An increase of vocational, social, and educational opportunities could be a consequence.

The development of a set of guidelines for the simplification of TOMs is a first step towards a usable support for blind people. I propose that TOMS are usable when it is constructed with *cognitively motivated* schematisation principles. in terms of conveying mental representations that allow for successful execution of spatial tasks such as mental wayfinding.

If environmental details in these maps are schematised differently to TOMs with uniform scale and if schematised maps are then less misunderstood, i.e. the conceptualisation of such maps is less prone to errors, then that would be an argument for using the proposed schematisation principles.

Focussing on the approach of how to turn inaccessible geographic data into usable tactile orientation maps might be a considerable hope to break this 'vicious circle' (Sherman, 1975, p.91) of lacking demand for tactile maps. Reason for the lack of popularity is that people have not learned to use them and therefore do not demand them. Still, there are many problems to be solved on the way to the automatic construction of usable tactile maps. Usable tactile maps should ideally communicate spatial knowledge in an effective way, be efficient, practicable and satisfy map-users.

1.3. Research Questions and Contribution

The goal of my thesis is to find effective concepts of map schematisation that yield efficient and satisfying computer-generated tactile orientation maps. Tactile orientation maps are viewed as communication tools that help to facilitate the comprehension of the depicted geographic environment. Understanding the structure of that environment is the primary goal of reading a schematised tactile orientation map. These maps are defined as cognitively-adequate tactile orientation maps as they are constructed with the objective of cognitive ecology in mind. They are built to fit human cognitive abilities. The goal of my thesis is to investigate schematisation concepts for usable, computer-generated TOMs that facilitate human survey knowledge acquisition. These TOMs should display environment details effectively, be understood efficiently, and used with satisfaction.

Understanding a map is achieved if the internal mental representation allows for successful execution of mental or real navigation tasks in the environment. A mental navigation task could be, for example, unaided route planning, i.e. planning the route from one position to another without having a map at hand. A real navigation task could be, for example, to find a route and execute it in the corresponding environment without a map at hand. Both activities are regarded as being of equal quality in the context of this work because I focus on the cognitive challenges of building up mental representation from a tactile map before planning a route begins. The locomotion-specific aspects of behaviour in a realistic situation, mentioned in the second example, is of no interest for this work. The benefits of internal mental representations, i.e. the conceptualisation of qualitative spatial knowledge, is assumed to depend on the qualitative aspects of external representation: the tactile map. In the context of this thesis, the cognitive challenge about the properties and entities of a map influencing the conceptualisation of encoded spatial knowledge, is more important than the sensory challenge of map-reading. The focus of this thesis is on how principles of schematisation used in the construction of tactile maps contribute to the understanding of the encoded spatial knowledge when using those maps for spatial reasoning tasks.

The general research questions can be formulated as follows:

> Which schematisation principles used in the construction of a hardcopy tactile map ease the comprehension of that map?

The approach taken in this thesis elaborates on already existing concepts for abstracting topology and geometry of maps presented on small displays or with restricted resolution and to propose new ones. Then I will investigate whether they are applicable within the area of tactile maps and propose means of facilitating the usage and comprehension of hardcopy tactile orientation maps.

Map construction and map-usage of tactile maps produced with an embosser differ from design and use of traditional tactile maps in several ways. This thesis sets out to understand how tactile maps produced with a embosser can be improved to be more comprehensible. It develops principles for the schematisation of hardcopies. This is the second specific research question.

> In which ways do the principles of schematisation have to be customised to the production technology to result in a usable tactile map?

Map-usage is influenced by the individual capacities and mental predispositions of map-users. These factors were regarded as external factors for map schematisation at this stage of research. They are discussed but not experimentally investigated.

From the results of my research I will formulate principles for abstracting survey knowledge of spatial configurations that are customised to the sensory and cognitive specifics of the usage of tactile orientation maps. Once defined, such principles could be implemented as constraints in systems that are used to (semi-)automatically construct tactile orientation maps.

The results are used for developing guidelines that constrain and advise future map design and development. This is important, as there are very few guidelines for map-makers to use. The guidelines could be queried each time such a map has to be constructed manually. Another option is to build automatic construction expert-systems based on the guidelines. I will make this pitch a part of the application and reach of my work.

If the promising work of different areas to advance knowledge about the principles of the communication with maps is taken into account, there may also be potential for the computer-based (semi-)automatic construction of tactile maps. In combination with tactile printers, the distribution of computer-generated tactile maps could become easier. I argue that fast production and facilitating the understanding of cognitively adequate, computer-generated tactile maps could make tactile maps more attractive in terms of usability and functionality. This may also increase acceptance in the target population, utilisation of tactile maps and therefore improve spatial skills related to map-usage.

Some visually-impaired individuals might benefit from tactile, external representations of the world and have the chance to improve independent navigation. This would contribute to their orientation and wayfinding abilities instead of largely depending on either personal assistance, which is not available at all times, or technical equipment, which can fail or have detrimental effects on their spatial knowledge (Parush et al., 2007). Tactile maps allow blind people to maintain a decent level of independence and self-determination.

The contributions of this thesis will be as follows.

1. A review of schematisation concepts from visual maps and an evaluation concerning their applicability to tactile maps.
2. A list of schematisation concepts customised to map production with a tactile printer.
   a) Concepts that support the task of survey acquisition in tactile orientation maps.
   b) Concepts that support the task of position localisation in tactile orientation maps.
3. Theoretically and practically backed guidelines for the schematisation of tactile orientation maps.

1.4. Structure of the Thesis

This thesis is composed of three parts. The first part is about theoretical foundations, conceptual considerations and technological constraints that have a reasonable impact on the question of how to find concepts for constructing cognitively adequate tactile maps. In the second part I present pilot studies that were conducted to show that some schematisation concepts adopted for a tactile printer might help people understand their geographic environment. In the third part I summarise and discuss the findings and identify more research questions resulting from this thesis.

In chapter 2 a review of the state-of-the-art literature presents specific background to understand the subsequent chapters and explains approaches. I will focus on cognitive aspects of tactile maps and their usage in section 2.1, then I elaborate on schematisation in geographic maps (section 2.2). Last, I review theoretical and practical findings about tactile map making and tactile map-usage (section 2.3).

In chapter 3 I will elaborate on the schematisation of tactile maps and how it can contribute to map-understanding. I introduce the characteristics of hardcopy tactile orientation maps in section 3.1, which activities are performed with tactile orientation maps, and how the former characteristics become useful in the latter activities. In section 3.2 I will look into technology challenges of producing tactile maps with tactile printers as well as into the sensory challenges of reading tactile maps. I will identify the constraints introduced and suggest schematisation as a relief to these constraints. Schematisation concepts that were used in other contexts are presented.

In chapters 4–5 I will present results from user studies. In chapter 4 I will elaborate on findings about the context of tactile orientation map-usage, including requirements for good usage. chapter 5 is about how to apply schematisation to some tactile orientation maps to make them more comprehensible for the map-user. In chapter 6 I will present a study about how to facilitate the usage of a tactile orientation map through cognitively motivated schematisation of position markers.

In chapter 7 I will take up the theoretical and practical findings from chapters 4–5 and extract recommendations for constructing usable TOMs. This chapter will discuss these recommendations in the light of existing recommendations with regard to neglected factors, relevance and applicability – including certain potential for the usage and a strategy for further development.

The final chapter 8 on conclusions and future work closes the thesis. I summarise what was achieved in this thesis and which issues were not addressed. I identify fields of future research that have the potential to deepen the insight into the principles of tactile map construction. I conclude this thesis with a speculation about the potential future of computer-generated tactile maps in the light of practical problems and theoretical concerns.

Each chapter will be concluded with a summary that assembles the most important insights from the corresponding part of the thesis.

Chapter 2.

Tactile Maps: State-of-the-Art in Theory & Practice

The abstraction of tactile maps can be investigated from various disciplines, including psychology, computer science, and geography, to name but a few. Researchers from these disciplines and practitioners (for example, manufacturers for special ability tools, mobility trainers) have contributed experimental findings and best practices during the past several decades. Based on these findings, the aim of this chapter is to lay theoretical and practical foundations for the quest of computer-made, not hand-made, usable tactile maps. Relevant parts of existing knowledge to understand the subsequent chapters are identified. Research about spatial knowledge acquisition with (tactile) maps, simplification of maps, and tactile map production is reviewed and related to the challenge of producing computer-generated tactile maps that convey survey knowledge to blind individuals enabling them to gain an impression of distant geographic spaces.

2.1. Acquisition of Spatial Knowledge with Maps

The portion of the world that someone regards as distant, i.e. the part of the world one cannot perceive directly, depends on this individual's sensory access to that world. Sighted people might not regard everything in *vista space* (Montello, 1993) as being distant. And most blind people only consider their *peripersonal space*, i.e. the space around the body that is within reach of hands (or tools such as a white cane), as directly accessible (in various degrees of perfection). Even though the auditory space has a larger reach, the ability to apply echolocation, i.e. recognizing objects that are within a distance of a few meters, is rare among the blind. It helps to avoid obstacles, but not to achieve an overview of the larger surroundings. In this situation, the acquisition of spatial knowledge through other means is crucial. If sources of mediated spatial knowledge, for example, a map, become available then navigating unknown territories would be feasible again.

2.1.1. Navigation in the Geographic World

Navigation is considered to be supported by different kinds of spatial skills, i.e. locomotion, the 'proximally coordinated movement part', and wayfinding, the 'distally coordinated planning part' (Montello, 2005, p. 258).

Locomotion is the physical activity of moving around in an environment, while coordinating the action in the local surrounds and solving behavioural problems. The local surrounds are immediately accessible to the human sensory and motor system (Montello, 2005, p. 279). Locomotion includes finding surfaces to step on, avoiding obstacles, course stabilisation within a corridor, or directing the movements towards landmarks. All these spatial problems typically do not require spatial memory[1]. As described in the chapter 1 scenario, blind people's locomotion can be supported by tools, for example, the white cane, guide dogs, or special purpose technology such as GPS-driven systems (for a review, see Giudice & Legge, 2008).

Wayfinding is 'the process of determining and following a path or route between an origin and destination' (Golledge, 1999, p. 6). Wayfinding is the targeted, efficiency-oriented and planned movement to a distant destination in an environmental space that extends the local surrounds. Targeted orientation towards a distant destination and the fact that direct paths to the destination are not perceivable, demands for the cognitive activity of inferring, planning and decision-making. Planning one's way through the environment, i.e. which route to take or whether short-cuts are available, involves (spatial) memory and (spatial) reasoning to a great extent. Obtaining a mental model of the environment without vision is a challenging task. It can be supported by representations of the environment that are accessible without vision, for example, verbal descriptions (Daniel & Denis, 1998, Giudice et al., 2007, Kesavan & Giudice, 2012, Taylor & Tversky, 1992b), tactile maps (Brambring & Laufenberg, 1979, Golledge, 1991, Wiedel & Groves, 1969), or a combination of both (Gallagher & Frasch, 1998, Habel & Graf, 2008, Lohmann et al., 2010, Lötzsch, 1994, Miele et al., 2006, Rice et al., 2005, Zeng & Weber, 2010)

Despite their differing concepts, locomotion and wayfinding often cannot be separated clearly. In an earlier conceptualisation (Downs & Stea, 1977, p.124) wayfinding has been divided into the following four sub-tasks:

1. Orientation, i.e. determining one's position in an environment with regard to other objects,
2. Choosing the route, i.e. planning one's route to the destination,
3. Keeping on the right track, i.e. dynamical updates while in locomotion,
4. Discovering the destination.

Both, Montello and Downs & Stea, include the activity of following a path and respectively keeping their wayfinding conceptualisation on track. This shows that one can hardly be

[1] For a systematic list of locomotion styles see Montello (2005).

separated from the other when analysing spatial behaviour. This is affirmed by Montello who points out that 'the great majority of acts of navigation involve both locomotion and wayfinding components to varying degrees; the distinction is less "either/or" than "part-this/part-that" ' (2005, p. 260).

The acquisition of spatial knowledge before arriving to the environment is especially important for the wayfinding part. In line with earlier research on spatial knowledge, this thesis assumes that improved knowledge acquisition has positive effects on (real and imagined) wayfinding. The acquisition of spatial knowledge as such is a prerequisite for solving wayfinding tasks as mentioned in the initial scenario (see chapter 1).

Humans capture spatial knowledge in different manners, namely (Siegel & White, 1975, Thorndyke & Hayes-Roth, 1982):

- landmark knowledge,
- route knowledge, and
- survey knowledge.

During locomotion along a path humans collect impressions of the immediate surroundings at different points in time. From the embedded salient objects navigators acquire knowledge about the locations of landmarks (*landmark knowledge*). By integrating spatio-temporal information from locomotion, the navigators acquire knowledge about the succession of path segments and landmarks and how to get from one location to another (*route knowledge*). Route knowledge is encoded from an *egocentric* perspective, i.e. the navigator's self is the centre of the *frame of reference* (FoR) for directions, distances and relations. Research has confirmed that routes and landmarks (Denis, 1997, Denis et al., 1999, Michon & Denis, 2001) as well as regions (Seifert et al., 2007, Wiener & Mallot, 2003) are of major importance for human spatial conceptualisation. *Survey knowledge* is encoded from an *allocentric* perspective, i.e. the frame of reference is navigator-independent. The FoR is grounded in the geographic space, i.e. relations and directions are given with respect to a static reference system, for example cardinal directions. Survey knowledge was regarded as being the most general form of spatial knowledge, as it affords the deduction of route knowledge and integrates landmark knowledge. Survey knowledge can be acquired from maps without direct perception of the environment, i.e., the navigator is not *on site* (Taylor, 2005, Thorndyke & Hayes-Roth, 1982). Maps as such are passive aids which provide information *before* the navigators arrive to the environment (Lahav & Mioduser, 2008). In contrast, active aids provide navigators with information on site, that is, they support locomotion (for examples of active and passive aids, see Lahav & Mioduser, 2008).

As a spatial problem solving process, navigation and wayfinding face perceptual and cognitive challenges when vision is absent. Information needs to be gathered, unfamiliar environments to be learned, familiar routes to be followed, and more (Long & Giudice, 2010).

For a review of navigational technology that helps in mastering those challenges, see the excellent book chapter by Giudice & Legge (2008).

Tactile maps have a history of being used in mobility training for route acquisition or for survey acquisition (c.f. Dacen Nagel & Coulson, 1990, Maglione, 1969, Ogrosky, 1975, Rowell & Ungar, 2003b, Siekierska et al., 2003, Spencer & Travis, 1985, Ungar et al., 1993). Tactile orientation maps are particularly useful tools to familiarise individuals with an unknown environment, i.e., travel preparation. They offer an almost simultaneous view of the represented space from an allocentric perspective, i.e., from a top-down, bird's-eye view. In tactile orientation maps all spatial information is simultaneously available, irrelevant noise is reduced and only the essential spatial information is displayed (e.g. Golledge, 1991, Ungar et al., 1993). In contrast, verbal descriptions put a higher load on the working memory system (relevant literature is reviewed in Cattaneo & Vecchi, 2011, Münzer et al., 2006). For blind people, tactile orientation maps are especially suitable for conveying survey knowledge (c.f. Ungar et al., 1995, 1997). Because of the important role of survey knowledge for independent travel, this thesis has focused on supporting the acquisition of survey knowledge with tactile orientation maps.

Wiener et al. proposed a taxonomy of wayfinding tasks that aims to characterise the nature of wayfinding more precisely than before (2009). The taxonomy is introduced because it allows to set this work into a systematic context in which tasks of wayfinding are supported by in advance knowledge acquisition with tactile orientation maps. Wiener et al.'s first distinction is between unaided wayfinding and aided wayfinding. Aided wayfinding involves the use of external aids, such as maps, signs, route instructions or (computer-based) route planners to solve wayfinding tasks. Thus, they reason that unaided wayfinding tasks afford other behavioural strategies and cognitive processes for decision-making, planning and learning. They distinguish whether wayfinding is necessary to reach a specific destination or not, i.e. directed or undirected wayfinding). Based on this dichotomy they reason which tasks are afforded with existing landmark knowledge (their term is *destination knowledge*), route knowledge, and survey knowledge (see also Figure 2.1):

- In undirected wayfinding there is no destination, thus route knowledge or destination knowledge are discarded in this case. If survey knowledge is available in undirected wayfinding, for example in well-known environments, it allows the navigators to do some *pleasure walk*—strolling around for the pure joy of walking without a specific plan or destination to be reached (this matches the requirement from the scenario in chapter 1).

- Considering the different tasks in directed wayfinding, i.e. having a destination, for example when returning from a pleasure walk and heading for a beer in a pub, there is a difference in knowing the destination or not.

– If the destination was not known and the navigators have some survey knowledge, they might engage in *informed search* to find the destination. Knowing the environment allows the navigator to systematically search for a route. If the navigators lack survey knowledge they have to engage in *uninformed search*, i.e. search for the destination without having knowledge of the environmental structure. Some intermediate situations might also occur, for example, when some parts of the environment are known and other are not (c.f. Schmid, 2008).

– If destination knowledge was available, the navigators can engage in *Target Approximation*. Depending on the existence of additional route knowledge, i.e. the destination and a path to the destination is known, the navigators could do *Path Following*, i.e. walk the path they already know.

– If route knowledge was not available, the navigators need to engage in *Path Finding*, i.e. a path has to be extracted or to be found[2]. According to Wiener et al., Path Finding can be further subdivided into *Path Planning* and *Path Search*, depending on existing survey knowledge. In Path Planning survey knowledge has to be queried and a new path needs to be extracted. In Path Search route knowledge has to be recombined and unknown transitions between different paths are reasoned or speculated about.

From Wiener et al.'s work one can learn that particular types of spatial knowledge enable particular wayfinding strategies. The wayfinding strategies enabled by survey knowledge acquisition from tactile orientation maps are described in the following:

Cruising/Pleasure Walk Even if there is no goal to reach (accordingly, destination knowledge and route knowledge cannot be used) there is a clear benefit of having (partial) knowledge about the structure of the environment. When cruising through an environment, for example, for the pure joy of travelling, there are some implicit goals set in the activity itself: the navigator would probably not go in circles or back-and-forth all the time to prevent boredom. It might be more entertaining to walk along paths that were not part of the route before. Having knowledge of how the streets are connected, it is probably easier to decide which way to choose to create a joyful pleasure walk. If I assume that at some point the pleasure walk ends and navigators want to return to some specific place, then they will perform an *Informed Search*.

Informed Search Knowing the specific destination and the structure of the environment but not the specific route makes it feasible to infer information, for example, which direction to go. Directional information could inform the choice of paths and the decision

[2]During path finding the subject might consider any salient object to be part of the path, for example a fence along a field, not only the existing tracks.

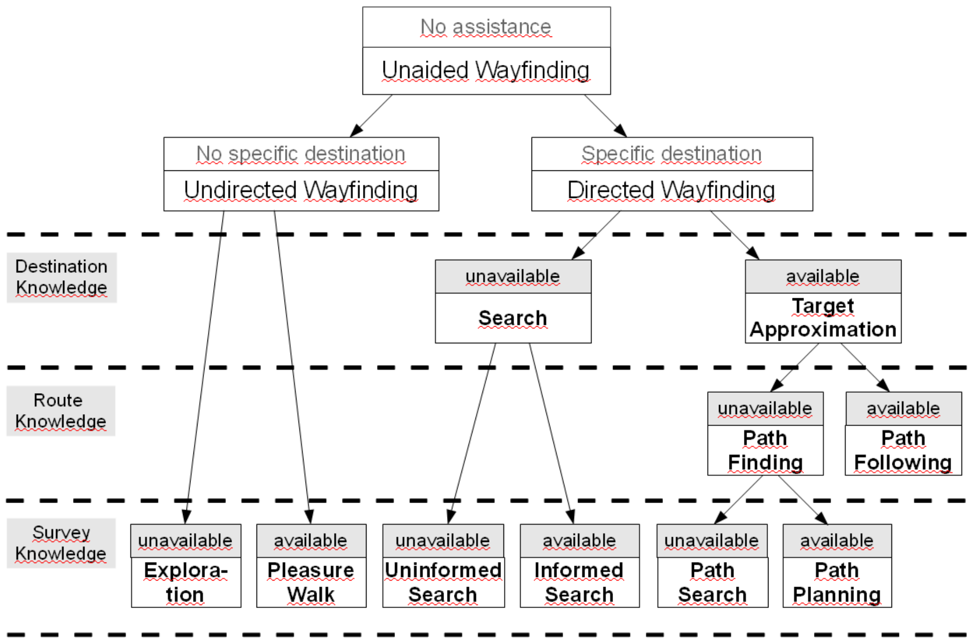

Figure 2.1.: Wiener et al. proposed a hierarchy of unaided wayfinding. The task, i.e., behavioural goal (depicted as light grey boxes) are related to different means of wayfinding, i.e., strategic cognitive processes and mechanisms (signified by bold type-face), according to the types of spatial knowledge available (2009) (illustration adapted from Wiener et al., 2009).

making at intersections during wayfinding. From survey knowledge one can infer route knowledge to find a solution to a specific wayfinding problem at hand. Cruising is very similar to Informed Search, the difference is that in the former there is no specific goal. In the latter there is and the navigators can engage in *Path Planning*.

Path Planning If a path is needed and some route knowledge is at hand, the navigators can check if they know a route that will solve the problem. In the best case they already know one. If not, the navigators need to select combinations from connected paths to generate solutions. It might happen that the route knowledge is not sufficient, i.e. no stored route or combination of parts of routes solve the wayfinding problem. Than the navigators have to fall back on Informed Search to build solutions from survey knowledge.

2.1.2. Maps as Support in Knowledge Acquisition

Reasoning about a particular large-scale spatial environment[3] and the relations in such an environment requires spatial knowledge about that very environment. A concept for capturing spatial knowledge as mental representation are *cognitive maps* (Kitchin & Freundschuh, 2000, Tolman, 1948). A cognitive map is not analogous to a map in the head but is abstracted and has many distortions (c.f. Kuipers, 1982). It is incomplete (not the whole reality is captured), distorted (cognitive transformations of both distance and direction apply), schematised (spatial entities are categorised), augmented (non-existing details are added), and highly individual (individual preferences and activities form the representation) (Downs & Stea, 2011).

Different types of representations can be reproduced from cognitive maps (Downs & Stea, 1977, p. 88), for example, as text or as sketch maps. Cognitive maps are not static but are reconstructed on demand.

Cognitive mapping is 'a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment' (Downs & Stea, 1973, p. 9). It is an active and constructive process of both analysis and synthesis and a re-constructive organizing process (Downs & Stea, 1977). Cognitive mapping is associated with several cognitive processes (for details, see Lobben, 2004). It takes place either in *direct* or *indirect* experiences of the spatial environment (Golledge, 1999).

Direct Experience Cognitive mapping thorugh direct experience is, for example, walking an environment[4]. While walking, the local surrounds are immediately accessible to

[3] A large-scale environment is 'space whose structure cannot be observed from a single viewpoint' (Kitchin, 1994, p. 2).

[4] I take walking as the prototype activity of locomotion because my focus is on blind pedestrians who very often cannot self-dependently move through the environment in other ways, for example, by bicycle. Exceptions are the rare individuals who know how to echolocate, see the corresponding Wikipedia article, accessed February 28, 2013.

the human sensory and motor system (Montello, 2005, p. 279). Observations of 'the sequence of places and paths encountered on a route, the magnitude of turns and distances (to some low accuracy), and the [...] positions of remote landmarks' (Kitchin, 1994, p. 2) are made and a cognitive model of the topographical space is formed. This direct experience behavioural strategy[5] faces certain practical and cognitive problems. It could take a lot of time and effort to walk each single track of an environment. During that journey, pedestrians might struggle with locomotion-specific aspects, for example, uneven ground, obstacles or inclinations. The terrain could demand locomotion abilities that the navigator cannot easily afford. Then the attention necessary for the cognitive activity of environmental learning has to be split. Adding to the demand of locomotion, the environmental learning itself could be a cognitive challenge: when walking a specific route all impressions along the route are successive, i.e. serial, and some kind of survey representation has to be created from them. In this process, cognitive maps obtained from the route perspective have to be transformed to a survey perspective. The transformation is especially demanding for inexperienced navigators (Brunyé & Taylor, 2008). This process is more demanding than learning the environment from a survey perspective in the first place (Golledge et al., 1995).

Indirect Experience Another possibility for capturing survey knowledge is indirect cognitive mapping. This involves the use of an analogue, external representation, such as a survey map, that depicts the spatial environment. This map represents a certain part of the world and shares inherent spatial properties with the represented world. The depicted properties and relations of the environment can be learned from the map as a small-scale depiction of a large-scale reality. The spatial knowledge acquired through a map is transferred into a cognitive map. This survey mapping with a map has some advantages over environmental learning: no locomotion is necessary, unneeded details are excluded from the map, attention can stay focused on the learning task, and—most importantly—the spatial details are all from the same perspective, nothing has to be integrated as in direct cognitive mapping.

With maps, reasoning about space is facilitated. Hölscher et al. reasoned that the acquisition of spatial knowledge and the choice of representational media to learn from is governed by the principle of *Cognitive Economy* (2007). Cognitive Economy means that humans will use the supportive means that inflicts the least cognitive effort and provides the best options for solution. Map-users can transfer information received by the media into the spatial environment[6]. This could be done to support orientation: After learning directional relations

[5]It was initially labelled 'combinatorial geographical orientation' by Berlá & Butterfield 1977, the later established term 'environmental learning' will be used in this thesis for the sake of coherence with other work.

[6]The ability to transfer from a medium to the environment was labelled 'transformational geographical orientation' by Berlá & Butterfield (1977)

and relative positions of certain landmarks from a map, it becomes easier for navigators to pinpoint their own location once they are in the geographic environment. Maps as external memory and reasoning aids can support the human navigator in solving spatial problems. With spatial knowledge acquired from maps, a wide range of human wayfinding activity is supported.

First, humans can conceptualise distant geographic environments that are not directly perceivable and they might never have the opportunity to visit physically. Second, maps as abstractions of the physical world highlight the essential (spatial) properties – these properties are promoted so that the map-reader focusses on them. Maps are tools for *external cognition* (Scaife & Rogers, 1996), i.e. they afford *computational offloading* (Hölscher et al., 2007). The amount of cognitive effort required to solve informationally equivalent problems is reduced. Maps afford to represent problems in another format. That facilitates cognitive actions, for example, specifying the spatial relations of many spatial entities. Maps realisation sets certain technical constraints so that graphical elements and their relations only allow certain relations and inferences (Scaife & Rogers, 1996, p. 188f.). With these properties, maps become external memory and reasoning aids. They can support solving behavioural problems (Zhang, 1997), for example to get to a certain destination using an alternative route in case the usual route is blocked. As cognitive tools for spatial reasoning (Berendt et al., 1998) they help the travellers to build up a cognitive map of a geographic environment that, in turn, enables them to accomplish tasks of navigation in that environment, such as orientating and wayfinding. Learning the structure of an environment from a map might serves for future activities as well, for example as part of trip-planning. In contrast to most propositional representations, maps allow for interpreting the displayed relations in a qualitative way. By abstracting from the metric properties and preserving the qualitative properties, for example, relationships between entities, 'qualitative spatial representations appear to be closer to how humans represent and communicate spatial knowledge' (Renz, 2002, p.2). Qualitative spatial reasoning with qualitative spatial representations was regarded a premium human strategy to handle the diversity of the spatial environment (Freksa, 1991). Maps could make that diversity accessible and are especially suitable if the following conditions are met (Freksa & Barkowsky, 1999).

1. The knowledge to be represented consists of a large number of interrelated relations and many of these relations can be captured simultaneously by arranging a comparatively small number of objects.

2. Implicit knowledge is to be represented.

3. It is not necessary to make all the knowledge represented explicit, because inferences can be made.

From a representational point of view, map-users need to understand three aspects presented in a map (Berendt et al., 1998).

1. Aspects that are represented pictorially, for example, street network as an analogue representation of geographic world entities.

2. Aspects that are represented symbolically, for example by labels.

3. Aspects that are not represented.

Looking at the aspects that are represented, the map maker's aims at determining building blocks in an environment that are essential to a specific map. In his work on the architectural structure of a city Lynch (1960) pointed out that the building blocks can be categorised as node, landmark, edge, path and district, according to their function in a cognitive map. Peucker & Chrisman points to the qualitative features in a data model for *Geographic Information Systems* (GIS) (1975). They suggested introducing a *neighbourhood function* (Peucker & Chrisman, 1975, p. 55) to indicate the relative location of entities instead of metrical measures. Building on such early work and his own interviews, Kuipers (1978) proposes to model spatial knowledge by routes, directions, position, and spatial relations, namely topology. *Topology* encompasses the relations between two neighbouring spatial features, including adjacency, connectivity, and containment (Theobald, 2001, p. 689). Besides topology, three other types of commonly recognised spatial relationships are proximity, direction, and object pair (Theobald, 2001, p. 695). Proximity describes the distance between entities and is often qualitative, for example, setting apart near and distant entities in relation to a certain reference entity. Direction describes cardinal directions ('in the north') or relative direction ('to the left') of entities. A generic relation is the object pair, describing the relation (to be qualified by the modeller) between two entities. These concepts will help to qualify the content of maps and how the knowledge they capture can support the acquisition of geographic knowledge.

2.1.3. Knowledge Acquisition with Tactile Maps

In the last section, the results of maps as tools for spatial knowledge acquisition that were presented were mainly from the visual area. In this section, we will learn that most of the discussed aspects are valid for tactile maps as well. Additionally some processes have to be discussed because touch is, in certain respects, quite different to vision.

First, there are limits to the resolution of what humans can understand from touch. This is a result of biological properties of receptors of the skin and cognitive limits in processing that input. As a consequence, the distribution of objects in tactile representations is much coarser than in visual ones. One can find about 20 dots per inch (dpi) in tactile maps (Gardner & Bulatov, 2004, p. 740) as apposed to about 300dpi and more in visual maps. Understanding the entities clearly in a tactile map is a problem for map-readers (Berlá & Murr, 1975). A reduction of complexity is necessary to represent a world full of details in a tactile map. Thus, the knowledge extracted from tactile maps cannot be as rich as from visual media in the same size. Second, beside the limitations that are grounded in sensory properties of touch, there are limitations that affect cognitive processes when using a tactile map. Instead of having an immediate overall visual impression of a map, the user has to explore the surface of a tactile map serially with his fingertips and integrate the properties and impressions of single points of contact into one holistic impression of the represented space (Révész, 1950). This is reverse to visual map-reading when the user first gets an overall impression and than reads the details. Visual map-reading is whole-to-detail. Tactile map-reading is detail-to-whole.

Some effects that are not fully understood currently make interpretation of tactile stimuli even harder. For example, some haptic illusions, like the distortion of co-linear lines (which are parallel but do not feel that way, see Kappers et al., 2008)), the length distortion of length-equivalent lines that have divergent or convergent fins see (so-called Müller-Lyer illusion, see Millar & Al-Attar, 2002)), the distortion of perpendicular lines (which have the same length but do not feel that way, see Gentaz & Hatwell, 2004). Encoding of tactile stimuli in an egocentric frame of reference (FoR) rather than in an allocentric FoR during visual map exploration seems to play a role in these effects (Kappers, 2007). Additionally, the principles of Gestalt that govern interpretation of visual scenes, for example, implicitly regarding two lines as one if one line can continue the other, seem to have no counterpart in haptics (Révész, 1950, Scholtz, 1957) although there are results challenging this view (Chang et al., 2007).

Thirdly, when it comes to the abilities of the tactile map-readers, Liben & Downs have shown that humans' 'natural' skills in map-reading are only rudimentary (1989, 1993). They argue that the development of skills to understand a map is the result of specialised practice and training with tactile maps over many years[7].

Although the presented findings might be interpreted as support of the idea that reading & learning a tactile map might not be the ideal way of bringing spatial knowledge to humans, blind people's use of tactile maps may be promising if the alternatives are considered. One alternative could be to engage in environmental learning by walking the environment. This is tedious and environments that cannot be travelled to cannot be learned—disregarding the effort of travelling. Another alternative could be to learn by reading out load the description of the environment. Integrating linear speech into a coherent mental representation is very tedious and completely passive, i.e. listening involves no kind of interaction, disregarding the self-driven close investigation (or omission) of specific details. Surprisingly, evidence was found that the spatial representations formed from vision or from touch are *functionally equivalent*. That is, performance on spatial tasks is similar, regardless to whether the spatial learning took place with tactile maps or from spatial language (Giudice et al., 2011, Loomis

[7] For details about developmental issues in tactile map learning see Liben (1997) in which a six-level, progressive typology for mastering external spatial representations is presented.

& Klatzky, 2008).

In the process of learning about geographic environment, learning with maps has the advantage that there is an analogy between the representing entity and the entity being represented. In order to apply knowledge extracted from maps to navigation tasks, there is often no transformation of representations needed. In this line of reasoning, learning the structure of a geographic environment from a tactile map proved to facilitate early blind (i.e. blind from birth and gone blind as babies) participants' abilities making inferences when they were tested in geographic spaces (Thinus-Blanc & Gaunet, 1997). Thinus-Blanc & Gaunet extend this statement and conclude that 'spatial processing of large areas is facilitated by small-scale models of the situation in comparison with the locomotor exploration of the actual environment' (1997, p. 32). Tactile maps as schematic representations of the geographic world can be used as wayfinding tools (Caddeo et al., 2006, Casakin et al., 2000, Golledge et al., 1996, Jacobson, 1998). They have become a promising aid to convey geographical knowledge to visually impaired persons (Espinosa et al., 1998, Gardiner & Perkins, 2003, Loomis et al., 2006, Ungar et al., 1993). There is an understanding that 'tactile maps have a clear advantage in facilitating the development of cognitive maps by providing a global perspective on the surrounding geography' (Simonnet et al., 2007, p. 259). Behavioural studies clearly point in that direction (see, for example Blades et al., 1999, Golledge, 1991, Ungar, 2000, Ungar et al., 1995)

In this section the benefits and limitations of map-use for spatial learning and cognitive processes involved in tactile map learning are discussed. One result is, that much of the said is not only true for visual maps but also for tactile maps, as behavioural studies have shown. Next, I will review literature and best-practise accounts of how to simplify the geographic reality so that the resulting maps may be understood.

2.2. Simplification of Maps

In this section I will reason about why map-making deals with simplification and what types of simplification can be identified in certain types of maps. In this thesis, simplification is regarded as the process and result of leaving out unnecessary details, i.e. capturing the relevant details. As map-making is often a task in cartography, the process of cartographic generalisation will be discussed shortly in the first part of this section, i.e. how to simplify some rich geographic reality to enable map-making. Then, in the second part, the purposeful simplification of a spatial representation beyond technical necessity is identified as *schematisation*[8]. Schematisation is the key method to facilitate map-understanding. From a review

[8] The reader should be aware of the fact that in different areas the term 'schematisation' is understood differently. In contrast to understanding schematisation in this thesis as a form of cognitively based abstraction, there

of approaches for mobile visual route maps, the transfer of the cognitive principles they provide are analysed. Then the transfer to tactile orientation maps and approaches, especially suited for tactile orientation maps, are discussed.

2.2.1. Cartographic Generalisation as Simplification

No map, either visual or tactile, can be fully equivalent to the geographic reality in the sense of an isomorphism (Castner, 1983, Gardiner & Perkins, 2005) – simplification is mandatory in all cases. Such simplification can be modelled by and is the result of a rule-based process (Casakin et al., 2000). The process of simplifying real world data to yield cartographic representations is referred to as *generalisation* in the areas of geography and cartography (Harrie, 2003, p.221).

Generalisation and simplification are intrinsically related to the term *abstraction*. Abstraction emphasises the removal of specific, random and unimportant issues from a rich physical world in order to concentrate on the important general and important specific issues of reality (Brassel & Weibel, 1988, p. 230). Generalisation is usually characterised through several operators. These operators encapsulate different functions that transform spatial data. Different authors have categorised these operators into hierarchies. Often the proposals from McMaster & Shea (1992) and from Brassel & Weibel (1988) have been cited. For a more recent review, see Foerster et al. (2007).

For the purpose of this thesis, the different operators that have been proposed are not very important as their differences are sometimes minor. The operator types are more important because they capture the general objective of what can be achieved with similar operators. Operator types connect operators that have similar results on the processed data. According to Harrie (2003, p.221) there are four operator types:

Simplification : completely discarding certain entities, for example, representations of small villages,

Smoothing : leaving out details that are considered unnecassary for communicating specific meaning, for example, straight representations for curvy roads if connectivity is important,

Exaggeration : displaying entities bigger/smaller than calculated with the scale, for example, representations of rivers and roads,

Displacement : separation of entities close to each other such that their identity is maintained.

are less strict definitions. For a discussion and further pointers to literature, see Klippel et al. (2005, chapter 2) and Dykes et al. (2011).

In chapter 3 I will extend this initial standardisation and categorise operator types according to the change they inflict on map-reading, i.e. qualitative or quantitative simplifications.

In the following section the concept of schematisation will be introduced in the context of spatial knowledge acquisition with maps, especially to make them usable.

2.2.2. Schematisation to Ease Spatial Knowledge Acquisition

When humans reproduce spatial knowledge acquired with maps, i.e. when they reconstruct spatial knowledge from cognitive maps, simplification takes place: intersections are prototyped, streets are straightened, details such as directional relations forgotten, distances neglected, and more (Barkowsky et al., 2000a, Chipofya et al., 2011, Dykes et al., 2011). Simplification may introduce errors into the reconstruction, for example, global inconsistency (Wang & Schwering, 2009). Casey also noticed this in blind peoples' reconstruction of models 1978.

The process of simplifying a spatial representation beyond technical necessity is called *schematisation* (Klippel et al., 2005). In the process of schematisation spatial information along different dimensions may be altered; this might affect map-reading on a perceptual or cognitive level, or both (Peters & Richter, 2008). *Schematic maps* are the result of map schematisation. In schematic maps only the information relevant to solve the anticipated or current task is provided (Freksa, 1999). Each map supports the solution of a specific (wayfinding) problem, such as self-localisation. The motivation behind schematic maps is to present spatial information in a way that supports cognitive processes. The motivation is to facilitate a correct interpretation of the represented environment and to highlight important details so that wayfinding problems can be solved successfully (Schmid, 2010).

An area in which schematic maps have proven their utility and value is wayfinding with mobile devices such as mobile navigation systems or mobile phones[9]. Only limited content can be displayed in these small limited visual displays. The same is true for TEMs because of the limited resolution of tactile modality. Consequently both types of displays do not differ largely in the total amount of basic structural entities (pixels, or tactile elements, respectively) that can be displayed simultaneously[10].

Over the last years a number of schematisation concepts have been developed for small visual displays to communicate specific types of spatial knowledge efficiently. Having found some structural similarities between small visual displays and TEMs that promise to be the basis for a transfer of certain schematisation concepts from small visual displays to tactile

[9] An earlier version of this part was published in Graf & Schmid (2010).

[10] Displays on mobile devices are approximately the size of a palm or a whole hand, usually with a resolution of less than 100dpi. TEMs are of a rather large and usually not smaller than an DINA4 sheet of paper. This makes them at least three to five times bigger than small displays. On the downside the resolution is much lower, about 20dpi in a typical tactile printer, which is one fifth of the graphics display.

displays, the schematisation approaches for small displays are presented in the following subsections.

2.2.2.1. LineDrive

Agrawala & Stolte introduced an activity-based schematisation for driving routes (2001). It is based on the observation that driving routes often incorporate long parts where no decision activity (like turning or changing a road) is required during wayfinding. They propose to adapt the scale of the particular route element to the corresponding wayfinding activity along this element: a high degree of afforded activity (and corresponding cognitive load) will lead to a more detailed view of the involved entities; a low degree of afforded activity will lead to a highly schematised view. As a result the distance information is no longer in a uniform scale, but relates to the activity required on route. The result is a route strip map (MacEachren, 1986) which requires significantly less display area if the route incorporates big parts with no required wayfinding activity.

2.2.2.2. Focus Maps

In Zipf & Richter (2002) the authors introduce a form of schematisation that improves extracting and processing the actual route and its context within a map that contains significantly more information than required. The route is highlighted and map features are faded out depending on their proximity to the route. This concept is based on the observation that a larger spatial context is helpful during wayfinding (in contrast to strip maps), but not all spatial regions are of equal interest for the given task. This idea was furthered in Klippel & Richter (2004) with the introduction of chorematic focus maps that improve map-understanding. Junctions and turns of the route are represented by means of wayfinding choremes (see Klippel, 2003), reflecting prototype mental representations of turns.

2.2.2.3. μMaps

Schmid introduces so-called μMaps, maps that effectively compress the visualization of geographic data by tailoring maps to the individual prior spatial knowledge of a user (2008). If a significant part of the actual route can be directed across familiar parts of the environment, the map can be compressed to only a fraction of the size required by traditional maps. Another benefit of μMaps is the absence of assistance where it is not required: the display is not cluttered with unnecessary information, and new knowledge is always related to existing knowledge (which facilitates spatial learning). The identified routes are cognitively 'lightweight': as the user knows the familiar segment of the route, these parts of the route do not introduce additional decision points.

2.2.2.4. Route-Aware Maps

In Schmid et al. (2010b) the concept of Route Aware Maps (RAMs) is proposed. These maps consist of a main route and alternative routes from an origin to a destination. The concept of alternative routes serve two main issues: First, to identify the functional context of the main route, as it communicates an alternative set of connections between both places. This set defines the spatial context in terms of the network it is embedded in. Second, these alternative routes serve as a tool to design wayfinding assistance that is more robust with respect to navigation errors. The alternative routes branch at points along the route which are plausible sources for navigation errors (for example, due to complex or monotone configurations at decision points). In order to support the localisation of the critical points on the route, RAMs further place landmark and region information where plausible and available.

2.2.2.5. YAH^{x}Maps

In Schmid et al. (2010a) the authors developed the concept of YAH^{x}Maps, a schematic map that allows fast and reliable self-localisation in unfamiliar environments. The self-localisation task is supported on different levels: First, the map utilises a trajectory-based localisation and map alignment approach. By orienting the map with respect to the trajectory, the environment is segmented into the area one comes from (as this is usually recognised) and the remaining part. Second, YAH^{x}Maps highlight the current vista space by detailing the corresponding area in the map. Third, YAH^{x}Maps use a stable frame of reference with salient landmarks that are meaningful for (re-)orientation. These landmarks, such as rivers or parks in an urban environment, allow reliable orientation independent from the task-related potential points of interest (POI). YAH^{x}Maps have been shown to be significantly superior in every aspect that was test compared to traditional approaches (Schmid et al., 2010a).

2.2.2.6. Halo

The visualisation of off-screen features is a main challenge for displaying maps in limited spaces. While schematic maps try to visualise information on different levels of granularity, other approaches offer visualization by pointing from a map view on a constant scale to off-screen locations of potential POI. A prominent approach is the indication by means of arrows, circle segments, or others (Baudisch & Rosenholtz, 2003, Gustafson et al., 2008) that encode direction or/and distance. These visualisations are subsummed under the term *halo* as they exist in the margins of the map, scattered around the map space. They are typically applied without text labels, i.e., they are only applicable if POIs of the same type (depending on the search query that is being answered) are visualised. These features inherently relate to the task of the map-user, i.e., they may be numerous or located very closely to each other (which might result in a cluttered interface).

2.2.2.7. ZoneZoom

In Robbins et al. (2004) the author proposes a discrete recursive zoom feature to access maps on constant scales. The authors propose a zoom accessible from the numerical keys of a mobile phone. The map shown in the display is segmented into nine discrete parts ('submaps') and the nine numerical keys (1-9) they are mapped to. Whenever a key is pressed, the map-reader views the respective submap in detail. This submap can again be segmented into nine parts and so on. The strength of this approach is the discrete and precise navigation within a map on different zoom scales. ZoneZoom allows fast access to details. However finding correspondence on different scales requires a considerable cognitive effort because the change of view and granularity proceeds abruptly.

2.2.2.8. Focus Line

Research in the field of tactile maps has shown that distortions in these representations are especially useful and usable (Hamel et al., 1996, Michel, 2000). Distortion can make tactile maps meaningful to users as it highlights certain entities, for example by making a street representation bigger so that it is prominent and can be followed more easily (König et al., 2001). Displacements and exaggerations help to focus on important parts of the map. It guides the attention and prevents misinterpretations (Hamel et al., 1996).

All concepts of schematisations discussed before are summarised in Table 2.1.

Name	Schematisation Concept
LineDrive	Shorten segments based on activity
Focus Map	Hide entities based on distance
μMaps	Show or hide entities based on prior knowledge
Route Aware Maps	Show alternatives
Route Aware Maps	Recess contextual information
YAH^{x}Maps	Show details based on succession & prior knowledge
YAH^{x}Maps	Show stable frame of reference
Halo & Wedges	Show off-screen POI
ZoneZoom	Use fixed grid to determine next zoom
Focus Line	Emphasise important entities

Table 2.1.: Overview of the concepts of schematisation used in different types of mobile visual maps.

These concepts were developed to support wayfinding (specifically path-finding, path-following, and orientation) with schematised visual maps on mobile devices. The concepts are used to hide certain elements, structures or relations and highlight others. Albeit the exact implementation and limitation differ between small visual displays and tactile displays, some of these concepts might be promising candidates for being transfered to tactile maps. In chapter 3, I will get back to these concepts and discuss the cognitive advantage they imply (for example, guide attention and support orientation). I will show how they can inform us about promising schematisation concepts for tactile orientation maps.

To apply schematisation concepts for automated map-making of tactile hardcopies we need to know which challenges have to be mastered when tactile maps are made.

2.3. The Creation of Tactile Maps

Occasionally three-dimensional miniature models of certain cities can be found when walking the surrounds. These models often represent the street network, shapes and heights of buildings, trees and other vegetation (see Figure 2.2).

Figure 2.2.: A photograph of a three-dimensional city model (located in the city of Leipzig) that can be explored haptically. It gives an impression of how the city of Leipzig looked like in 1840.

Occasionally such models contain labels written in Braille – a clear indication that these models are meant for the visually impaired, too (see Figure 2.3). The models are often not feasible for navigation support if they are only explored by touch. They show too many details of the geographic environment, details that are not helpful for navigation. The last two decades have brought some new objectives to the field of cartography, for example, that map design should be adopted to the way a map is read and understood. Perceptual

Figure 2.3.: A photograph of a detail taken from a three-dimensional city model (located in the city of Basel) that is specifically made for haptic exploration. Notice the Braille labels on the model (to the lower right).

and cognitive processes that happen while using a map should to be taken into account. For example, MacEachren (1995) discussed how components of a visual scene are detected, discriminated and identified in the context of cartographic legibility.

In the following sections I will review how tactile maps are made. I will conceptually subdivide the map-making process into three stages: *map generalisation*, *map production* and *map dissemination*. Map generalisation is used to select, symbolise and place map entities according to the prospect purpose of the map. In the context of map generalisation, I will argue that tactile maps are highly abstract representations of geographic environments. Map production concerns the activities that put the result of map assembly into physical reality. Map dissemination captures the activities to distribute the produced tactile maps to the target audience. To clarify the different approaches to map-making and disentangle the aspect of human creativity from map-making, I will refer to experience-based tactile map-making as (analogue) *tactile map manufacturing* that yields *traditional tactile maps*, and to algorithm-driven map-making as (digital) *tactile map generation* that yields *traditional tactile maps*. The result of both map-making approaches are physical tactile maps that share some properties but differ in others.

2.3.1. Tactile Map Manufacturing

The following three sections will explain how traditional tactile maps come into existence. The process has not changed very much over the last decades and only involves modern technology to a small extent. Nevertheless the results are generally considered to be of excellent quality. For a short visual impression of the results of skilled tactile map manufacturing, see Figure 2.4 and Figure 2.5.

Figure 2.4.: Photograph of a hand-made vacuum-formed tactile map (format 30x30cm, map produced by Deutsche Zentralbücherei für Blinde, Leipzig).

2.3.1.1. Map Generalisation for Traditional Tactile Maps

In the institutions that produce tactile maps today, experts are trying to find the best compromise between the different conflicting forces they encounter when composing a tactile map. For example, the requirement to allow for a minimum separation between entities, on the one hand, and the need to place a certain number of elements in a limited space on the other, are two of the main forces. The manual activity of selecting entities, assembling them, potentially adjusting their positions and sizing them to satisfy potentially contradicting constraints, and eventually building a more complex structure is often called 'design (a map)'.

The research on mobility and tactile graphics has brought about a multitude of best-practice guidelines on tactile map design to help map-makers recognising the requirements and finding appropriate compromises, for example Amick & Corcoran (1997), Canadian Braille Authority English Braille Standards Committee (2003), Challis & Edwards (2001), Chan (2007), Edman (1992), Gardiner & Perkins (2002), Jentzsch & Kurt (2001), König (1997)[11]. This pro-

[11] A great resource to work with on tactile graphics and available online is `http://perkins.pub30.convio.`

Figure 2.5.: A tactile thematic map of Australia with a vacuum-formed translucent plastic sheet for tactile exploration and underlying colour coding. Map © by Deutsch Zentralbücherei für Blinde, Leipzig, Photograph © by the author.

ductive body of guidelines was supported through research on assistance in navigation for the visually impaired (Challis & Edwards, 2001, Eriksson, 1999, Eriksson et al., 2003, Jehoel et al., 2006, 2009, 2005, Rowell & Ungar, 2003a,b) and on how blind people use tactile maps (Jehoel et al., 2006, 2005, Loomis et al., 2006, McCallum et al., 2003, 2006, Ungar et al., 1993, 1996, 1997, 2004).

Although there seems to be numerous recommendations from psychological studies, these psychophysical and neuro-physiological studies were found to be 'too controlled in their method and too sensitive in their measures' (Jehoel et al., 2006, p. 68). They often reflect requirements about sensory limits that were tested without relating to their use. Only a few researchers have specifically studied the influence of these factors with real tactile map-usage. For example, Jehoel et al. (2006, 2009) investigated the following four factors on tactile map readability:

Tactile Noise The effect of tactile noise on discriminating target stimuli.

Line Tracing The effect of different types of lines on line tracing.

Sizes for Symbols The effect of point sizes and sizes of area symbols on discriminating target stimuli.

Symbol Elevation The effect of symbol elevation on reading time.

The recommendations for traditional tactile map design drawn from investigations in these categories are on a rather high level. They only implicitly take cognitive consequences

net/scout/geography/creating-tactile-graphics.html, last accessed September 9, 2010.

into account by assuming that superior performance in sensory tasks is an argument for superior performance in spatial tasks. However, they can be useful to promote certain conventions among map-makers that it is possible to produce accessible tactile-maps[12].

2.3.1.2. Production of Traditional Tactile Maps

After finishing the design (that may take a lot of time) the production, i.e. the process of bringing the design into a material form, can begin. Manual production methods for tactile graphics have been around for quite some time (Perkins, 2001). In the following list (which is not meant to be detailed) certain manual production methods are evaluated regarding the durability of the produced map, the quality of the display and their use.

German Film : German Film is very thin plastic. A sheet of this material is put on a special rubber drawing board. Using a ballpoint or stylus, a graphic can be drawn onto the paper (Hinton, 1996). Each copy of a graphic has to be drawn by hand, which is why multiple copies are hardly ever exactly the same. The material is relatively cheap compared to other production methods. Only the drawing board is costly (Hinton, 1996). This method is primarily suitable for ad-hoc production of a single tactile graphic. The result is sustainable, as the drawing sheets are made of plastic. It is only possible to use one level of symbol elevation but the results are instant. Thus this method is suitable for interactive scenarios, for example, when two people discuss a topic and need to draw something for better mutual understanding.

Swell Paper : Swell paper, also known as Minolta, is paper with a special coating in which alcohol capsules are embedded (Perkins, 2001, p. 2908f). By drawing or printing onto the paper, (preferably) with black ink, arbitrary graphics and symbols can be applied (design principles were described in, for example, Perkins, 2001). Then the paper is processed in a special machine, the so-called 'fuser' (see Figure 2.6), that contains a very bright source of light. All the black areas on the paper absorb more light and through the heat the capsules explode. The chemical reaction causes the paper material to rise in the tinted areas. The effect is gradual – grey areas with just a little ink rise less than the black areas. The result is a tactile artefact, as illustrated in Figure 2.7.

The charm of this method is its simplicity and inexpensiveness (Perkins, 2001, p. 2909). The swell artefacts are as continuous as the visual graphics and both, the visually-impaired and sighted can use such maps. On the downside, only one level of symbol elevation can be produced and different surface structures are not possible, i.e. symbols and geometric entities can only vary in geometric shape. Therefore the amount of

[12] But despite of all the findings, no standard 'tactile vocabulary' for tactile maps has been established over the last decade (personal communication with Mr. Beyer-Killisch, Director of TOUCH, a manufacturer of tactile maps in Germany, 2008).

Figure 2.6.: Photograph of a fuser used to create swell paper (see text for explanation).

different semantic entities and the information a graphic can communicate is limited. Another disadvantage is that swell paper maps degrade rapidly with use (Perkins, 2001, p. 2909).

Thermoforming aka Vacuum Forming : Thermoforming is a two-step process: First, a mould is created manually and then, a plastic sheet is pulled over the mould and sucked in with a special machine. The plastic sheet is heated and becomes elastic. A vacuum is created between the mould and the plastic sheet so that the plastic is thoroughly drawn into each detail of the mould. After cooling off the formed plastic sheet turns hard again and is an exact copy of the mould (see Figure 2.8).

Manufacturing a mould for the production of a tactile map can take days, weeks, or months of work depending on its complexity[13]. Drawing one tactile map from the mould is finished in minutes, for exemplary results see Figure 2.5 and Figure 2.4. First vacuum-formed maps were produced in the 1950s and the method has been widely used (Perkins, 2001, p. 2908).

Tactile maps produced with vacuum-forming are typically up to 60cm x 60cm in size (a little larger than format A2), depending on the vacuum-forming machine[14]. This

[13]Personal communication with Dr. Hanisch, Head of the 'Deutsche Zentralbücherei für Blinde' (German Central Library for the Blind) in Leipzig, April 13, 2008.

[14]Personal communication with Mr Beyer-Kyllisch, the director of TOUCH, a company based in Hamburg that produces materials for individuals with special needs, including maps for the blind. February 2, 2010.

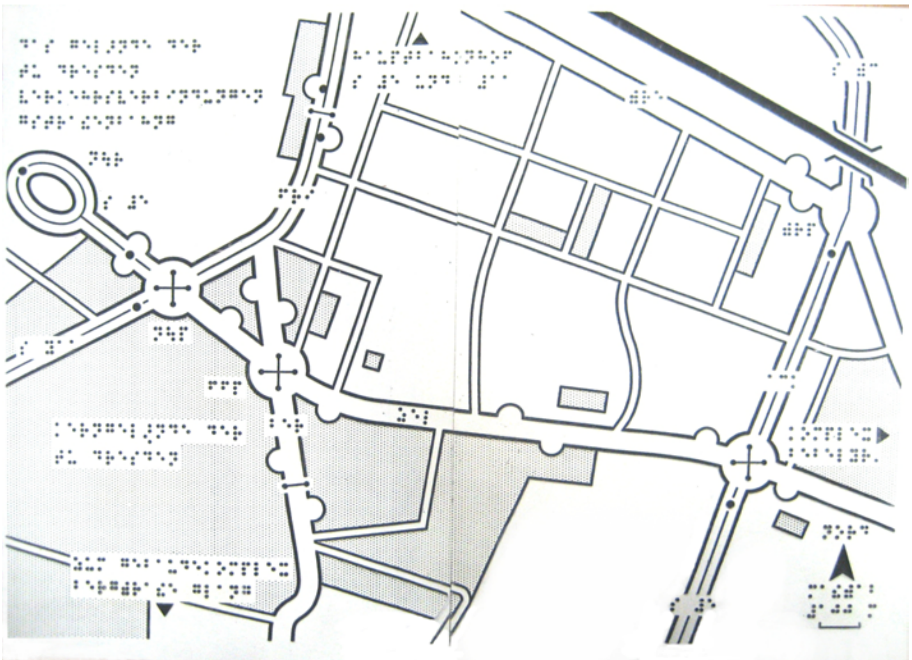

Figure 2.7.: Picture of a traditional tactile map made from two sheets of A4 swell paper glued together (map published as part of Kinzel 1995, ©Katrin Kinzel).

almost exceeds human manipulatory space. Tactually rich surfaces can be produced and each plastic copy is cheap. The maps are very robust but the mould can wear off through use (Perkins, 2001, p. 2908). This method is labour-intensive and designing the mould requires skilled craftsmanship. Expensive and bulky machinery (see Figure 2.9) is needed to produce tactile maps in this way.

Thermoforming allows the use of more than one level of surface (i.e. multiple raised surfaces), so that high and low contours are possible. Different levels offer possibilities to put different kinds of information onto the same tactile graphic. Apart from this, fine-grained surface structures, each with a different meaning, are possible. As the plastic sheet can be translucent, coloured information can underlay vacuum-formed maps so that usage for low-vision users or simultaneous usage of sighted and visually-impaired individuals is possible (Perkins, 2001, p. 2908), see for example Figure 2.5.

In a review about the production of traditional tactile maps, Rowell & Ungar found that thermoforming accounts for 55% of all maps 2003b, p.260f. As for the special requirements in the production of thermoformed maps, they are only produced in a few special places. For example, there are less than 10 traditional tactile map producers in Germany (a result

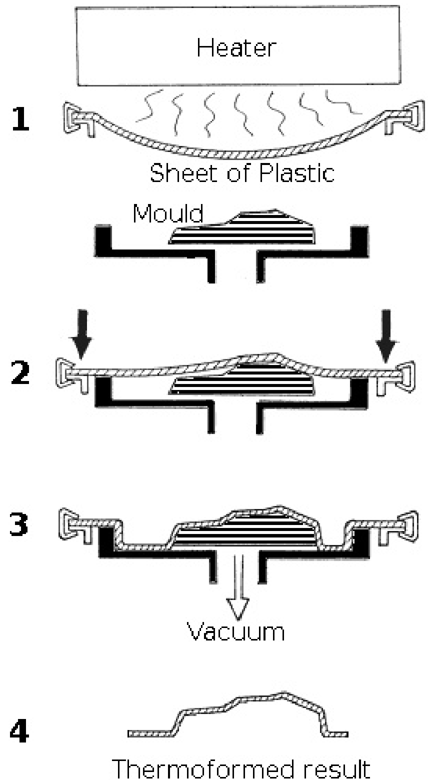

Figure 2.8.: Schematic illustration (lateral view) of the thermoforming process. In Step 1 a sheet of plastic is heated so that it becomes elastic. In Step 2 the sheet of plastic is pulled over the mould and a vacuum sucks the elastic sheet into the mould (Step 3). Finally, the cooled plastic is separated from the mould and excessive material cropped (Step 4). Illustration adapted from Walsh (1990).

Figure 2.9.: Photograph of an industry standard thermoforming machine, here the Formech FM660, 94cm wide, 128cm high, and l90cm deep, with a total weight of 260kg (according to the manual).

from my own review of the market situation in Germany).

2.3.1.3. Dissemination of Traditional Tactile Maps

Traditional tactile maps are often found in institutions that provide learning experiences to their customers and can afford buying these expensive maps. Generally users only experience the use of tactile maps in school, occasionally in mobility training, or when they visit places that offer special support for blind people, for example public transport hubs or community agencies. There are businesses that are obliged to provide access for everyone – including blind people. In Germany an example of a big company that provides tactile maps is the 'Deutsche Bahn'. It is partly owned by the Federal State and special regulations apply. Therefore, some—but not all—railway stations (for example Bremen) have installed tactile maps that can be used for orientation and wayfinding. These tactile maps – regardless who ordered them – are all made by special manufacturers in very limited editions (typically one or two pieces).

But even if maps are available for acquiring spatial knowledge about the surroundings, existing additional support is often not announced beforehand. And, there are no existing regulations or standards of positioning tactile survey maps when equipping parks, zoos or the like so they are often not found. If people don't know about the existence of maps and know from experience that in most cases, there is no such support, they do not inquire about it. Thus, dissemination of tactile maps to the general public is very limited. Dissemination to private households is even less common as the maps are expensive, production takes a while, and other means of support are directly available, for example, using a GPS driven navigation system or asking others for help.

Because design and production are exclusive and expensive, traditional tactile maps cannot be altered quickly, produced individually or distributed quickly and upon demand. Therefore just a few institutions produce them and teach how to use and interpret them. An approach that enables abstraction from map-makers knowledge and can be used at home would be a step towards easier access to tactile maps for everyone.

2.3.2. Digital Tactile Map Generation

Despite saving time through layout software in tactile map manufacturing, using information technology for the whole process of map-production promises to provide fast, dynamic, and individual access to models of the geographic world.

The advent of affordable, computer-controlled, digital devices to produce traditional tactile maps offers possibilities to yield a seamless technology-based map-making process. That is, both steps of map-making, namely map simplification and map production, are based on digital data: This data is processed during the simplification process on a digital device and then fed into another digital device to produce some kind of sensible output to the human reader, for example hardcopies. The ultimate goal is to make map simplification independent of design knowledge of human map-makers, i.e. automatic processing of input data (for example, GIS data or an image) and to promote easy, fast, and individual production.

Neither transforming geographic digital data into virtual tactile maps that are explored with special hardware (see Jansson et al., 2006, Lohmann et al., 2010, Miele et al., 2006) nor digital maps on vibro-tactile touchscreens (potentially in already owned, multi-purpose equipment such as mobile phones) are in the scope of this review. For a recent discussion of reading graphs and shapes (including maps) from a vibro-tactile touchscreen (potentially including other modalities such as language and sound), see (Giudice et al., 2012, Kaklanis et al., 2013, Raja, 2011).

In the following two subsections I will review what has been achieved in the field of hardcopy tactile orientation map generation and identify what is still missing to make the generation of tactile orientation maps a viable option.

2.3.2.1. Simplification Approaches for Hardcopy Tactile Orientation Maps

A consideration for simplification is the size and resolution of the output device, i.e. how much information can be communicated. This concerns the factor of quantitative abstraction. On the one hand, the technical constraints that result from the map production of choice must be involved. On the other hand, the best practices in traditional tactile map-making (see subsection 2.3.1) can inform the definition of schematisation recommendations for generating understandable digital tactile maps. Both map generalisation and map-production must be affected.

One challenge in reviewing digital tactile map-generation is that in some cases the step of map generalisation is not conceptually separated from the map production. Often, approaches to provide a tactile model of some visual complex structure (such as a map) follow the *sensory substitution paradigm*. Entities following this paradigm in the source sensory modality are substituted with corresponding entities in the target modality. As early as 1966, Linvill & Bliss proposed a device that translated a graphic into a tactile image. The tactile image was presented through a dense array of pins. In recent years, this approach has been revived (c.f. Völkel et al., 2008). For a review of sensory substitution technologies see Pun et al. (2007). Some more recent work can be found in Kraus et al. (2008). The substitution approach often implies a reduction in resolution as filters are used and some details are maintained and others vanish – but it was only due to the raster/kernel size of the filter and not to cognitive consideration. This only provides a solution on the level of sensory accessibility. It does not address the challenge of ensuring that the content of the map is understandable for the visually impaired. As the sensory substitution of vision lies beyond the scope of this thesis, the interested reader will find more details about cognitive and perceptual processes in the excellent book chapter by Loomis et al. (2012).

A first approach beside the technology-driven abstraction was proposed by Way & Barner (1996). Beyond simple filters it proposed an automatic transformation of images, via image processing algorithms, into an abstract graphical form. This approach was one of the first to alter the qualitative content of the image. Nevertheless, there were no discussions or tests as to whether the proposed concepts in the abstracted image were plausible cognitive schematisations that facilitate learning.

Regarding the cognitive requirements, it makes a difference whether congenitally blind or late blind individuals try to understand tactile maps, discounting the difference between legally blind people that still have some visual impressions and those that do not. For congenitally blind people who have never had visual access to the spatial world, it is far more difficult to learn spatial concepts, but not entirely impossible. People who once had visual access to the world developed spatial concept that are not lost when they become blind later in life (Chen et al., 2010, Dulin, 2008, Fortin et al., 2006, Heller, 1989a, Heller et al., 1996, Noordzij et al., 2006, 2007, Postma et al., 2007, Tinti et al., 2006). See Heller (2002), Heller et al. (1995) for details about the challenge that, for example, congenitally blind people face when interpreting tactile and haptic stimuli, although the results are not entirely conclusive (Heller et al., 2001, Heller & Kennedy, 1990). As already motivated in the scenario in chapter 1.1 this thesis will focus on support for late-blind people because the late-blind predominately contribute to the number of blind or visually-impaired people (WHO Media Centre, 2012).

2.3.2.2. Digital Production of Hardcopy Tactile Orientation Maps

A technology to produce hardcopies is tactile printing. Tactile printers transform base material, often paper or cardboard, by embossing small metallic rods into the paper. Raised dots (conventionally called *taxels*) are created. Similar to matrix printers for Latin characters, the dots can only be placed using a fixed matrix. Some printers are made to produce Braille text only, others can output rudimentary graphics. Some printers can produce different elevations of taxels and some additionally allow to add shades of black ink or colour ink to the tactual print. Most of the other tactile printing systems are specifically made for printing Braille text. Braille text is made from tactile characters, each printed by a cell. Each cell can display one Braille character that is composed of 6 or 8 dots in a 2 by 3 or 2 by 4 matrix arrangements. To distinguish two characters more easily, two cells are separated through extra space. When printing continuous objects with other printers than those equipped with TIGER technology, this mandatory space results in unprinted areas between two cells and larger objects are regularly separated by empty space. This makes the fast and easy recognition of continuous tactile graphics tedious if not impossible with standard Braille printers.

Figure 2.10.: The ViewPlus Emprint SpotDot: A tactile printer that can produce tactile graphics.

In this thesis a Microsoft Windows XP® system with a tactile printer from ViewPlus was used. The ViewPlus Emprint SpotDot (see Figure 2.10) offered one unique feature that is important for this thesis: It was one of the few, probably the only, available tactile printing system on the consumer market in the years 2008 to 2012 that was able to produce high resolution tactile graphics (see Figure 2.10). ViewPlus printers are not primarily Braille printers, but were specifically designed to enable graphical output (see Figure 2.11). The production of tactile maps with the Emprint Spot Dot is fast, as every graphical input is converted automatically. Regardless of the input graphics, the printer produces the same coarse results due to a down-scale process. See chapter 3, section 3.1 for further details.

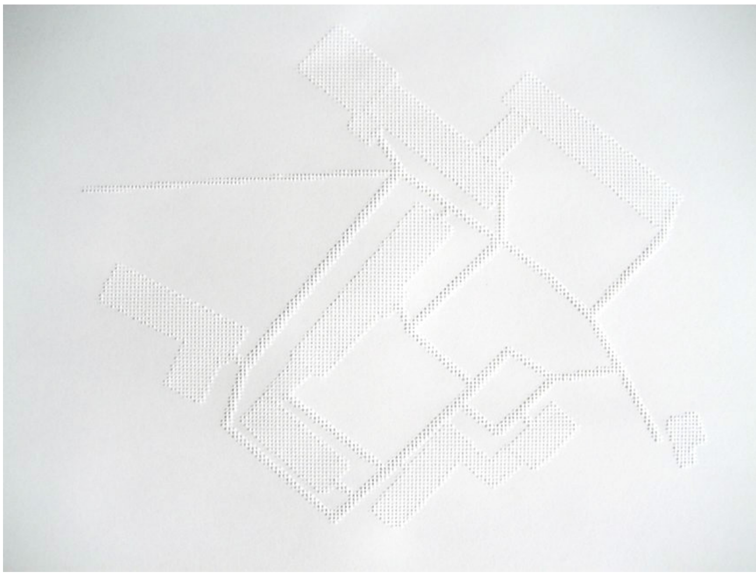

Figure 2.11.: A sample tactile map produced with a computer controlled tactile printer. It represents the buildings and track network of the Informatikum at the campus of the University of Hamburg (for a enlargement see Figure 3.1).

The costs for printing with the ViewPlus printer are limited to the cost of buying the printer and the base material to print on, i.e. copy paper or cardboard. Printed on paper or cardboard, the taxels become rather indistinct using several times. The sustainability and richness of the surface is related to the base material itself, i.e. rather limited compared to, for example, traditional tactile maps made of plastic. Therefore, hardcopies made of paper should be used only once if a rather limited range of surface characteristics as coding dimension is needed (Foulke, 1994). Generally, the choice of technology to support the communication through the sense of touch depends on the purpose for which it is used (Foulke, 1994). Hardcopy tactile graphics are inexpensive and easy to produce with tactile printers such as the ViewPlus Emprint SpotDot. With them, tactile maps can be produced in big numbers in the same quality, and “what really makes them useful is the ability of individuals to produce dot graphics” (Foulke, 1994). Those tactile printers are still not cheap, around € 6,000. But considering the high volumes possible with the printers, the single map becomes inexpensive compared to traditionally hand-made one-off tactile maps. The immediate print-outs are another big advantage.

2.3.2.3. Dissemination of Hardcopy Tactile Orientation Maps

The way hardcopies are produced today provokes rather awkward situations when it comes to their dissemination to the public or to private customers. As the production needs special bulky hardware and specially trained personnel although the demand is low – partially due to the high costs – production facilities are relatively rare and spatially dispersed. In Germany, for example, there are only about ten producers, often subsidised by the public administration and private and public foundations. Some are well-known like *Blista* in Marburg[15] and *Deutsche Zentralbücherei für Blinde* (German Central Library for the Blind) in Leipzig[16] . Other producers in Germany are smaller but none-the-less prolific, for example, *TOUCH* in Hamburg[17], or *Grenzenlos* in Erfurt[18]. With regard to hardcopies these producers are largely involved in business-to-business activities, i.e., schools or other official organisations that order hardcopies, often several at once. Only a small fraction of the customers are private households[19]. Delivering maps to the customers may take weeks or even months depending on the complexity of the map and the resulting time to manufacture it.

Tactile maps as envisioned in this thesis – as a communication tool easily available to everyone and customised to individual needs – have not been established yet. In contrast to traditional tactile maps that need bulky hardware, hardcopies that are printed with digital hardware can potentially be produced anywhere. Access to such maps would be more immediate in terms of distance between producers and customers and in terms of time between demand and delivery. Realistically, local producers that gather the demand of many potential users, such as their local community centres, schools, sport clubs, malls, or administration offices, could be the first to realise the potential of the quick and easy production of individual tactile maps that are easy to understand. One scenario could be as envisioned in section 1.1: If blind individuals need to visit, for example, the local community centre, a school ground, or administration buildings they could first call and order a tactile orientation map with the next local provider. Even if tactile printers are not going to be available to all blind people, organisations for the blind, or schools for the blind could afford one and equip their customers with hardcopies. With the local providers accessibility to everyone they would become much closer to blind peoples' everyday lives. The difficulties to achieve hardcopies for home use would be much less than in before.

[15] Homepage of the tactile media branch: `http://www.blista.de/taktilemedien/`
[16] Homepage of the tactile media branch: `http://www.dzb.de/index.php?site_id=4.2`
[17] Homepage: `http://www.touch-hh.de`
[18] Homepage: `http://www.grenzenlos-erfurt.de`
[19] Personal conversation with Mr. Beyer-Killisch, tactile map expert at TOUCH, producer of tactile maps and globes, 2008

2.3.3. Discussion about Tactile Map Generation

A major problem comparing approaches to generation of tactile maps is that the final goal of what should be achieved by computers is not agreed upon. For some, 'generation' means having the computer as a tool that 'makes the editing task easier by making it possible to add, delete, and change aspects of the map in relatively simple ways' and provides 'rapid access to the effect of the changes on the screen' (Jansson, 1983, p.70). This is what one can see today: computers as tools to facilitate laborious tasks. For others, 'generation' means that the computer should independently work out an optimal solution, balancing several constraints that potentially contradict.

As Barkowsky & Freksa noted, computer-based map-making is generally different to human map-making and a qualitative approach might cope with the problem in general (1997, chapter 2.1). Other authors do not have concerns about that difference (Coulson, 1991, Douce & Gill, 1973, Way & Barner, 1996). They have technology-centred approaches that do or do not consider qualitative or cognitive aspects to a very limited extent.

Concerning user-studies or reports about user-experiences made with hardcopies, a literature review has not delivered any findings about recommendations to ensure the usability of such spatial representations. Therefore it is not clear a) whether map-readers intuitively grasp the concept of composition, i.e. that objects are composed from single, separate taxels, and b) which characteristics of tactile signatures support the discrimination and understanding of tactile objects.

2.4. Summary of State-of-the-Art

The first section of this thesis elaborates on the acquisition of spatial knowledge with tactile maps. It considers human navigation and the wayfinding tasks that could be supported by using survey maps. The challenges of communicating spatial (survey) knowledge with tactile maps are explained and the benefits that visually impaired people could gain from using tactile maps. In the second section, the concept of simplification inherent to every map-usage is introduced: on the one hand as cartographic generalisation and on the other hand as cognitive schematisation. Then simplification approaches proposed in the literature to cope with the problem of displaying abundant information on limited information displays were reviewed. The principles of schematisation applied to tactile maps and subsequent improvement of the usability of a map are argued, showing that map-users perform better with it or have usage preferences for it. In the third section, technologies and processes of tactile map-making were reviewed focussing on the distinction between manual (aka 'traditional') map design and digital map generation with computer-controlled printers. Once defined map generation could be automatised. Then map generation could be entirely performed in a digital processes that have the potential to bring tactile maps to the customers quickly – quite different to today's situation. But there is little knowledge about the generation of schematic tactile maps for communicating potentially complex environments. A lack of principles for schematising tactile survey maps produced with a modern tactile printer demands further concepts and investigations.

Chapter 3.

Schematisation of Hardcopy Tactile Orientation Maps

In this chapter I will introduce the concepts that help understand and use of a tactile orientation map. First, I will build a characterisation of tactile orientation maps and how they are used. This will lead to an understanding of which tasks and strategies are involved in using tactile maps.

Then, schematisation strategies that have been used for other navigation tasks are presented. I investigate each strategy and whether it can be applied in a context of tactile orientation maps. I propose schematisation strategies that promise to facilitate comprehending tactile orientation maps.

3.1. Characteristics of Hardcopy Tactile Orientation Maps

In this section I will present different aspects of tactile orientation maps, which activities are performed with tactile orientation maps, and how the former aspects are involved in the latter activities.

3.1.1. Aspects of Hardcopy Tactile Orientation Maps

Hardcopy tactile orientation maps can be characterised from different viewpoints. I characterise them with the focus on their sensory, representational, and schematisation aspects.

3.1.1.1. The Sensory Aspect

The sensation of TOMs is heavily influenced by the production technology used. The printer used in this research was the Emprint SpotDot from the manufacturer ViewPlus and uses embossing technology. This printer can handle single pieces of paper, size A4 (29.7 x 21 cm), with a maximum weight of $200g/m^2$.

To produce hardcopies the printers need driver software. The driver is an intermediate between the operation system of the computer and the printer. To produce a hardcopy with a ViewPlus printer, the print API of the Windows® operation system is addressed, for example by using a drawing program and starting the print command. The driver implements the TIGER printing technology[1] that performs an automatic translation of visual graphics to

[1] Tactile Graphic Embosser, see http://www.viewplus.com/solutions/braille-technology/

tactile graphics. The TIGER technology is applied to yield a low-resolution, anti-aliased, and brightness-indexed version that is then sent to the printer. The brightness index is equivalent is to 8 different elevations of the raised dots[2].

Raised dots produced with the Emprint are less than one millimetre high (the same as swell paper but far less than vacuum-formed tactile maps, see Gardner 2005 for all figures mentioned in this paragraph). With the Emprint the raised dots are smaller (diameter of the dot base: less than 1.2 mm) than dots in traditional Braille letters (dot base: 1.2-1.5 mm). The dots differ in curvature as well: Emprint raised dots have rather sharp heads (the shape of a dot is similar to a pyramid) compared to the round heads of traditional Braille dots (the shape is similar to a half-sphere). With the Emprint the raised dots can be placed closer to one another, other than dots produced with a Braille printer arranged in cells. With these characteristics taxels made with the Emprint feel a little different than the traditional Braille dots, on the one hand. On the other hand, a print resolution of 20 taxels per inch (that equals 8 taxels per centimetre or one taxel per 1.27 mm) can be realised (Gardner & Bulatov, 2004) , and that 'would produce much higher resolution tactile graphics than had been possible before' (Gardner, 2005, p. 26). And the difference in curvature of the dots means extra space around the dots, so that Emprint dots can be perceived more easily by people with poor tactual sensitivity (Gardner, 2005, p. 27). With about 60 taxels per square-centimetre the sensation of discrete taxels is probably missed when interpretation suggests some continuous object (see Figure 3.1).

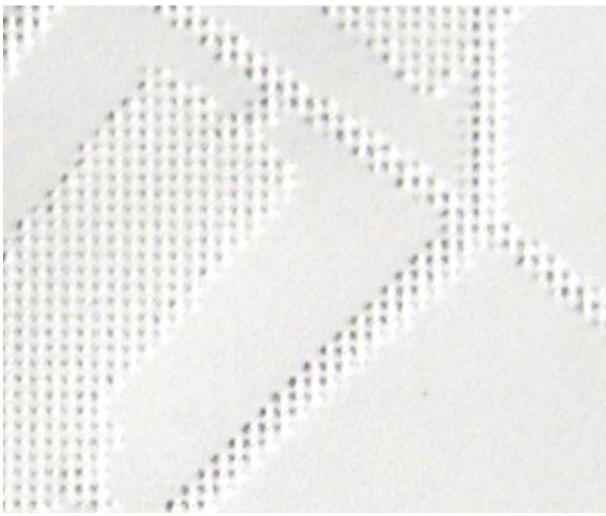

Figure 3.1.: A section of a central part of the tactile map shown in Figure 2.11. All geometric entities are composed from single taxels (different elevations of raised dots can be noted in this photo by differently cast shadows).

[2]Technical details can be found in the ViewPlus Emprint SpotDot specifications, see `http://www.viewplus.com/products/ink-braille-printers/emprint-spotdot`, last access April 20, 2013.

3.1.1.2. The Representational Aspect

The representational nature of the printed TOM is uni-modal. In contrast to visual maps that are typically multi-modal artefacts and provide linguistic components (for example, labels) besides the spatial component, only a network of streets and embedded landmarks is represented. That is, information is encoded with spatial components only. No Braille labels representing linguistic components were used in TOMs. This was based on three rationales.

1. There are no definite numbers on the ratio of blind people reading Braille world-wide. The World Health Organization does not number them in their statistics. Estimations in Germany are that only 20-30% of the blind are literate[3]. Demographics in the USA show that literacy among all blind people is 10%[4]. The literacy rate only among students is still about 20%[5] but has decreased dramatically over the last 40 years[6]. It can be concluded that most blind people do not understand Braille and it would be difficult to reach high acceptance with material that locks potentially important information behind unintelligible code.

2. Braille labels would take too much space and prevent other elements with spatial meaning to be displayed.

3. Potential clutter had to be reduced as it might have distracted map-users.

To give certain meaning to landmarks, regions and streets, clearly distinguishable symbols with meaning attached were used. The meaning of each symbol was provided through a legend. The legend was verbalised by the experimenter before map-exploration and on the map-user's demand during map-exploration, i.e. a pre-defined explanation for the symbol touched was read to the user. With these properties TOMs thesis are *pure tactile graphics* in the sense of Lötzsch who proposed to distinguish tactile graphics according to the amount of textual elements (i.e. propositional content) contained (1994).

This thesis has not set out to investigate the qualities of the mental representations formed when conceptualising a TOM and the forms of mental representation of the map were of secondary interest. For the sake of simplicity it assumes that the mental counterparts of TOMs were cognitive maps, see chapter 2. But other types of *functionally equivalent* mental

[3]see online article "Hintergrund: Blindheit" (`http://www.planet-schule.de/wissenspool/das-besondere-lernen/inhalt/hintergrund/blindheit.html`, retrieved May 12, 2013) and Niederstadt (2009)

[4]Braille Institute (2011). About Blindness - Myths and Realities. Retrieved from `http://www.brailleinstitute.org/documents/index.php/item/myths-and-realities`; May 12, 2013.

[5]Department of Field Services of the American Printing House for the Blind (2009). Distribution of eligible students: Based on the federal quota census of January 01, 2007 (fiscal year 2008). Retrieved from `http://www.aph.org/fedquotpgm/dist08.html`, May 12, 2013.

[6]National Federation of the Blind (2009). The braille literacy crisis in America: Facing the truth, reversing the trend, empowering the blind. Retrieved from `http://www.nfb.org/images/nfb/documents/word/The_Braille_Literacy_Crisis_In_America.doc`, May 12, 2013.

representations could have the same explanatory power (for example, mental maps Downs & Stea, 1977, Gould & White, 1974). Regardless to whether cognitive maps are the appropriate model of the mental representation formed from tactile orientation maps, the important property is that the spatial knowledge is captured in a form analogue to the structure of the environment; although analogous, spatial knowledge about streets, regions, landmarks and their relations is assumed to be subject to some kind of distortion, simplification, and filtering. The constructed cognitive map might not necessarily be a single mental representation but a set of representations. Although a single reconstruction of parts of the knowledge might be correct, multiple reconstructions could be inconsistent when integrated, i.e. they potentially lack global consistency.

3.1.1.3. The Schematisation Aspect

When analysing the operators of map simplification (see subsection 2.2.1) and the nature of changes they imply, I conclude that there are two kinds of simplifications:

Abstraction : The approach to simplification is quantitative, i.e. the number of map entities is reduced so that a) less entities have to be discriminated (less cluttering) and b) the amount of relations between entities to remember is reduced. Without the clutter more tactile entities significant to the task at hand can be discriminated and recognised successfully. Reducing the cognitive demand to process and having to memorise fewer spatial relations could contribute to fewer recognition errors. The cartographic operator of simplification contributes to this goal.

Schematisation : The approach to simplification is qualitative, i.e. the number of map entities stay the same but individual details are removed from the encoded information. The focus is on accommodating and facilitating the processes involved in forming a cognitive map by chunking details into categories. This means that approaches facilitate map-understanding, for example, by affording conceptualisation through categories instead of individual details. It is easier for humans to deal with a few categories than with many individual items. One example are directions and intersections. Instead of exactly remembering the angular direction of a landmark, people often use *cardinal directions*, typically with four distinctions: North, East, South, and West, or more fine-grained with eight distinctions: North, North-East, East, South-East, South, South-West, West, and North-West (Frank, 1991, 1996, Klippel, 2003). Each sector covers $45°$, the first starts at $-22.5°$ (measured clockwise from the vertical). For a schematic illustration see Figure 3.2. And people make *distorted estimations of distances* (Friedman & Montello, 2006, Tversky, 1981, Xiao & Liu, 2007). The cartographic operators smoothing, exaggeration and displacement can be used to contribute to the qualitative nature of this type of simplification.

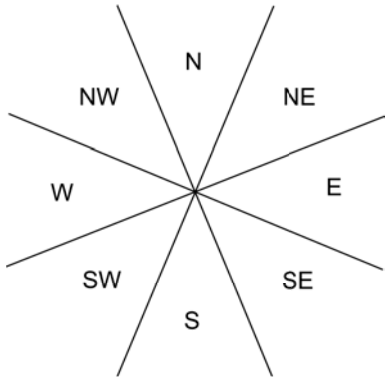

Figure 3.2.: By separating the plane into 8 sectors there are 8 directions defined: North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W), and North-West (NW).

Both types of simplification, abstraction and schematisation (as introduced above), effect the usability of tactile maps. Abstraction contributes to the usability of a tactile map by safeguarding detection and discrimination of the entities. Schematisation supports the map-readers' cognitive processes when recognising parts of the map and conceptualising the whole map, i.e. map-understanding.

3.1.2. Activities in Tactile Orientation Maps Usage

The use of tactile maps introduces all sorts of challenges, as we have learned in section 2.1. However, learning with tactile orientation maps could open opportunities to independent wayfinding. Potential users can be found in the group of late-blind individuals, i.e. people who have acquired some visio-spatial concepts that help understand the information encoded in a map. This group of people is the largest among all blind, so that the outcome of this research is possibly applicable to tools that have a huge user base. There are common spatial tasks that blind people need to solve when navigating the word. Tactile orientation maps can be consulted before a journey to help solving those spatial problems when in the environment: *localisation* (i.e. identifying the position in the environment by matching different salient landmarks with the cognitive map), and *survey mapping* (i.e. knowing the structure of the environment from a bird's eye view). When preparing to go to an unfamiliar environment, a first interest taken in the spatial layout of the area, could be in presence and location of important landmarks. The prospective navigators will assume that in each city has well-known landmarks such as main streets (e.g. the Champs-Élysées in Paris), important central places (e.g. the Marcus Plaza in Venice), and main public or administration buildings (for example, the Grand Central Station in New York). Map-readers might be interested in finding these landmarks to use them as anchors for the newly established cognitive model or to align their pre-existing cognitive model. Establishing a match between the structure of the environment and the cognitive model offers an opportunity to subsequently detailing knowledge, probably about side streets between two main intersections and connecting paths so that eventually, survey knowledge will shape. This assumption is grounded in research about the development of spatial knowledge. This knowledge is not created suddenly, but develops slowly involving different levels of knowledge complexity: from location knowledge, to route knowledge, and eventually, to survey knowledge (Siegel & White, 1975).

With these considerations in mind and against the background of research on map learning (c.f. Kulhavy & Stock, 1996, Lobben, 2004, Winn, 1991), one can distinguish different activities in map-usage:

(Self-)Localisation : Map-users specifically search for distinct locations on the map (possibly their own).

Survey Mapping : Map-users explore the map to get an overview of the environment.

I will elaborate on these activities in the next paragraphs:

3.1.2.1. (Self-)Localisation

Map-users search for a distinct location on the map. To clarify what might happen when searching for a certain position in a TOM, let us re-consider the zoo scenario (see chapter 1). Map-users will most probably set the entrance of the zoo as their first point of interest and reference for the further tour through the zoo, because it is the location they first arrive at. Thus they need to find the entrance as a symbol on the map. They have to perform a search for the representation of the zoo entrance. First they will probably gather information with the map legend on which symbol represents the entrance. Then they will thoroughly search for matching information on the map. If they find it, the search was successful. If they do not, they give up and the search failed. This demanding search could be supported by different indicator types that help finding a symbol on the map. An indicator is an artefact that has no geographic meaning but that is introduced into the map as cartographic aid to ease the map-usage. Such an indicator can highlight an object (e.g. some explicit symbol) or a location (e.g. some implicit way-point such as an intersection) on the map.

Having pinpointed their location on the map, map-users can proceed with *Survey Mapping*, i.e. the interpretation of an external representation on map space leading to conclusions of environmental space (see Lobben, 2004).

3.1.2.2. Survey Mapping

According to Lobben (2004), *Survey Mapping* is the cognitive strategy to get acquainted with the spatial structure of the environment by exploring certain external representations, i.e. a tactile map. This might happen with or without prior *Self-Localisation* (see above). If map readers do not have a specific destination in mind, but instead, want to wander around, they could explore the whole map to get an overview of the area. Ideally, map-users could later use the survey knowledge acquired and different wayfinding strategies without any map(see subsection 2.1.1, Figure 2.1 above), including *Path Planning* and others (see Wiener et al., 2009).

In summary, the core function of a TOM is to afford survey acquisition that supports trip preparation: spatial knowledge is conveyed before locomotion in the environment takes place. The different aspects of production and usage of TOMs constrain their expressiveness but different approaches of schematisation can support and maintain their usefulness. Independent navigation in the environment is supported through communication of survey knowledge captured in schematised TOMs.

3.2. Challenges with Schematised Tactile Orientation Maps

In this section I will look into technology challenges of producing tactile maps with tactile printers as well as into the sensory challenges of reading tactile maps. I will identify the constraints introduced and suggest schematisation as a relief to these constraints.

3.2.1. Sensory and Technology Constraints

In section 2.3.2 I reasoned that there are hardly any findings about how to ensure the usability of hardcopies, including TOMs. Only recommendations for traditional tactile map-making of thermoformed maps were discussed (see section 2.3.1). These recommendations have to be reviewed with respect to their applicability before transferring them to computer-generated tactile orientation maps made of discrete taxels. Without the knowledge of basic characteristics that are grounded in technology, recommendations or rules for generalising readable tactile maps can not be developed. Thus, there is a need to investigate the effect of new production technologies with regard to understanding generated tactile objects. Basic tactile objects can be represented by symbols, lines and surfaces. They may differ in size (e.g. small vs. big), surface patterns (e.g. broken vs. continuous vs. patterns), and elevation (e.g. almost indistinguishable from level paper vs. maximum elevation). It is particularly necessary to know which parameters are essentially useful for production of detectable, discriminable, and recognisable tactile objects that map-readers can make use of. These three concepts interconnect and should be understood in this thesis as follows:

1. Detection: deciding for tactual sensation whether it is a (yet unspecific) tactile entity or not.

2. Discrimination: specifically assigning properties like shape, coarseness etc. to differ from others.

3. Recognition: assigning meaning to a tactile entity (with or without other entities present).

Another factor that needed to be investigated was the technology for tactile prints. As reported in section 2.3.2 any graphic that is printed with the TIGER technology is subject to a degree of pre-processing before being printed. Most notably this includes anti-aliasing, i.e. high-contrast edges are blurred to show a continuous transition. Anti-aliased graphics may change the sensory characteristics of the print which might influence the tactile reading process and thus influence the quality of the conveyed spatial knowledge. As the driver software is a closed-source it is not clear how the resolution reduction is computed and how the anti-aliasing exactly works, i.e. which adjacent taxels are print with what intensity. It is also not clear how the algorithm can be used advantageously or, in the case of detrimental effects, how it can be deactivated. Therefore, the focus was on the translation of several graphic layouts to hardcopy results in order to prepare for more elaborated investigations. Specifically the following questions were sought to be answered:

- Which dimensions in the layout (distances, angles, surface structures) translate to which dimensions in the final tactile map?

- Under which circumstances is anti-aliasing active and under which is it not?

- The minimum separation between tactile entities on the map to be able to discriminate them.

- The characteristics of tactile entities so that they can be discriminated.

- The characteristics of a tactile entity so that it can be recognised.

- The influence of shape, position, orientation, and composition of tactile entities on detection, discrimination and recognition.

With knowledge of the dimensions of differences, the discriminable levels in each dimension and the effect of the anti-aliasing, a tactile vocabulary can be created. These results would be a good start for defining discriminable and recognisable tactile signatures for tactile orientation maps. The first human user survey (see chapter 4) investigated the lower bounds of separation between entities and recognizable surface structures to clarify the characteristics of hardcopies. It recommends symbolic, linear and areal tactile signatures for tactile orientation maps produced with the ViewPlus Emprint tactile printer.

3.2.2. Schematisation for Map-Reading Improvements

Regarding the goal of the schematisation in a tactile map, one can imagine (at least) two effects: First, the schematisation contributes to the *usage of a single map* by supporting the three basic navigation tasks identified in section 3.1.2: localisation, path-planning, and survey mapping. Second, schematisation contributes to the understanding of how (a part of, or a single entity of) a map relates to other parts of the global environment that are not shown (i.e. the *embedding* the displayed environment in the world), for example, by representing information about distant landmarks.

The review of schematisation strategies presented in chapter 2, subsection 2.2.1 was a starting point for selecting appropriate schematisation strategies for tactile orientation maps, see Table 3.1. The table summarises the cognitive advantage each schematisation strategy holds, and whether the type of simplification is quantitative (i.e. reducing the number of elements displayed) or qualitative (i.e. changing the geometry of the maps).

Schematisation Strategy	Cognitive Advantage	Type of Simplification
Shorten segments based on activity	Focus attention	Qualitative
Hide entities based on distance	Prevent clutter	Quantitative
Show or hide entities based on prior knowledge	Prevent clutter	Quantitative
Show alternatives	Wayfinding support	Quantitative
Show stable frame of reference	Orientation support	Qualitative
Show off-screen POI	Orientation support	Qualitative
Use fixed grid to determine next zoom	Orientation support	Qualitative

Table 3.1.: Overview of the strategies of schematisation used in different types of mobile visual maps.

Details about these schematisation strategies and their potential transfers to TOMs are summarised in the following subsections.[7] I investigate the applicability of identified strategies and aim at determining whether the schematisation strategy can contribute to improve the comprehension of TOMs.

Shorten segments based on activity

The schematisation strategy to shorten street segments in which decisions are unlikely to be taken is used in the design of tactile orientation maps. The metric information is often lost in tactile maps as the size of the entities on the map forces to impose a flexible scale (Flem-

[7] The text is partly based on Graf & Schmid (2010).

ing, 1986, Gardiner & Perkins, 2002). For visual maps, Wood concludes that 'fixed scales often fail to coincide with the variability, contingency and fluidity of cognitive assessments' (1978, p. 207)[8]. For tactile maps, Fleming found that performances with flexible scale are at least equal to those with fixed-scale (1986). However, she also found that people prefer the dynamic scale maps. These are enough initial findings to consider shortening segments for tactile orientation maps, i.e. focusing on topological veridicality rather than on geometric veridicality.

Hide entities based on distance

Fading out segments depending on the distance of certain routes given would probably confuse the readers of TOMs. As I have already pointed out, no holistic view on the map is possible with tactile perception. Readers must concentrate on local properties of the tactual entity and integrate them mentally. Orientation maps will presumably make it hard to integrate different parts of the map if entities fade out, because the ones that fade out could be considered to be of minor interest, i.e. clutter. In general, the question arises which elements of a survey map should be hidden and which should not. In studies that were reported in Graf (2010) it was noticed that readers of TOMs concentrated on the central part of the map, often leaving out the periphery. This could be a lead on some kind of unconscious adjustment-to-distance behaviour with the centre of the map as the point of highest interest. Because of its main relevance for maps that support route navigation, this strategy was not investigated further but is open to future work.

Hide entities based on prior knowledge

The concept to detail segments and regions that were not walked but passed by and to leave out contextual details of passed tracks and areas could be used to customise a map to the user's prior knowledge. If map-readers already know part of the area, the resulting TOM could build on that knowledge by, for example, strongly abstracting the known part and detailing the unknown. This could help to reduce clutter on the map and provide the details map readers are not aware of. If the user is new to an environment (as assumed in the usage scenario of TOMs investigated in this thesis) than this principle has minor impact.

Show alternatives

For route maps it may be of advantage to display the context of a given route by visualizing alternative routes. In TOMs this concept is 'built-in' as there are no specific routes displayed but a network of tracks and landmarks. The map-users might find several alternative routes, from a starting point to a certain destination, by themselves. This concept could be used to emphasise side-streets with good ergonomics and to facilitate the alternative conceptual models of the area. For example, safe pedestrian zones or streets with broad side-walks that have a clear marking and sound signals at intersections could be candidates

[8] The interested reader might consult Muehrcke (1976) about the cartographer's view on map distortion and map scale on maps, particularly Böttger et al. (2008) about 'correct' street maps and schematised maps, such as metro maps.

for respective accents. The downside of this approach is that the TOM has to show more tactile entities to represent more information. It would quickly be more cluttered and harder to understand. Therefore this principle is estimated to have minor impact with TOMs.

Show stable frame of reference

The proposed usage of a stable frame of reference that builds upon salient, potentially off-screen landmarks is a concept that might be of a greater importance if considered for route maps because the orientation of the map often changes. Nevertheless the concept of embedding a tactile map in the greater surrounding could be beneficial for TOMs as well and help the map-reader becoming aware of major salient landmarks with a 'global' meaning. This is especially so if more than one TOM is used and the relations between different TOMs have to be learned. All the TOMs have to be aligned mentally and connected with each other in the right way. The same landmarks in different TOMs could be helpful for matching them. Other elements, like the same streets existing in more than one map, could help mentally connect maps. In this thesis the schematisation for improving the usage of a single map was the focus of my interest. See section 8 for discussion of schematisation strategies for multi-part maps.

Constrain panning and zooming

The dynamic changing scales with zoom features, as observed in digital maps, may be more problematic to apply to tactile maps because the recognition of common landmarks that match two maps on different scales could be laborious. In the same way dynamic pan in tactile orientation maps could be a challenge because the correspondence between an element before and after dynamic pan would not be clear. This results from the displacement in dynamic panning that is usually not known. Instead, the concept of cutting a large map into discrete small pieces, using a fixed grid, makes perfect sense because it allows to define static relations between pieces. During transition from piece to piece, the map-users can maintain orientation as panning is discrete as it takes place between the parts of the displayed environment. Map-users probably have less difficulty in assembling the different maps in their mind, if there is a fixed arrangement and fixed transition zones between different maps. When cutting a big tactile map into pieces there probably should be some kind of alignment support, for example, by showing a stable frame of reference. In this thesis, I investigated only single TOMs, therefore the strategy is of minor interest.

On the one hand, the original works about the various types of schematised maps show that these maps are useful and often better than non-schematised versions. On the other hand, abstract tactile maps have proven to convey spatial meaning and support building-up wayfinding competence (Gardiner & Perkins, 2003, Sherman, 1975, Simonnet et al., 2007). The application of the discussed schematisation principles in tactile orientation maps might result in better understanding and better usage of those maps. Some strategies are mainly applicable in route maps: *Show alternatives*, *Hide entities based on distance*. Others are important for adapting to individual users: *Hide entities based on prior knowledge*. Further strategies control multiple maps: *Constrain panning and zooming*. These strategies seem to be of limited use for single non-interactive tactile orientations maps. They have been identified to be potentially interesting in interactive contexts, but they were not investigated in this thesis and have been left open for future research.

The schematisation strategies described so far were all transferred from the area of route maps on small graphic displays. In chapter 2 I showed that tactile maps afford special strategies to be read and understood. They differ from visual maps in important ways, especially as they can offer much less information and as the information is read linearly. So far, the investigated visual maps were designed to primarily provide route knowledge, whereas TOMs are designed to provide survey knowledge. There might be approaches to schematisation that have not been proposed for visual maps or do not make much sense for route maps. In the following two subsections, I propose three that promise to improve hardcopy tactile orientation maps.

3.2.2.1. Guides and Pointers for Better Map-Usage

Different to visual maps that afford fast spotting of visually prominent entities, a tactile entity that pops out of its surroundings has to be searched for serially. Serial exploration takes a lot of time and a highly cognitive effort. The sensory details explored with fingertips have to be integrated in and checked against the goal pattern. In the worst case, without support of any kind of indicator, the whole map has to be searched.

No Indicator (Base-line) : The search space is not restricted. Thus the whole map space has to be touched to look for a match with the target symbol. However, most information encoded on the map is not helpful to the search and can be neglected.

This search strategy is similar to an *exhaustive search* in computer science with no indexes or pointers as auxiliaries. In an exhaustive search each item in the data has to be compared with the query item. This may take long as the target item could be found as the last items in the data set.

When reconsidering the zoo scenario (see chapter 1), self-localisation is the first task navigators have to struggle with. It would be of advantage to support the map-readers to find the position they are looking for. The demanding search can be supported by different indicator types that help to find a symbol on the map. An indicator is an artefact that has no geographic meaning but that is introduced onto the map as cartographic aid to ease the map-usage. This kind of indicator can highlight an object (e.g. an explicit symbol) or a location (e.g. an implicit way-point such as an intersection) on the map. Another idea is to limit the search space and thus limit the effort in searching.

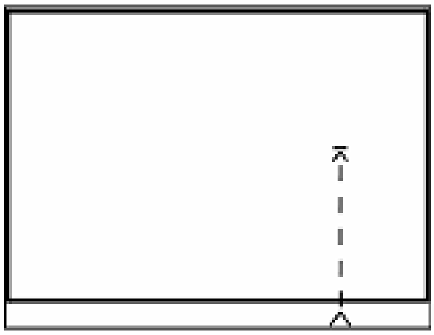

Figure 3.3.: The arrow symbol at the map margin (at the lower frame border) notifies the beginning of the indicator line (stippled). The indicator line guides from the map margin to the symbol on the map space.

Three indicator types, *Indicator Line*, *Frame Marks*, and *Grid* are proposed for usage in the tactile area. These concepts are not completely new for tactile maps. For example, arrow signs (like the Frame Marks) to demarcate a direction to a certain symbol have been used in traditional tactile maps (see Figure 2.7). However, the indicator types were not systematically reviewed and compared for application in hardcopies.

The tactual realisation of all indicator types follows the recommendations found in the earlier sensory tests for hardcopies. To describe them, I have adopted the terminology of Kosslyn (1989) for maps. A map is one single sheet of paper. The 'inner framework' (Kosslyn, 1989, p. 188) is termed 'map space'. It is limited by the 'map frame', composed of four lines, that together constitute a rectangle. The map frame separates the map space from the 'map margin' (Kosslyn 1989's 'outer framework'), i.e. the space between the frame lines and the limits of the media the map is shown on. In the following illustrations only the indicator symbols are visualised and the map space is empty to exemplify the concepts. The map frame is visualised by a thick black line. The map frame was tactually prominent as a tactile line in the original. To make the relative dimension of the map clear in the visualisations, the limit of the media is shown as a thin black line encircling all entities. All maps are visualised on a smaller scale than the originals that had the format DIN A4.

Indicator line : A unique line guides the map-user from a prominent starting point at the map margin to the position of the symbol on the map space (see Figure 3.3).

Frame marks : Four marks at the map margin, two at the vertical lines of the map frame, and two at the horizontal lines, indicate at which horizontal and vertical position the symbol is located on the map space (see Figure 3.4).

Grid : Two sets of perpendicular grid-lines partition the map space into rectangular regions (Kulik & Klippel, 1999). Labels at the map margin assign coordinates to certain hori-

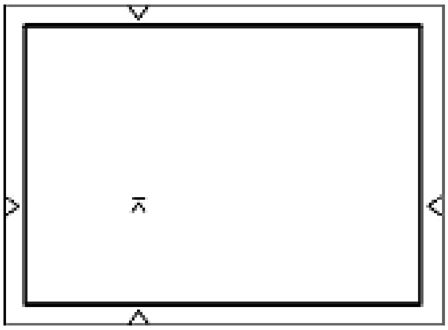

Figure 3.4.: The arrow symbols at the map margin point to the symbol on the map space.

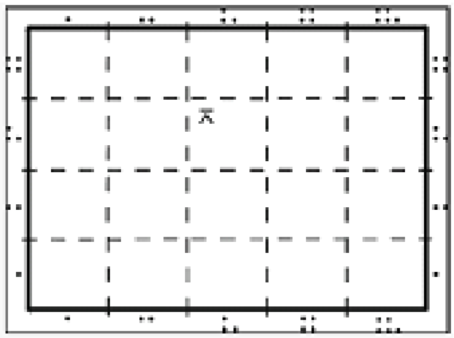

Figure 3.5.: The grid lines partition the map space into many sub-spaces. The horizontal and vertical position of a specific sub-space is given by two coordinates, one for the horizontal component, the other for the vertical component. See text for more explanations.

zontal, respectively vertical, sections of the map space (see Figure 3.5). Thus each sub-space is indexed by an (x, y) map coordinate. Labelling is represented through conventional symbols—not Braille—that are explained in the map legend (not displayed here). Klippel & Kulik point to the advantages of grids in (visual) schematic maps, in that 'they enable inferences that are not possible using only the spatial map features' and that 'they provide additional design freedom, as important information that is not represented in the schematic map itself, can be encoded in the grid structure' (2000, p. 486). Grids can also be found in traditional tactile maps (Rowell & Ungar, 2003b). Some 48% of tactile map designers used them in some of their maps, although their usage is not undisputed. The extra lines on the map disturb the exploration and potentially clutter the map (see Rowell & Ungar, 2003b, p. 109).

The main effect of indicators is that the search for the target symbol is limited to a sub-space somewhere on the whole map space. And, as spatial search with the fingertips is slow, the less map space that has to be read, the faster the search should be. Thus any prestructured search or limitation of the search space should result in a reduction of search time. Subsequently, the behavioural strategy has an advantageous impact on the search performance. Indicators are expected to achieve this effect.

When locating any position with the help of indicators, the indicator itself has to be found first (this can be termed *local search*). Thus the overall search time consists of two components: the time for a local search to find the indicator (Step 1), the time for following the indicator (Step 2a), and a second local search to find the position of the target and to recognise and confirm the target symbol (Step 2b). The easier the indicator itself can be found in step 1 (e.g. through a very distinct shape) and the easier the indicator can be used to locate the target symbol at the goal position with step 2, the smaller the overall search time should be. Therefore, I distinguish two ways of indicating: guiding and pointing.

Guiding is when the map-user (after having successfully performed Step 1) can follow the indicator to reach the goal position, i.e. the map-user can use the indicator to omit Step 2a and 2b. Guiding only involves one local search. *Pointing* is when the indicator simply points to an area and map-users cannot take a short-cut but have to search for the target, however, only to a smaller extent. In contrast to guiding, pointing involves two local searches. Guiding is as if you find rails, put your finger on them and by pushing forward your fingers will end up directly at the target symbol. Pointing is as if someone just tells you the general direction but you have to search on your own, and it includes the danger of getting lost.

The different indicator types afford different behavioural and cognitive strategies when searching. To stress the difference between strategies that are based on indicator and indicator-less strategies, please compare to the 'No Indicator' strategy at the beginning of this section. The search strategies are set in relation to the science of information processing (including search), i.e. informatics/computer science[9]

"Indicator Line" : To find out where the indicator line starts, the indicator line at the map margin must be searched. The start of the indicator line is usually marked by a conventional start symbol (announced in the legend). If there are no other concurring symbols at the frame margin, it is the only symbol that has to be found. If there are other symbols at the frame margin, each one has to be identified in order to find the indicator. After finding the start symbol and the beginning of the line, the line guides the map-user onto the map space. This operation is subject to the uncertainty of following the line as other entities on the map might confuse the map reader. The target symbol can be found by virtually extending the indicator line onto the map space.

[9]'Informatics' as term for the science of information processing and all the involved issues is more established in European, non-English speaking countries. However, there is a tendency in Anglo-Saxon countries to favour the term 'informatics' over 'computer science' (Prof. Freksa, personal communication). It enhances the general nature of inquiry into algorithmical, technical, social, and humanistic aspects that are detached from computing machinery.

This search strategy is a form of *indexed search*. For indexed search an extra data structure is maintained holding pointers to single elements. The index is much smaller than the indexed data structure and can be quickly accessed. The access to indexed elements is similarly fast as the element does not need to be searched for.

"Frame marks" : Frame marks are distributed at the map margin, one next to each frame line. This limits the search space for frame marks to two linear searches at the margin of the map along one horizontal and one vertical frame line. The frame marks only have to be detected, the do not need to be distinguished from other symbols, as there is only one single mark close to each frame line and no other concurrent symbols. By projecting the indicated x- and y-position onto the map space (usually effected by moving the hands of the markers at the borders onto the map space, either one-by-one or simultaneously) the map-user is pointed to an open sub-space on the map, i.e. in the vicinity of the alleged intersection of the projected x- and y-positions. This potential point of intersection might be wrong due to the uncertainty of the manual projection process. Having found the frame marks, map-users can at least limit their search behaviour to the pointed region.

In this strategy the potential search space for the target symbol can be conceptually modelled by a two-dimensional Gaussian probability function that 'covers' the space of the tactile map. One function models the probability of the existence of the target symbol in x-direction, the other models the probability of a y-direction. Each function has its origin at the position of the corresponding frame mark. Both functions together form a three-dimensional Bell curve. The curve then models the probability of the target symbol in the map space. It can guide to where a search for the target symbol seems promising.

"Grid" : Assuming that the coordinates of the grid cell containing the target point are known, the frame margin along one horizontal and one vertical frame line has to be searched for the corresponding coordinates. This search involves detecting the separation between the different segments at the map frame and the recognition of segment labels. After finding both segments that correspond to the coordinates of the target point, the x- and y-grid lines guide the map-user to the grid cell with the target symbol. This operation is subject to the uncertainty of line following as other entities on the map might confuse the map reader. Having identified the target cell, the target symbol must be searched for in the specified sub-space.

This search strategy is a mixture of *indexed search* and the *divide&conquer* approach. A large search space is divided into smaller, closed sub-spaces that can be identified by the index. The identified sub-space is smaller and the search is faster than on the whole map space.

Table 3.2 summarises the discussion of the characteristics of different indicator types. They are structured into the steps needed to finally reach the target position.

	Find indicator	**Follow indicator**	**Find target symbol**
Indicator Line	detect one start point	follow guide	search unrestricted, but small area
Frame Marks	discriminate two entities	follow direction	search unrestricted, vaguely set area
Grid	identify two entities	follow guide	search restricted and small area
No Indicator	n/a	n/a	search the whole map

Table 3.2.: The characteristics of behaviours and search space in the different steps for finding a position in a TOM with different indicator types.

3.2.2.2. Schematised Streets & Schematised Intersections for better Map-Understanding

I propose two types of schematisation: schematisation of streets for faster map-reading and schematisation of intersections for better map-understanding. The baseline to compare the results of those two approaches against is a congruent, non-abstract map type. Before using any of the maps describe here more elements are added: a) symbols to signify the existence and position of landmarks, b) a legend to describe all signatures, and c) a short introductory text explaining what the map displays.

Non-Abstract Map Type (Base-line) : The least abstract type of map investigated in this thesis is the *non-abstract map*. It displays all street representations as curved lines with up to two inflexion points. The simplest form of such representation is a line with constant or no curvature. In this way, the representations would be able to carry as much geometric resemblance with the represented streets as possible at this scale, see Figure 3.6.

The conceptual idea behind *schematisation of streets* is to speed up map-reading through smoothing out geometric details. In the non-abstract map type every line detail has to be detected, discriminated and potentially remembered. Although most of the detail is probably not be important for getting an overview of the environment, it will enter cognitive processing. Instead of learning those details and then discarding during cognition is prevented from entering cognitive processing from the beginning.

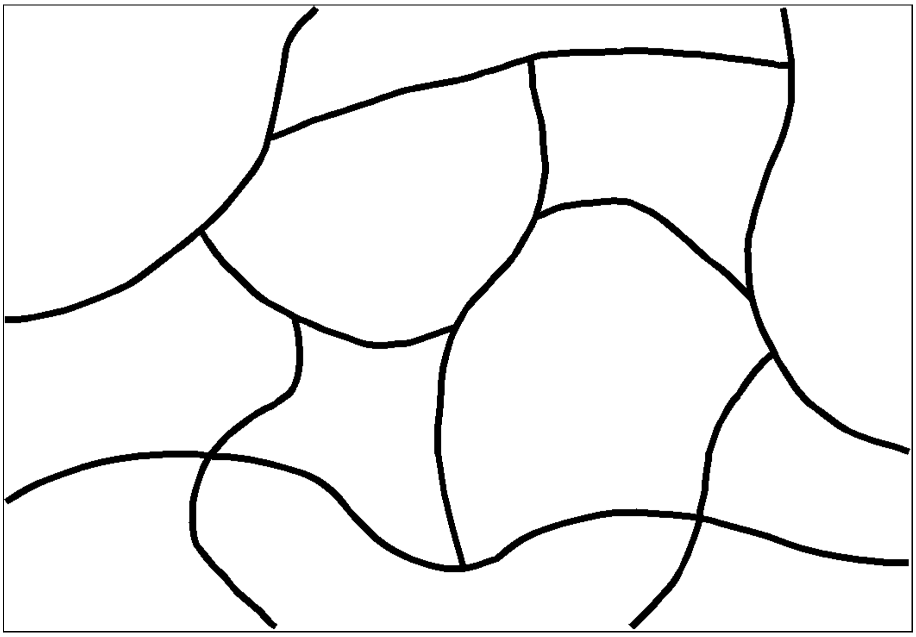

Figure 3.6.: Non-Abstract variant: The map represents the shape of streets displayed to scale.

Low-Abstract Map Type : In the *low-abstract map* lines representing streets are simplified. The original start point and end point are connected with a straight line. All street representations become straight lines and loose their distinct geometric characteristics. As a result, the intersections change positions slightly in comparison to the non-abstract variant, but they keep their relative positions on the streets, i.e. the relation of the length of street segments remains constant. For the procedure of how to abstract a non-abstract map to the low-abstract map see Appendix 8.3.7.3. The result is a representation of the base street network with different geometry, see Figure 3.7.

The idea behind *schematisation of intersections* is to speed up map-understanding. Instead of preserving the individual (geometric) characteristics, the conceptual . Without schematisation each geometry detail had to be read and to be integrated into the cognitive model. Although most of it would probably not be important for the spatial task. Instead of learning those details and then later discarding it is left out from the beginning.

High-Abstract Map Type : The most abstract type of map was the *high-abstract map*. As in the low-abstract map typw, it only contained straight street representations. Intersection are schematised to prototypical intersections that conform to a 8-sector model (see Figure 3.8 and Figure 3.9) such that all edges are realized in one of eight directions: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° (measured towards the up-direction in the map, i.e.

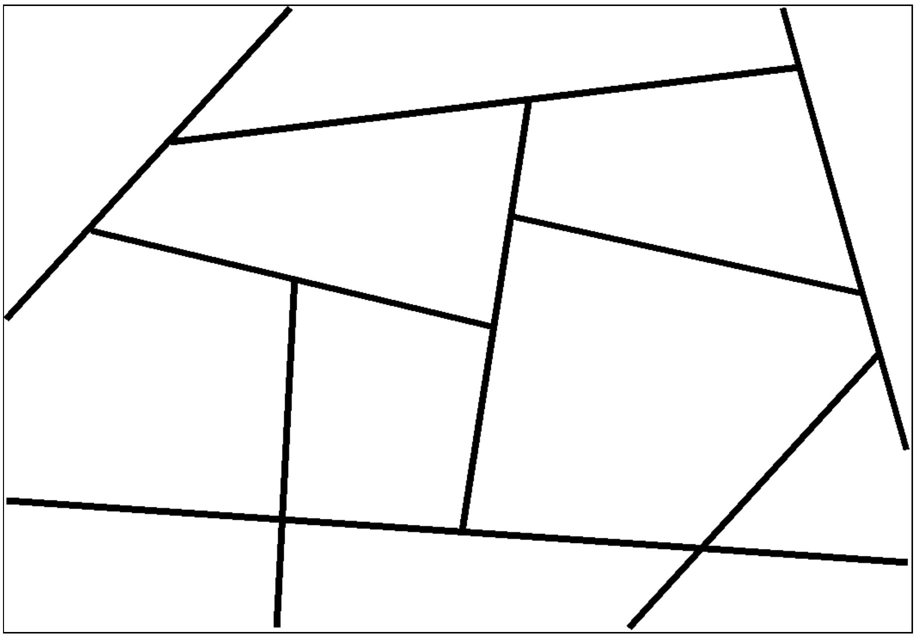

Figure 3.7.: Low-Abstract variant: The map only includes straight segments representing the streets in an low-abstract form, ignoring shape but preserving directions.

the vertical axis). For details why the displayed configurations represent all possible variations, see Appendix 8.3.7.3.

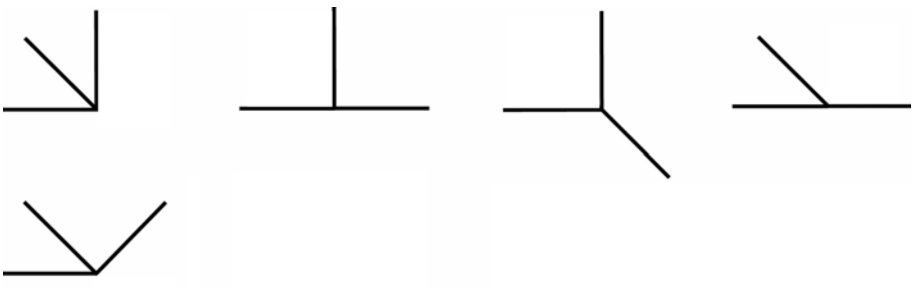

Figure 3.8.: All prototypical intersections of three streets according to the 8-sector model (variations by rotation and mirroring in the frame of the model not displayed).

In cartographic terms the results of schematisation came into place by exaggeration. When applying this schematisation, a change in the position of vertices follows (propagated from outside in), as can be noticed as difference between Figure 3.7 and Figure 3.10.

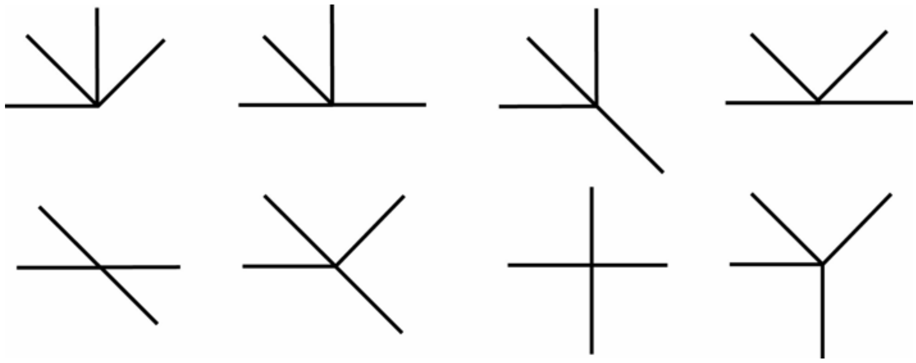

Figure 3.9.: All prototypical intersections of four streets according to the 8-sector model (variations by rotations of multiples in the frame of the model not displayed).

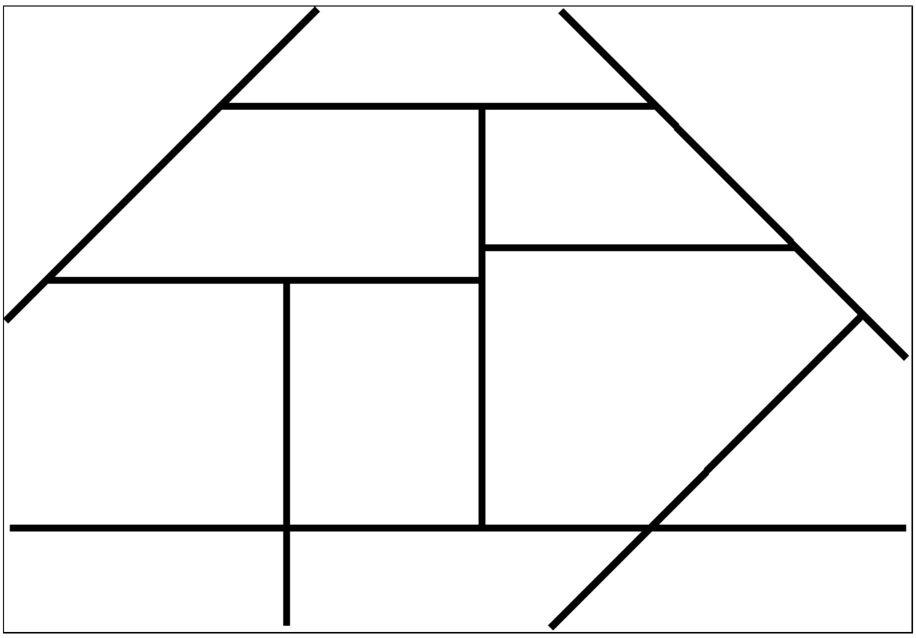

Figure 3.10.: High-Abstract variant: The map only includes straight segments and represents all intersections with their prototypical shapes (conforming to the 8-sector model) .

Such categorisation has occurred when people conceptualise routes (Casakin et al., 2000, Klippel, 2003, Klippel et al., 2005) and survey descriptions (Taylor & Tversky, 1992a, 1996). It enhances the communication of essential geographic concepts[10]. With this schematisation, the simplification that is most likely to happen during the mental process of conceptualisation is already introduced on the map. The cognitive effort that had to be invested in the conceptualisation can be used for further tasks.

The schematisation strategies for qualitative simplification presented so far could be promising adoption candidates for tactile orientation maps: As the use of metric information seems to be limited and people have a distorted perception of distances anyway, we might shorten segments, i.e. focus on topology. However, the cardinal directions and relations among spatial objects should be maintained. The approach allowing distortion on the map space while keeping the relations of streets intact in the map frame (see Show a stable frame of reference) was considered helpful. It ensures to contain the distortion within one map. Otherwise the distortion would be propagated to adjacent maps. Then no map can stand for itself without knowing from which of its neighbours distortion has been propagated. For this computational reason, the distortion of a single map must ideally be contained in that same map. In this thesis, this recommendation is realised by establishing static outbound streets, i.e. the presence of outbound streets (not the necessarily the position!) on each side of a map is maintained.

The discussion has shown that not only are there multiple constraint in the domain of hardcopy tactile maps but there is also potential for improved tactile orientation maps. This is in line with the findings of Ware et al. (2006). The following summary is based on Ware et al.'s list augmented by aspects discussed in this thesis.

Minimum Separation : Each entity must be spatially separated from any other entity so that it can be discriminated, i.e. displacement is introduced if necessary.

Unique Signatures : Each map entity must have a unique shape, texture or size to be detectable, discriminated against other entities, and recognisable.

Minimum Angle : Each angle between two lines must be bigger than the least perceivable angle to make it clearly distinguishable.

Topological Veridicality : The topology, i.e. the connectivity and containment relations should be prevailed.

Static Outbound Streets : The connections to off-map areas need to persist to ensure the transition from the schematised map to the adjacent one.

Simplified Intersections : The shape of intersections should conform to a simplified model that represents typical directions.

[10] In classical map-making, such a simplification would be said to be the result of some exaggeration operators.

Directional Relations : Directional relations between distant spatial objects should prevail to maintain the 'global' structure of the map as representation of the environment.

Orientation of Streets : The orientation of a street in a schematised map should mimic its original.

On the one hand, these constraints limit the schematisation that takes places constructing TOMs. But on the other hand they also open up opportunities for schematisation. For example, directions are not understood literally any more but must only fit into a range (one 45° sector). Constraints as such can adapt as long as certain limits are not crossed.

3.3. Summary

At the beginning of this chapter I introduced the concepts that have been used throughout this thesis. First, I built up a characterisation of tactile orientation maps and how they are used, namely for the spatial tasks of localisation and survey mapping.

Then, the schematisation concepts proposed by other authors were presented and investigated as to whether they could be applied in a context of tactile orientation maps to help performing the above mentioned tasks. I reasoned that some of the schematisation concepts proposed by others have the potential of being transferred to Tactile Orientation Maps. For example, the strategy to *Shorten Segments* does not need a decision (for example, at long segment of a street without intersection) and should be used in TOMs as the knowledge obtained from a map like this is qualitative and not metric. Then I proposed to employ additional schematisation strategies that promise to relieve map-reading but could inhibit:

Guides and Pointers : The search for tactile entities can be supported by guides and pointers. However, as these additional entities do not contribute to the information on the map they might be considered harmful for later exploration of the map.

Straightening Lines : Generalised, straight lines might be better to explore tactile maps as they reduce the amount of sensory information to be integrated. However, the (unique) shape of lines might provide information that is helpful for certain spatial strategies (like orientation).

Prototypical Intersections : Intersections that conform to a certain sector model might be easier to remember than those with arbitrary angles between two incoming tactile lines. However, the uniqueness of particular intersections might be lost and thus nullify their function as landmarks for orientation.

In the next part extending over three chapters, I will first investigate the quality and sensory basis of hardcopy tactile maps, and present interviews about the acceptance and usage of tactile orientation maps. Then, I will present some studies about how the proposed schematisation strategies Guide and Pointers, Straightening Line and Prototypical Intersections might be helpful in comprehending and using tactile orientation maps.

Part II.

Pilot Studies about the Schematisation of Tactile Maps

Chapter 4.

Technological Constraints and Usability Requirements of Hardcopy Tactile Maps

This chapter explores the technology and sensory basis for the construction of usable hardcopy tactile orientation maps. Given the technological constraints in producing hardcopy tactile maps and the sensory as well as cognitive challenges when reading the hardcopies, this chapter explores the usability requirements to enable successful map-usage. Especially, it will be investigated which factors influence the identification, discrimination, and recognition of objects in tactile maps produced with a matrix-based tactile printer.

4.1. Motivation & Research Questions

In a map it is crucial to have a contrast between foreground and background to be able to identify the important objects. In a visual map, the visual vocabulary (in cartography this is called "signature") is based on the properties size, brightness, pattern, colour, direction, and shape as 'fundamental' graphic variables (c.f. Bertin, 1974)[1]. For the tactile domain a set of unique and distinctive dimensions had to be found. But as described in chapter 2 not all tactile dimensions are equally well suited for production with tactile matrix printers. Motivated by those considerations the research question came up: Which are the key dimensions of tactile printing with discrete entities to display objects that can be discriminated? The questions extents to the aspect of how well two entities can be discriminated from each other and the aspect of how well one entity could be recognized such that a meaning can be attributed to it.

Another motivation for the research described in this chapter was to find out which properties constitutes a useful tactile orientation map for blind users. It should be explored how blind people acquaint themselves with some previously unknown environment today, in which way they want to use maps and which information should be represented such that they concern the map as usable. Speaking with some prospective users can be informative about the context of use of tactile orientation maps, such that the generation could be customized to the target population.

[1] Bertin's work about semiology was later extended by (MacEachren, 1995) to a total of 10 graphic variables (size, saturation, hue, brightness, orientation, pattern, direction, texture, focus, and location). Other authors proposed extensions and re-interpretations of Bertin's graphical variables, for example for maps on dynamic displays (Ellsiepen, 2005) or for an analysis of the complexity of maps (Buziek, 2001).

Taken together, the technology constraints, the sensory limits and the prospective context of use, one can learn about the requirements for tactile orientation maps. That can inform the further construction of usable tactile orientation maps with a technology that only produces discrete spatial representation. To get an idea whether blind and sighted people touch and interpret hardcopy tactile differently, candidates from both groups were invited to participate in the study.

4.2. The Readability of Tactile Hardcopies

The tactile printer ViewPlus Emprint SpotDot uses a fixed matrix of metallic rods to emboss small convex tactile elements into paper. The discrete nature and arrangement of the taxels in a fixed matrix is a stark contrast to the continuous nature of graphical entities found in traditional hand-made tactile maps. On the background of these considerations a small informal study should gain some insights into the sensory quality of discrete entities that should be interpreted as continuous objects. The quality of object discrimination and object recognition was investigated to find out how this printing technology could be used to communicate spatial arrangements of geometric objects. Specifically I set out to

1. determine key factors on how to realize continuous geometric objects with an tactile embosser that only can produce discrete points, specifically
   a) which line width in the graphical master was translated to which tactual line width in the hardcopies,
   b) how oblique lines that do not coincide with the strict matrix arrangement of the tactile embosser are tactually rendered and perceived by the human reader,
   c) which designs of lines can be easily distinguished tactually (e.g. lines of different width, broken lines with differently sized gaps),
2. investigate the differences in sensation and cognition of combinations of tactile entities with respect to the
   a) Relative position,
   b) Orientation,
   c) Distance,
   d) Surface texture.

In tactile maps there is often the need to highlight some object to make it salient for the map user. As part of the study it was investigated what are feasible designs for tactile symbols (an optimal design was regarded being of secondary interest as it depends on many contextual factors). For feasibility, two criteria were important: high discrimination and high recognition. Discrimination is to tell that one symbol is different to other symbols. Recognition is to be able to tell which symbol is touched. The influence of orientation on discrimination and recognition was questioned as part of this thesis.

4.2.1. Participants & Procedure

The participants were 2 late-blind persons and 6 sighted person, 3 males and 5 females. Both blind participants had no training in reading tactile maps albeit both had limited contact with some before. None of the sighted participants had been in contact with tactile materials before. According to a self-rating by each participant, the Knowledge of map concepts was ″good“.

The materials for the test were different sample pages showing variations of single objects (symbols, lines, shapes) or variations of combinations of two geometric objects (line-to-line, line-to-shape, shape-to-shape), two of them are displayed in Figure 4.1. All materials can be found in Appendix 8.3.7.3. In the case of single objects, variations were along three dimensions: orientation of the object (horizontol/vertical vs. diagonal), size of the object (1 cm, 3 cm, 5 cm in diameter), and surface texture (full elevation vs. medium elevation). In case of combinations of two objects there was no variation of the size. All test materials were produced with the ViewPlus Emprint SpotDot with 200 g/m^2 inkjet paper, because it has a very smooth surface.

Participants were asked to explore the different sheets in the order of increasing complexity. First, symbols and lines were explored, then single shapes, then combinations of two geometric objects (order as mentioned above). It was explained to the participants how many objects each sheet contains and how the objects were distributed over the sheet. The sheets were instructed to be read from top left to bottom right. Each participant was asked to discriminate between objects or to recognize objects. Think aloud was motivated such that the observer would know which objects were hard to read and why. Time was not kept. No ranking was asked but the identification of a favourite variation for symbols, lines, and two geometric objects.

4.2.2. Results

Findings from the interaction of test-subjects with the hardcopy tactual material[2]:

[2] As this was a qualitative investigation and because the number of subjects was too limited no quantitative measures were taken. As descriptive or inferential statistics on such a small sample would only give false impressions, they are omitted here.

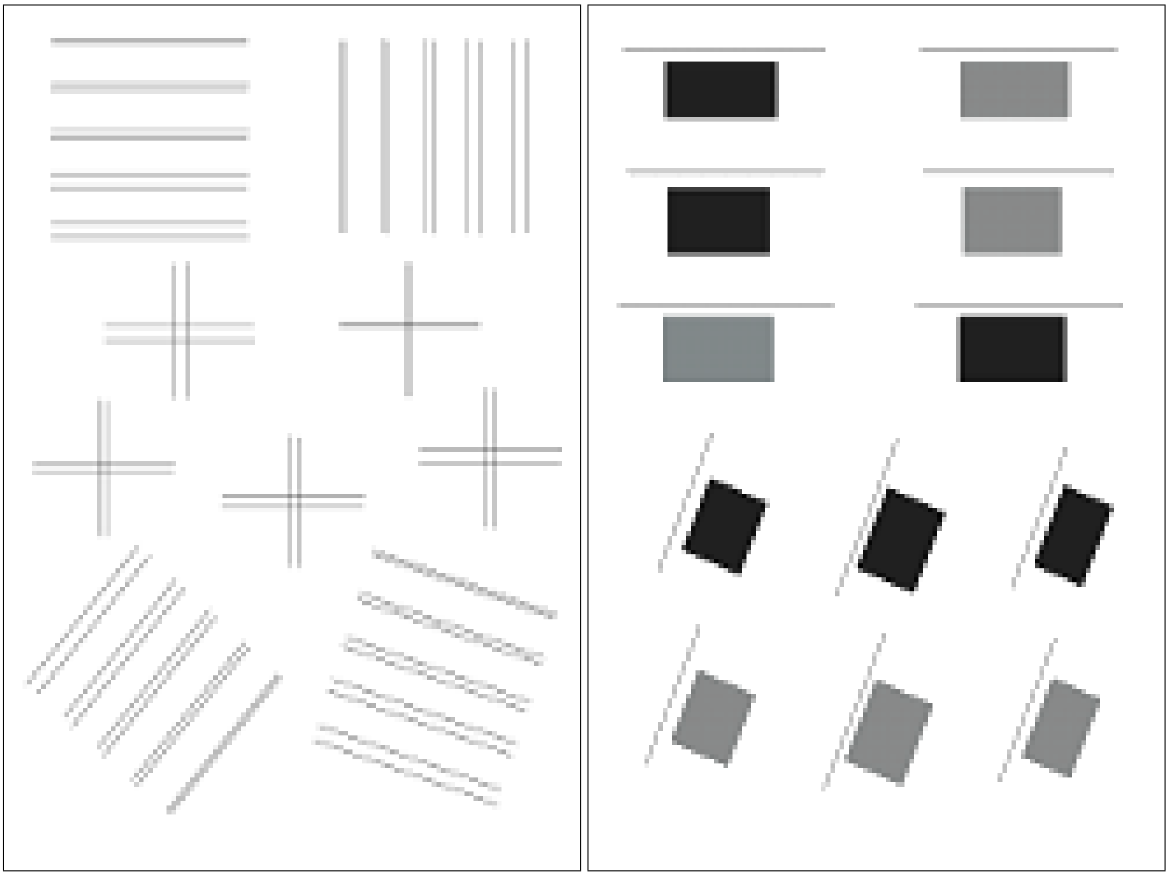

Figure 4.1.: Two selected sheets of paper with geometric objects to test the minimum discrimination distance, i.e. at what distance from each other two geometric objects can be discriminated depending on the type of relation (line-to-line versus line-to-shape), the orientation (vertical/horizontal versus diagonal) and the surface texture (full elevation [black] versus medium elevation [grey]).

- Textures, lines and symbols were reported to be clearly distinguishable tactually both by blind-folded sighted and by visually impaired persons when presented with maximum embossing elevation.
- The 7 possible embossing elevations could not be discriminated. Only some combinations (1.2mm vs. 0.7mm vs. 0.3mm) could be told apart, most prominently in textured areas. All the blind participants were confident in their judgement, but half of the blind-folded sighted participants were not. They preferred to have only two levels in the map: 1.2mm and 0.7mm.
- When printing corners, especially sharp corners of objects, the last taxels in the corner was not printed such that the participants got the feeling as if those corners were round, not sharp. Those artefacts could not be foreseen before printing. They are not deterministic and grounded in the algorithms implemented in the closed-source device driver of the Emprint printer.
- **Tactile Symbols**
  - Simple symbols with few details (square, cross, triangle) were faster to discriminate than complex symbols, for example combinations of simple shapes with other shapes as fillings. Simple symbols were described as being easier to remember than the more complex ones.
  - Rotated symbols that were introduced with an orientation other than in the legend were hard to recognized by the participants. They needed a lot of time to recognize the symbols compared to other symbols that kept their orientation. Blind participants did not have that problem so much but needed longer in the non-aligned cases.
  - Small symbols (9mm in diameter, i.e. 7 taxels) were read faster and participants liked them for being handy, but at the same time it was harder for them to discriminate between the symbols, let alone to recognize them. Simple symbols at size of 1.1 cm (9 taxel) were found to have a good discrimination and recognition rate, complex symbols with a diameter of 1.4 cm and 1.7 cm (equals 11 taxels respectively 13 taxels).
  - Filled symbols could not be recognized as good as symbols built from outlines, i.e. no filling.
  - The participants could not correctly tell the filled circle apart from a filled square when the print size was less than 1.7cm respectively 13 taxels (measured as diameter of the symbol).
  - A proposed You-Are-Here symbol to support self-localisation had the form of an abstract arrow (indicating the heading of the map-user) combined with a stop

sign. It was regarded as easily distinguishable and recognizable by both the visually impaired test subjects and the blindfolded test subjects.

- **Tactile Lines**
  - Lines that only differ in width (1 taxel vs. 2 taxel) could hardly be discriminated, especially not if they were oblique AND anti-aliased. 1 taxel lines and 3 taxel lines could be discriminated clearly, regardless of being straight, curvy, anti-aliased, or in whatever orientation on the paper.
  - For short lines (less than 2cm) participants could not recognize, whether they where straight or curvy.
  - Oblique lines that were designed to be of the same thickness as horizontal or vertical lines appeared to be wider than the horizontal and vertical counterparts. This effect was stronger with anti-aliased lines but did persist (albeit not as strong) with not anti-aliased lines. The test persons regarded that fact more apparent for 1 taxel lines than for 3 taxel lines.
  - Lines of 1 taxel width were regarded most appropriate to display vertical and horizontal straight lines, especially when line crossings were to be displayed. Test persons uni-vocally reported that wider lines made it harder to distinguish how many lines meet in one intersection.
  - Among several proposals for different line types to complement the continuous line the broken line with 1 taxel width and regular pattern of 4 taxels segments and 4 taxels gap between segments was regarded easiest one to sense and to recognize.
  - Minimum separation between two lines to be clearly distinguishable was 2 taxels in the vertical/horizontal case, 3 taxels in the oblique case.
  - Intersections of lines with 1 taxel or 3 taxels (regardless whether straight, curvy, oblique) could be recognized without problems.
  - Change in direction of a straight line were almost not interpreted as such. A great majority of the participants noticed a change but interpreted it as curvy line, not as change of direction of an perfectly straight line. Only one out of four participants attributed the change correctly.
- **Tactile Textures**
  - Surface elevation was not an easy-to-use discriminator between textures and the represented objects. Most blind-folded participants did not notice any difference between texturesy of maximum elevation and textures of 50% or 30% elevation. The blind participants noticed elevation differences right away.

- Textured areas could not be recognized as well as areas with an outline, i.e. border only and no texture.
- Areas with an outline could be told apart regardless of their rotation if the outline was 1 taxel or 3 taxels.
- The differences between outline and filling of some object and the nature of the filling was best sensed when there was a separation between outline and filling. With 3 taxels separation, outline and filling could be differentiated regardless of the orientation of the object.
- Textures that differ by only 1 grade of elevation could not be discriminated (i.e. the participants felt no difference between grade 7 and grade 6 or 5 and 4, for example). But elevation grade 7, 6, and 5 were regarded as more similar than 4, 3, and 2. Grade 1 could not be told apart from grade 0 (plain paper).
- Neighbouring textures that shared a common edge and had the same surface structure but are with different elevation could hardly be discriminated by the participants. With some gap along the edges the existence of the two areas and their different surface elevation became clear.

• **Combinations of Tactile Entities**

- The combination of a straight line and a straight contour (e.g. a filled rectangle) afforded a separation of 2 taxels. The separation must be increased to 3 taxels if objects had oblique straight or curvy edges.
- Symbols that were more than 3 taxels apart from a line or a contour were often described as hard to find as they were often not touched when following the line/contour. When placing a symbol beside a line/contour it was regarded as helpful when there is some parallelism between the two objects such that the chance to feel the symbol is given in a greater segment of the line, not only at one particular position.
- Small symbols (under 10 taxels diameter) were harder to sense tactually when placed beside a thick line (from 3 taxels width) and having the recommended gap for discrimination (2 taxels). More prominent, bigger symbols do not suffer from that effect of neglect.

4.2.3. Summary about The Readability of Tactile Hardcopies

The readability of tactile hardcopies made with the ViewPlus Tiger technology was found to depend on several parameters. The tests showed that the discrimination and recognition of objects is influence by

1. the shape of objects shown beside each others,

2. the distance between objects (more precisely: the distance between their edges),
3. the orientation of the edges with respect to the horizontal and vertical axis of the base material,
4. the width of lines or edges, and
5. the surface of objects (texture and elevation).

Recommendations drawn from the observations and interviews in the pilot study for other studies with tactile maps produced with a ViewPlus Emprint embosser are listed here[3]:

1. It is better to use horizontal and vertical straight lines as oblique lines are anti-aliased if printed such that they appear to be wider than they are meant to be.
2. Use 1 taxel (1.27mm) lines to display some line-like graphical entities. For a 1 taxel line, a 2 pt (0.7mm) graphical entity should be used in the graphics that is later printed.
3. To set apart lines by their line width, use a 2pt (0.7mm) graphical entity versus a 10pt (3.5mm) graphical entity in the drawing. That will result in a 1 taxel to 3 taxel line when printed and can be easily discriminated.
4. To set apart lines types use broken lines versus continuous lines. Broken lines should be drawn in 2pt (0.7mm) width with segments of 23pt (8.1mm) length and a spacing of the same length. Such drawing will produce an evenly broken 1 taxel line with 8.1 mm spacing between segments of 8.1 mm length.
5. The minimum distance between tactile entities in the hardcopy should be at least 3 taxels (3.8mm). If area textures are produced by stripes there should be gaps of 4 taxels (5mm).
6. Area texture is not a good coding dimension. Only use it with care to differentiate between objects.
7. Only use non-rotated symbols (i.e. use symbols as introduced in the legend of the map).
8. The proposed symbols for signifying landmarks are distinguishable and could be used as representing salient entities in tactile maps.

[3]It is assumed that the input is a black and white line graph that was constructed with some graphics software. The dimensions used in such graphics software for specifying the width of some line is usually point ('pt'), that is 0.3527mm. For describing the qualities of a tactile output the width (in taxels) and the elevation (in embossing levels) of the resulting tactile object is given. One taxel is 1.27mm wide. The elevation of taxels in the hardcopy is directly connected to the brightness of the graphical entity. There are 7 levels, i.e. each level equals 14% of brightness in the graphic and 0.2mm of elevation in the hardcopy. 100% black in the graphics means 100% tactile elevation (1.2mm high) in the hardcopy. All figures given in the list are rounded to multiples of 0.1mm.

9. Symbols should always be printed with maximal elevation.

10. Only two clearly separable elevation levels should be used with lines and textured areas (level 4 and level 7, respectively 0.7mm and 1.2mm).

11. If three elevations should be used with areas, then use the level 2, 4, and 7 (0.3mm, 0.7mm, 1.2mm). The existence of level 2 should be specifically introduced to the users. Otherwise it will most probably not be realized because the difference to plain paper (equals level 0) is very subtle.

12. The coding dimension of elevation should not be used with symbols as the differences are to gradual. It is better to print all symbols with maximum elevation.

13. For tactile objects that have only horizontal or vertical edges a gap of 2 taxels (2.5mm) is enough to clearly set them apart from other objects. To achieve this they should be 17pt (6mm) apart from each other in the graphics.

14. Textured areas must differ by 2 or more grades. A set of elevation levels that was discriminated quite well was 2, 4, and 7 (0.3mm, 0.7mm, 1.2mm).

15. Neighbouring textured objects should be modelled with a gap of 17pt (6mm) between them (this would equal to 2–3 taxels (2.5–3.8mm) of separation in the hardcopy tactile map).

These findings and recommendations can serve as a basis for the other studies such that test materials are properly prepared. That should reduce the probability of having poor results with hardcopy tactile maps because of tactile features that can be poorly discriminated.

Much of the implicit limitations found in these recommendation relates to the specific technology used, the embosser. For instance, on fixed maps made of plastic or metal, texture is frequently used to indicate elements like water, grass, etc. Texture is quite salient in those maps. Thus the findings reported here are limited to tactile material embossed with the ViewPlus Emprint Spot Dot or the like. The findings relate to this one source of tactile output. If these recommendations should be applied to embossers with different hammers (e.g., embossing heads) the transfer might not be directly possible as the taxels would be of different diameter, spacing, and height. For instance, if embossed on a normal Braille printer that does graphics (such as the Index Braille), the taxels are 2.2mm high, no nuances in elevation is possible, and the dot base is wider. Then all the recommendations for gradation of textures and minimum distances between graphical entities to result in separable tactile objects would be obsolete. Quite clearly, these guidelines would not hold for the vibro-tactile lines displays on touchscreens.

4.3. The Context of Use of Hardcopy Tactile Maps

In times of GPS-driven navigation systems it might seem an odd idea to confront prospective travellers with hardcopy tactile maps. Therefore one interest was to find out how blind people cope with the challenge of getting to know new environments, which strategies they usually employ and how these strategies could be supported. I was interested to know whether people would welcome the idea of providing a survey map as preparation aid for later navigation in formerly unknown areas. If so, a next question was whether simple tactile maps, that only show streets and major landmarks, would be sufficient to acquire a survey view. Which geographic objects should be represented in such maps to allow for (self-) localisation and navigation? What contextual and individual parameters must be regarded to gain a high acceptance and to satisfy the prospective users? Group interviews about these questions were conducted.

4.3.1. Participants & Procedure

Two groups of three people each were recruited through the *Blinden- und Sehbehindertenverband Hamburg* (BSVH). All participants were legally blind by the regulations in Germany (less than 5% vision) and between 27 and 60 years of age. Two participants were blind from birth (i.e. congenitally blind), one in each group. Another two participants (one in each group) had no vision at all, but initially had some before the loss of eyesight later in life (i.e. late-blind or adventitiously blind). All six participants self-reported as being mobile and having a fairly good orientation. This self-assessment was not tested or verified. All participants used some tools for mobility support, be it the white cane or/and some electronic guidance system. The late-blind participants knew map concepts from the times before they lost their sight. And the congenitally blind were introduced to tactile maps and their concepts in school. No participant had actively used tactile maps of any kind before. One reason for that might have been that traditional tactile maps use Braille to convey some meaning. But only one blind participant felt competent enough to read Braille fluently. All other participants had not learnt it at all or felt not competent enough to read it.

The interviews were conducted as semi-structured group interviews in the year 2012. Two different but similar sets of questions were used, both can be found in the Appendix. Included were questions about the individual mobility, the experience with navigation and with maps, the individual need for navigation support, especially for wayfinding, strategies for wayfinding especially in unknown areas, and expectations towards and requirements for hardcopy tactile orientation maps. To have an idea about hardcopy TOMs each participant got the chance to experience one that was embedded in a usage-scenario (told to them by the author). The narratives were recorded (all participants gave their consent), condensed into a written form, and similar answers grouped. They are reported here in the condensed and grouped form.

4.3.2. Group Interview A

The participants characterised their approach to pre-trip planning as being allocentric and focused on distal, abstract information. The information they needed was described as being abstract and rather coarse. To serve that need, the most important landmarks should be highlighted. The participants reported that during the preparation phase their mental representation of the environment was often structured based on allocentric directions (which landmarks were in the north, south, west, or east). They would like to be supported with information that they could easily integrate into their existing mental representation. Contrasting this was the information need in the execution phase. During locomotion in the environment, orientation was described as being egocentric and focused on local information. The information they reported to need was detailed and rather fine-grained, for example, focused on some local details such as the position of traffic lights at some intersection.

When concerning what to display in a tactile orientation map for pre-trip planning the participants pointed out that it was important whether blind pedestrians already know the environment in question and how well they knew it beforehand. If one assumes that someone was completely new to an environment then it might not be a good idea to fill the map with too much detail. Then the existence of tactile walking indicators and the characteristics of the ground should possibly not be displayed as they could overwhelm the map reader. It would just be too much tactile clutter. Such information could be added for later versions of the same map used by blind pedestrians that have already experienced that environment in reality. Such maps could be tools for fostering the learning process by reminding about local details. Such details help to recognise a formerly travelled environment during repeated locomotion. For first-time travellers the participants regarded such information as less important. The participants agreed that in the preparation phase information about ground properties such as inclination or surface texture (e.g., gravel vs. tar), and information about groove plates and attention fields do not provide substantial help to blind pedestrians. They expressed the wish to be supported in building up an abstract, rather coarse mental model of the environment. Clearly, these participants preferred information about the global structure beforehand.

When discussing the types of spatial concepts that should be represented in a tactile orientation map to build up that coarse cognitive map of the environment, these concepts were named (in the order or appearance).

1. Cardinal directions were named first. Using cardinal directions in learning the position of some spatial entity (for example, a landmark) in relation to the displayed area gives the opportunity to roughly know the layout of the environment when being situated in the environment.

2. The spatial concept of ″nearness“ was often used to help describing some spatial position of an object related to some other object. There was no common ground to what extend ″nearness“ can be understood as direction-dependent or direction-independent, as property of the representation space (i.e. the map) or as property of the represented space (i.e. the geographic environment), for example as a certain distance between map entities, respectively geographic entities. Factors such as density of the geographic entities were not mentioned.

3. Common ground was on the ranking of landmark types concerning their importance in a tactile orientation map: point-like landmarks were regarded as most important, line-like landmarks second and area-like landmarks least important. The ranking of landmark types seemed to reflect the distinctiveness with that each landmark type can support navigation in space. The participants regarded point-like landmarks very distinctive concerning their positions in space. But the qualification always depended on scale. For example, the Barcaccia fountain is unique among the more than 2500 fountains in Rome and marks a very distinct spot at the lower end of the Spanish Stairway. On a tactile tourist map of Rome it would be a good idea to mark the position of that well-known landmark. In the same way, the Berlin Wall stretching over more than 100km between the former West-Berlin and East Germany can be considered a line-like landmark when displayed in a historic map of Berlin. But the representation of the city of Berlin could be considered an area-like landmark if the map was showing whole Germany or Europe.

4. Setting a constant scale of a tactile map that allows estimating real-world distances was considered less important than being exact in topology. The participants equivocally reported that self-location in the environment by monitoring the passed streets during locomotion was very common and monitoring the distance travelled by counting his steps was rather uncommon. The latter was reported to only be used in environments visited regularly to make frequent re-orientation obsolete and thus increase travelling speed. Thus metric distances could be regarded as less important in tactile orientation maps than topological veridicality.

5. For controlling the locomotion in some environment, the acoustic properties of the space were considered important. When walking through an environment, the unique acoustic characteristics of obstacles and the acoustic differentiation between the (noisy) traffic side of the side-walk and the (calmer) other side is important. The constant car travel along sideways for pedestrian constitutes what mobility trainers call an ′outer acoustic guiding line′. From mobility training or from their own experience the participants knew that it was best to orient towards walls of houses, fences etc., the so called inner acoustic guiding line. First, it is save to walk in some distance to cars. Features

such as walls and fences that can be sensed with the cane are welcomed in such situations. Second, the inner acoustic guiding line is better suited for self-localisation than an unsteady flow of cars that bears no uniqueness. In contrast to the unspecific noise of cars, stationary features like walls have certain sound characteristics. Those local characteristics can be recognised during locomotion and thus can function as landmarks that support self-localisation. The participants reported that for their orientation in an unknown environment, it would be helpful to know what acoustic characteristics to expect along a potential walkway, especially at the inner guiding line. Changes of echo cues were regarded as especially important as they allow estimating how far someone has already progressed. To benefit in this way the traveller must have learnt the sound characteristics to be expected beforehand. The reason for changes in the echo could be manifold. For example, it could be a wall, a drive-way, another street intersecting, or simply an interruption in the formerly close walls of houses because a building has been but further away from the street. This information was regarded as especially important to identify the parts along streets between intersections. This finding shows how important echo location is for blind travel, in fact some blind individuals have mastered this art to perfection and, for example, can mountain bike [4].

6. The participants reported that the sound characteristics of acoustic guiding lines are less important at intersections because traffic was usually louder. The subtle echoes from static environmental features such as walls are masked in the presence of dynamic noise made by the moving cars and bulks of pedestrians. The attention switches from tracking the echoes to directly accessible guides, for example aids perceivable like attention fields and signalling traffic lights. The participants argued that these aids should not be displayed in a map as they can be detected during locomotion when approaching an intersection. Nevertheless knowing about their existence was judged to be an advantage for tour planning. But constrained by limited space in the map they were considered as being of minor importance. Aside from those detectable aids, it was considered important to know about undetectable aids. For example, at a pedestrian crossing it is usually not clear to the participants whether there was an island in the middle of the street where pedestrians could stop to be save from traffic. The existence of such islands cannot be known at planning time except when being shown on a map. As those save crossings are currently not hinted for in the geographical environment, notifying about them in some way becomes even more important. The participants opted for inclusion of safe crossings in orientation maps because such crossings are more likely to be chosen when a safe route has to be found.

[4] Finkel, M. (2011). The Blind Man Who Taught Himself to See. The Magazine, March 2011. `http://www.mensjournal.com/magazine/the-blind-man-who-taught-himself-to-see-20120504`, accessed March 3, 2013.

7. During the interviews the participants equivocally expressed their opinion that long streets that bend significantly (albeit there was no common ground about what qualifies for a 'significant bend') should not be displayed as straight objects, because the map would represent a model of reality that can hardly be matched with the experience when walking that part of reality. This would be especially true if the direction in which an intersection was approached differs significantly between the map and the reality.

8. The interviewees regarded some spatial information as potentially misleading. The names or type of shops could change often and is not as persistent as navigators need to rely on it.

9. Aside from the information in the map information of the general context should be given, for example, whether the map shows a rather flat or rather hilly area, whether the depicted urban environment was a small town or a big city.

For being successful in navigating an unknown area, the participants expressed their information needs with a ranking:

1. Intersections, places and adjacent streets
2. salient landmarks (central buildings, sights, transportation hubs)
3. cardinal directions
4. distances

When asked for object representations that should be present in a tactile survey map the participants equivocally voted for streets and walkways as being the most important information. Valued second most important were natural, static features of the environment such as parks and water bodies. Monuments and salient, persistent landmarks were ranked third. Some suggestions were railway stations, churches, and the mayor's house. Last were crossings and traffic lights with auditory signals.

Integrating both rankings, distance and cardinal directions were of lower importance for the participants compared to landmarks and streets when it comes to displaying spatial concepts in a tactile orientation map. Cardinal directions might have been ranked low because often maps have a preferred reader orientation in which the 'up'-direction is equivalent to North. Features that mainly support safe locomotion in the terrain were regarded to be of minor importance[5].

[5]This might be surprising in the light of orientation and mobility experiences. Instead of piloting with the maps through an actual environment, the maps were used in an off-line mode. Therefore the maps are not needed to support real-time navigation. The rankings might differ if the map was used in an online mode.

From the interviews the following information resulted as being helpful for inclusion in tactile orientation maps for giving an overview of some unknown environment:

1. Distinct, persistent locations that could be asked for, for example important or historical buildings, monuments, churches, fountains, bridges, sightseeing spots, stations, stops for public transport
2. Squares, major roads and side streets, pedestrian pathways and intersections
3. Open areas that can be sensed by sound or by smell, for example parks or soccer fields, and water bodies such as streams or lakes
4. Labelling distances if the map was not metric or if scale varies in the map
5. Cardinal directions to get a feeling of the positions of landmarks

4.3.3. Group Interview B

The experience to navigate an unknown environment was equivocally described as sometimes unpleasant by the participants. They do not like to repetitively need to ask about where they are or what type of shop is in front of them when they search for one specific shop. It was described as especially problematic when they believe to know how the environment is structured but the environment has changed, e.g. shops have moved. Often that is not known beforehand and the people are puzzled by the change. One participant described how she got lost in a re-designed mall. After that experience she had never visited that mall again.

When asked how they usually get to know a previously unknown environment most of them reported that they did not particularly prepare for travels to unknown place (if they had ever done that) because no options were available. What they did is preparation for the travels to the area, i.e. which public transportation to use and how to find the right station and platform. If they knew someone familiar with their destination area, friends could give some clues to easy navigation. When being there, blind people were commonly forced to ask other people for what was around and for the right way. But often, either nobody was available or in reach, or people did not know, or the blind navigators did not want to ask. The opportunity to rely on pedestrian navigation systems for blind people was regarded as sub-optimal as such GPS-driven systems do not work everywhere, are only as good as their digital map data, need to be learned to be operated correctly, and are expensive[6]. Some blind participants pointed out that they like to interact with people rather than with technology

[6] This opinion was counterweighted by one participant from another interview who reported to use one such system without problems. By some, pedestrian navigation systems for the blind are regarded as one of the most successful navigation aids for accessibility in the past decade (Nicholas A. Giudice, personal communication, 2013).

or do not want to rely solely on technology. It was pointed out, that blind people are often elderly persons who do not easily accept technology. Therefore and in the light of the mentioned weak points "one has to think about whether it is really worth the money" (as participant FL but it in one interview) before buying such a specialised pedestrian navigation system.

As an alternative to navigation systems the concept of hardcopy tactile orientation maps to get to know a previously unknown environment was welcomed. It was seen as opportunity that might help to prevent break-downs like described in the first paragraph. They would be used as support for pre-trip planning, for orientation and re-consultation once being on tour. It was expressed as being important for acceptance of the tactile orientation maps that they could be produced individually on demand, disseminated quickly and would not cost much. The participants reasoned about acceptance gains if the tactile orientation maps were easy to read and to understand, i.e. usable. In this regard one important requirement was expressed: the TOM must not be cluttered, otherwise the participants asked themselves how they should remember what they read from such a map. To ease memorizing symbols should be iconic , i.e. should resemble the characteristics of what it represented. For example, the symbol for a church (that usually has some bells that can be heard from far away and therefore is a good acoustic landmark for blind people) should be a standing, tall, arrow-head like entity that could be said to resemble the bell tower. Such tactile iconographic symbols would be better than symbols that are introduced by pure agreement, i.e. conventions[7].

About the entities that should be displayed there was large agreement that representation depends on the individual needs for the map, i.e. for a shopping trip it might be important to have all shoe shops represented, for a leisure walk restaurants, coffee shops with waiter-service and where to enter the parks would be more important, and for a day in public museums the locations of museums and their entrances would be of interest. What was expressed as requirement for each type of TOM was that the maps must display side-walks and must not be too big in size. If displayed to scale, the map could be used to estimate distances and walking times.

The participants expressed their willingness and tendency to use tactile orientation maps as they were regarded as a help for getting to know some areas and for wayfinding purposes. Such tactile maps could serve as a memory aid even for areas that had been already travelled, for example to update about changes in the placement of stops for public transportation or of new shops in a shopping street. The opportunity to produce such maps for individual needs was stressed as a very important factor, for example, that it should be possible to get an up-to-date TOM of new city districts, like the Neue Hafencity in Hamburg. The participants estimated that they are likely to invest a fair amount of time to learn a tactile orientation

[7] Iconography may also add a lot of space for these elements on the map. In the end, there is likely a trade-off between space requirements and memorability here.

map. All agreed that half an hour exploration would be okay, but that one hour is too much. A learning effect was assumed such that more tactile usage would result in less exploration time in the long run. All participants agreed that they would consult such maps again if they saw that it helps in getting around. They welcomed the idea of having more than one map displaying the same environment but different aspects of it, for example different kind of landmarks (for example, public services, transportation, shopping). On the background of the general lack of availability, some indoor usage was motivated in which generated tactile maps could offer advantages for blind navigators, for example, tactile plans of the transportation system, floor-plans for big buildings (like train stations) where especially non-visual orientation was difficult.

Potential users of tactile orientation map regarded the maps as a benefit for the mobility of blind people. With such maps the preparation for a visit should be possible. Prospective visitors could be acquainted with or updated about the un-known or not well-known spatial environment. The quick production of TOMs was regarded as the main advantage in contrast to traditional tactile maps. The participants highly welcomed the concept of tactile orientation maps that could be produced individually and would represent up-to-date, customized geographic knowledge. The map-users estimated their willingness to invest a fair amount of exploration time in such TOMs as long as they felt that it provides an advantage to them.

4.4. Discussion about the Requirements and Recommendations for Computer-generated Tactile Orientation Maps

On the one hand, the usefulness of a tactile orientation map was related to the amount of information in the map. On the other hand, interaction with the map should satisfy the user, for example the map should not be cluttered but clearly communicate its meaning. The tactile vocabulary should not be set by convention that have evolved over time but should be scientifically backed. For example, tactile iconographic symbols that resemble some basic characteristics of the represented geographic entity would be better than arbitrary symbols that are introduced by conventions. Conventional symbols have to be learned and remembered. Iconographic symbols reduced the cognitive load on the human memory system as the meaning of the symbol is cued by its shape. Another aspect is that the meaning of the tactile vocabulary between maps should stay the same, such that the repeated learning of new symbol sets and their meaning is avoided.

For traditional tactile maps some symbols were proposed (Lambert & Lederman, 1989, Lawrence & Lobben, 2011, Rowell & Ungar, 2003a,b), some general guidelines given (Blasch et al., 1997, Wiedel, 1983), and even some conventions were agreed on[8]. Both iconographic

[8]Only single institutions adhere to standardised symbols sets but there is no national standard, at least not in

symbols and a persistent tactile vocabulary for hardcopy TOMs are factors to facilitate the usability of TOMs.

4.5. Summary

From the studies one could learn that there are at least two sources of requirements that must be concerned when aiming for the production of hardcopy tactile maps: A) the prospective context-of-use including task, user and the support tool, i.e. the tactile map; and B) the technology that is used to print the tactile map.

With respect to the prospective context of use it was found out in an interview with 6 potential map-users that these blind, mobile people welcomed the opportunity of learning about some unknown environment from a tactile orientation map. They gave insight into their style of navigation, which information they need from a map to navigate a previously unknown environment, and which properties of such maps are beneficial. For example, tactile iconographic symbols would be better than symbols that are introduced by conventions.

With respect to the technology used for printing the tactile maps it could be learned through a series of tests that many parameters of construction and printing influence the result. The interaction of some of these parameters were not always deterministic, most notably the automatic anti-aliasing that is activated by the driver when printing through the API. Anti-aliasing of oblique lines makes identifying line width difficult, such that when simplifying maps this has to be taken into account. Other parameters that need to be adjusted are the separation between objects and the texture of areas and symbols such that the map-user can easily discriminate them. All these adjustments could increase the usability of tactile materials produced with the ViewPlus Emprint.

The studies in this chapter showed the technological constraints in producing tactile maps and the sensory challenges in reading the hardcopy tactile maps. It informed the further construction of usable tactile orientation maps with a technology that produces discrete spatial representations.

Germany (personal communication with Mr. Beyer-Killisch, Director of TOUCH, a manufacturer of tactile maps in Hamburg, Germany).

Chapter 5.

Support of Schematisation Strategies for Better Map Understanding

This chapter provides insights whether two types of schematisation in TOMs can help in decreasing cognitive complexity while save-guarding the usability of the maps for the reader: 1) straightening segments between vertices and 2) moving vertices such that any two adjacent segments only coincide in predefined angles. It is discussed how both types of schematisation approaches contribute to the usability of tactile orientation maps. The chapter ends with proposing and discussing other types of schematisation, how they could decrease the cognitive demand when reading TOMs and what recommendations can be drawn from the findings.

5.1. Motivation & Research Question

When humans learn an environment (be it from a map or through environmental learning) they do not remember all the spatial information they need when it comes to make decisions (for example, which directions do I need to go to get to the elephants). Mental representations of spatial environments usually only hold a fraction of the perceptual information originally available to build that mental representation, see subsection 2.1.2. When recalling this knowledge from memory to execute some spatial task, the representation humans reconstruct usually only hold certain aspects of the original and other aspects are left out. The spatial information reconstructed is *simplified*, i.e. some details are missing and the whole might even be inconsistent. This can be assumed to be true regardless of the mode of knowledge acquisition, i.e. whether someone wandered that geographic environment (i.e. in-situ, direct environmental learning) or whether someone explored some map of that environment (i.e. ex-situ, mediated learning from a representation), see subsection 2.1.2.

I will investigate a) approaches to the schematisation of tactile orientation maps and b) whether it could be an advantage to do schematise TOMs in order to reduce cognitive demand during map-reading without loosing essential information. It is investigated whether schematisation of tactile orientation maps, i.e. the simplification along cartographic variables on the background of cognitive motivation and beyond pure cartographic needs, holds any cognitive advantage.

The motivation behind the approach is that instead of letting the user cognitively simplify the map at reading time, i.e. forming a cognitive map from the sensory input, the tactile map is schematised at the time of construction according to human-inspired cognitive principles. The assumption is that reading the schematised map will provide some cognitive and usability advantages, e.g. faster map-reading or better ease of use, while providing the same insights about the depicted spatial environment.

The approach to decrease the burden of learning some detail-laden tactile orientation map can be operationalized differently. One option is to enable some schematisation that changes the geometry and thus results in different sensory parameters. Such a schematisation happens, for example, by changing the style of street representations with a rule that all segments between intersections must be straight. Another option is to restrict representations of intersections to configurations that adhere to the 8-sector model, see section 3.1, Figure 3.2. Note that both kinds of simplifications are qualitative, i.e. the underlying data model is not changed (the quantity of map entities is preserved) but the rendering style is influenced.

The investigations in this section contribute to the following research question:

Do qualitative simplifications contribute to the usability (i.e. high memorability and satisfaction[1]) of a tactile orientation map?

I wanted to find first results as support for the hypothesized dependency between the level of schematisation and the usability of TOMs.

Shape of the segments Acquiring survey knowledge with a partly schematised tactile map (only straight segments) is predicted to be faster than learning the map without schematisation applied.

Shape of intersections Acquiring survey knowledge with a full schematised tactile map (only straight segments AND intersections within the 8-sector model, see section 3.2.2, and Figure 3.2) is predicted to be faster in comparison to a partly schematised tactile map.

Two hypotheses are relating the usability of the map to the schematisation of the map.

1. The schematisation the shape of lines results in less cluttered interface and thus in higher usability of the schematised TOM (compared to a non-schematised version). Map-users are predicted to be faster with such a schematised TOM and prefer it over the non-schematised version.

2. Restricting the configuration of intersections to the 8-sector model contributes to the usability of tactile orientation maps. Map-users are predicted to be faster with such a schematised TOM and to prefer it over the non-schematised version.

[1] The concepts are adapted from Nielsen & Hackos (1993) but can be found in recent definitions of usability as well in a similar form, for example in DIN EN ISO 9241-12 (2006)

5.2. Participants & Procedure

The four participants AR, MN, HH, and JM (between 32 and 60 years old) were all legally blind by German standards.

At the time of the case-study, two participants had no residual vision: AR was congenitally blind, HH went totally blind just nine months before the case-study. The other two participants had residual vision and were both subject to a deteriorating visual condition. Concerning their tactual acuity, AR and JM were used to reading tactile stimuli in the form of Braille characters for over 30 years. In contrast to AR who regards himself to be 'very trained', JM regards his experience in reading Braille only as 'fair'. The other two participants were not accustomed to read Braille. No participant suffered from neurologic defect or organic defects that would have impaired his/her tactual acuity. All participants were highly mobile and navigated the geographic environment on their own, often with the white cane, sometimes even areas they had not visited before. No one relied on the assistance of a guide dog. HH used an electronic wayfinding system for the blind. The demographic information collected from the participants can be found in 5.1.

ID	Sex	Age	Vision Condition	Residual Vision	Usage of Braille	Experience with tactile stimuli
AR	m	41	Congenitally blind	-	for 35 years	"very"
MN	m	32	Decreasing sight since birth	10%	"never"	"none"
HH	m	60	Adventitiously blind (with 59 years)	-	for 0,75 year	"moderate"
JM	m	48	Decreasing sight since birth	1-2%	for 32 years	grade 4 (out of 6)

Table 5.1.: Demographic information about the participants in this study.

None of the participants had any significant experience in reading tactile map, neither traditional maps nor computer-generated ones. All participants rated themselves as having been familiarized with map concepts, mainly from either handling visual maps (MN, HH, JM) or, in case of deprivation of sight from birth, contact with tactile maps in school (AR). No one had solved spatial tasks by using a tactile map. All information about the participants' self-reported abilities can be found in 5.2.

The base for all map variations was one constructed map, i.e. the structure of the street net-

ID	Current Usage of tactile maps	Experience with maps	Self-rating of expected map-usage success	Success rate in tactile acuity test
AR	"much too little", always when offered, approximately once a year	Since primary school, tactile maps at home	n/a	95%
MN	none	Visual maps every 1-2 weeks, no tactile maps	"good"	>92%
HH	"none, as no maps are available", "I got them in my mind."	Seldom usage of visual trekking maps, no tactile maps	"relatively good"	n/a
JM	"none", "but an interest"	In school as part of a tactile atlas; during vocations with other blind people	Grade 4 out of 6	>97%

Table 5.2.: The participants' backgrounds and self-reported abilities concerning (tactile) map usage.

work and the placement of landmarks were not representing any geographic reality. Instead, it was constructed with constraints, i.e. the street networks displayed were not arbitrary. In each variant, the same neighbourhood relations between regions were in place, i.e. if region A is a neighbour to region B in one variant of the map then this was the case in all variants. There were 15 edges used to connect 12 vertices (each representing an intersection). The map contained vertices with valence three or four representing intersections with three or four incoming streets.[2] At each side of the map there were two segments running 'out' towards the map limits . In total there were 23 edges represented 23 street segments that together formed nine streets (two edges are said to belong to the same street if the gradient in the direction of progression does not change at their common vertex). Five streets were of approximately vertical orientation and four of horizontal orientation. There were no dead ends (except for the eight segments towards the map limits) and no non-connected parts. Through pre-tests with a second cohort of participants it was checked that the networks in the different map variants were not recognized as being the same. No participant noticed the commonalities in structure nor did anyone speculate about any commonalities except for what was obvious through the common legend, i.e. the fact that the same street types and the same landmarks

[2]Some pre-studies suggested that more complex intersections would probably have introduced more sensory arbitrariness and more recognition errors. Representing only the basic intersection types there was a high probability that the characteristics of the tactual realizations would be recognized correctly even if not highly trained people take part.

were present.

Aside from the street representations, the map variants were equipped with two different kind of lines (representing three main streets and six normal streets), seven unique symbols (representing different shops as landmarks within a local context, i.e. referenced against the objects in proximity, usually a street or an intersection), and two unique surface patterns (representing a park and a sport ground as landmarks within a map-wide context, i.e. reference against the edges of the map). All tactile signatures used in the maps and the optimal distance between tactile objects were based on the findings reported in chapter 4 to guarantee for good readability and sensory uniqueness of the embossed tactile map. That was necessary to exclude poor usability as a limiting factor in knowledge acquisition with the tacile maps.

With exception of the park and the sport ground no representation was intended to provide any clue about the real extension or location of the entrance to the represented object. Abstracting the entrances from the buildings was due to the function of the map: in survey maps it would involve too many details if all buildings were represented with their shape and entrances. For the purpose of an orientation map, the existence of the buildings at certain locations was important. In the map only buildings were represented that were near to intersections or near to regions to highlight those spatial elements, hence their function as landmarks. That is the reason why the symbols are always near to (directly beside but separated from) intersections or street segments and not somewhere in the middle of some region.

All the maps used in the study were equal in size, namely A4, see Figure 5.1, Figure 5.2, and Figure 5.3. The maps differed in the relations of landmarks, regions, or segments. Specifically the *contains* relation between regions and landmarks, respectively the *near-to* relation between landmarks and segments. This was introduced deliberately to make it difficult for the participants to realize that all maps were displaying the same street network. For the same reason, the maps were administered in different orientations. In one trial the map was presented as an up-side-down version of the other trial (compare the structure of the street network in Figure 5.2 and Figure 5.3) and in a third trial the map format was changed from landscape to portrait (see Figure 5.1).

Prior to the study, all participants received Information about the aim and the method of the study. They gave their informed consent. To guarantee for comparable tactile proficiency there was an tactual acuity test that the participants needed to pass with 80% success rate. They were asked to recognize different types of tactile lines, tactile symbols and tactile surfaces. Specifically, each participant had to identify some experimental tactile materials (see Appendix 8.3.7.3) that exhibited the complete tactile alphabet of the to-be-used tactile

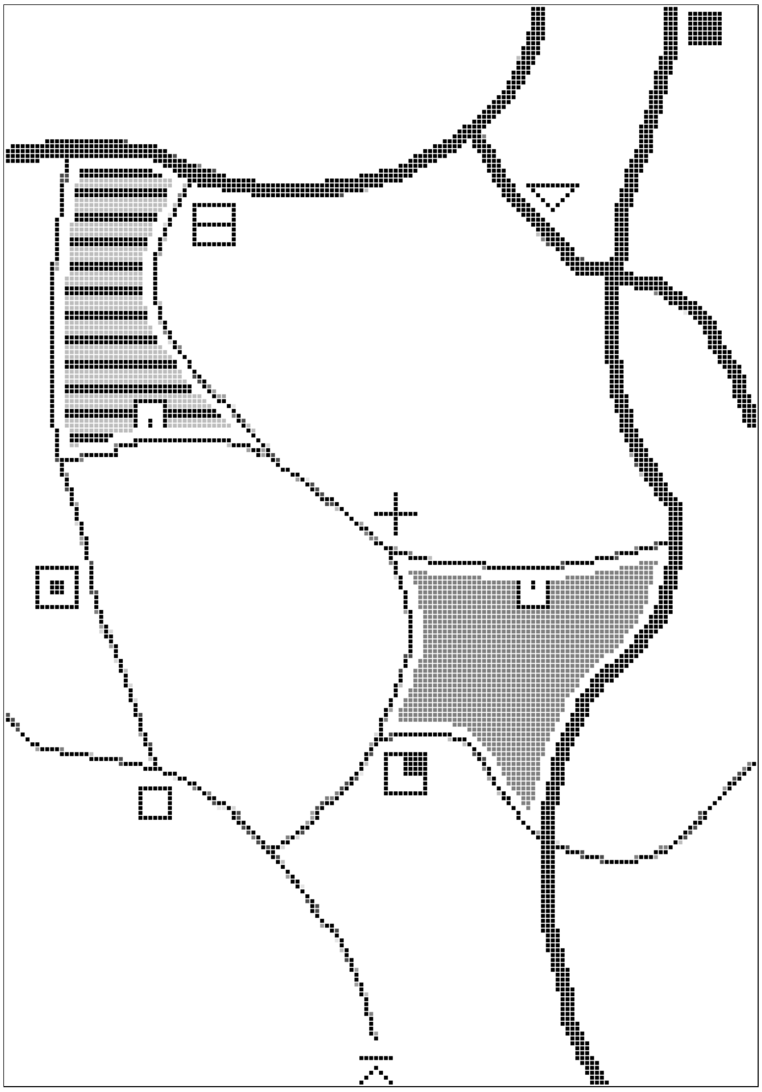

Figure 5.1.: Tactile orientation map used in the non-abstract trials. Original in format A4 portrait, see Appendix 8.3.7.3.

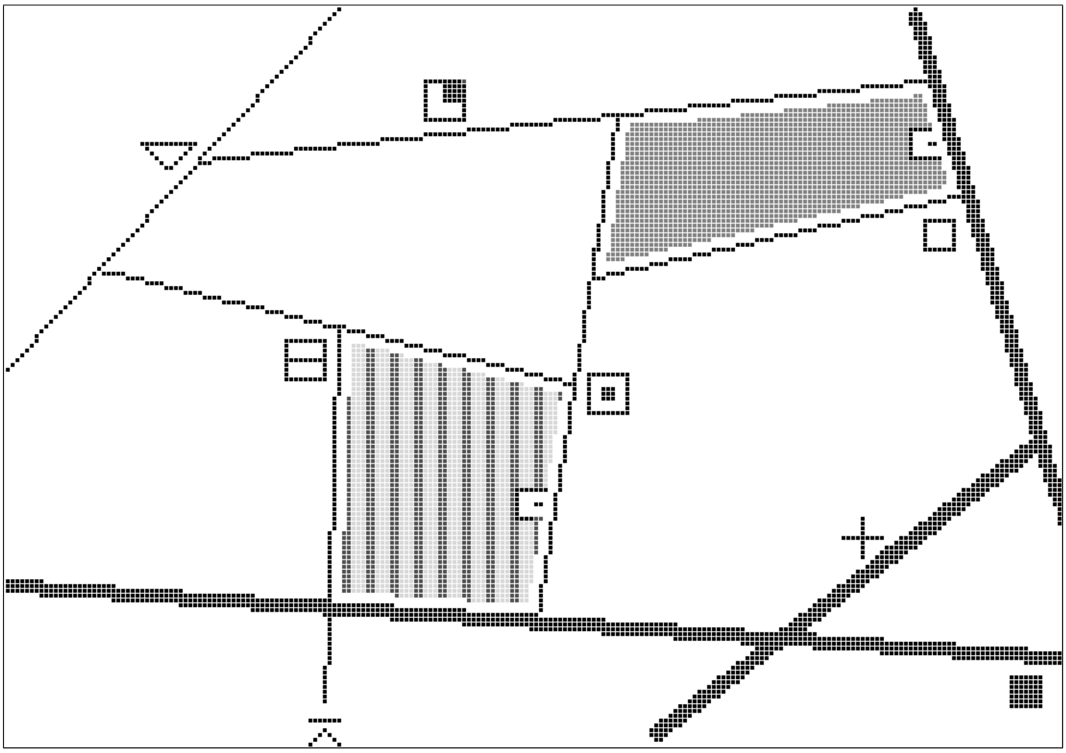

Figure 5.2.: Tactile orientation map used in the low-abstract trials. Original in format A4 landscape, see Appendix 8.3.7.3.

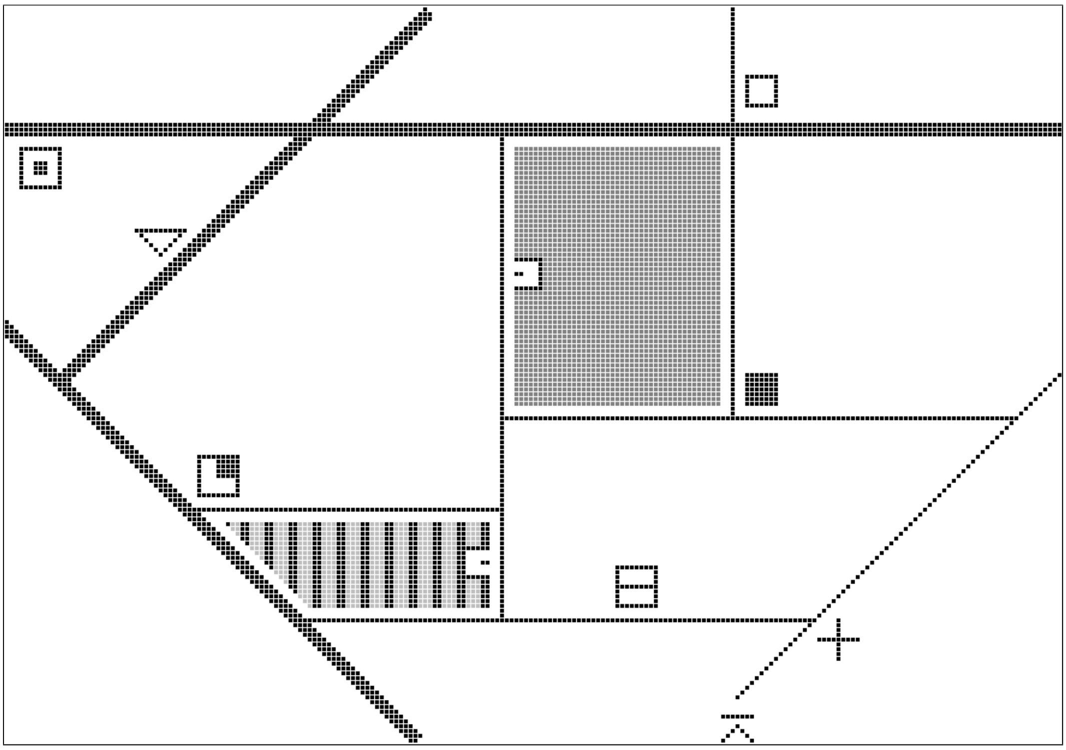

Figure 5.3.: Tactile orientation map used in the high-abstract trials. Original in format A4 landscape, see Appendix 8.3.7.3.

orientation maps.

- Four symbols
- Straight lines that varied in
  - line width (one or three taxels)
  - tactual prominence (maximum raised line or 40% raised lines), and
  - direction of presentation (oblique, vertical or horizontal)
- Freehand lines of different line width
- Polygons that varied in
  - number of edges (three or four)
  - width of the border (one or three taxels)
  - surface structure (full elevation or 40% height)
  - orientation of the whole object,
- T-intersections of lines that varied in
  - line style (straight or irregular)
  - width of the lines (one or three taxels)
  - and orientation of the whole object
- X-intersections of lines that varied in
  - line style (straight or irregular)
  - width of the lines (one or three taxels)
  - and orientation of the whole object

After passing the acuity test, participants had to read the tactile legend customized for the tactile orientation maps that were to be used afterwards. Each tactile signature available in one legend was used in the corresponding map. The meaning of each signature was communicated verbally as not all participants could read the Braille alphabet. The meanings never changed during the course of the study.

The participants had to explore all three tactile orientation maps in separate runs with the following instruction: 'Explore the tactile orientation map and extract spatial meaning from it such that you could independently answer questions about the spatial environment displayed without the map at hand.' While exploring the maps or the legend, the materials were fixed to the table (no rotation was possible). The task was to memorize the TOM such that the reader felt confident in performing mental navigational task without the map after the exploration. There was no time limit for map exploration nor for legend reading. The legend could be re-requested during map exploration at any time to clarify the meaning of tactile signatures.

During each run the time to finish exploration was measured (without the time to consult the legend). After each exploration the participants had to solve several spatial tasks (without consulting the map). The following list specifies the spatial task and the corresponding instructions given to the participants.

Survey Description : 'Recall the spatial organisation of the environment! Describe the course of main streets, which landmarks are in the periphery and which ones are more central. Name the cardinal direction from landmark X to landmark Y, and the distance (close, or far) between them.'

Route Directions : 'Recall route A from landmark C to landmark D!' and 'Recall route B from landmark E to landmark F!' (each route contained at least two intersections and three segments)

Sketch-Map : 'Draw the structure of the environment including streets, intersections and landmarks.'

For the survey descriptions and the route directions the participants answered verbally and their answers were recorded. The sketch map was only asked from participants that felt capable of drawing given the specific eye condition.

I assessed the number and relevance of correct information and of errors that each description/map contained. In route descriptions, five points could be earned for each correct decision point with turn action (denoted by 'dp+' proposed by Klippel et al. (2003)). For a correct description of a decision point with no action ('dp-') one point could be earned. For correctly describing the existence of a landmark along some street two points could be earned. If the placement of that landmark (left or right in relation to the route) was correct too, one extra point could be earned. Locating the entrances of parks or sport grounds correctly was worth one point as well as specifying the turn action from the start landmark onto the first segment or from the last segment towards the goal landmark.

For each participant and each task I assessed a success rating from grade 1 (best) to 5 (worst). The ratings were uniformly and linearly scaled to the spectrum from 0% (no correct information specified) to 100% (all of the possible information correctly specified). In some cases, recalling the position of the start landmark or goal landmark went wrong such that the route reconstructed had no correspondence in the street network and as such had to be assessed with 5 ('fail'). In other cases a landmark specified in the task was mixed up with some other existing landmark in the map such that the verbally specified route could be assessed, even if it was the wrong one. If an externalisation of spatial knowledge is assessed with rating 1 one could argue that the navigator has sufficient knowledge to navigate the environment without additional help and without getting lost. Rating 5 could be interpreted as self-dependent navigation would surely fail and additional help or cancellation of navigation is inevitable.

After each run, aside from the quantitative assessment, satisfaction with the map was asked about to evaluate subjective usability: 'How satisfied are you with this map as tool to provide spatial knowledge about the environment? What was missing? What could be improved?'

After all runs were administered in the same fashion, the participants were asked

- whether they recognized if there were any similarities between the maps to indicate unwanted carry-over or position effects, and
- how they would rank the three types of maps in terms of ease-of-use supporting the task to get an overview of an unknown environment,
- whether they consider the approach to convey spatial meaning by schematised tactile maps as valuable and as consequence would intend to use it, would intend to recommend it to friends (maybe for specific tasks, users and contexts).

5.3. Results from Observations, Verbal Protocols, and Task Evaluation

During the pre-studies it turned out that in printed maps the direction of a tactile element is a major factor. It makes a difference whether a gradient (any change in the embossing height, i.e. an edge) is aligned with the embossing matrix (i.e. running horizontally or vertically) or not. If the edges are parallel the minimum separation between two geometric objects can be as low as 2.54 mm (with the ViewPlus Emprint that is two taxels of 1.27 mm each). If displayed with oblique edges there should be at least a gap of 3.81 mm (three taxels) in-between objects to understand them as being separated. Otherwise the readers would not recognize the separation of objects with confidence. There were hints to a small effect concerning which geometric objects are side-by-side, for example, a line beside another line was better recognized than two rectangles beside each other[3].

During the study, all the participants expressed their regrets that there were just too few tactile maps out in their daily lives. They saw that fact as potential limitation to the personal success in the tactile map-reading study and as a general problem for establishing tactile maps among blind people. Their ratings about their potential success in tactile map usage were heterogeneous. It ranged from grade 2 ('good') to 4 ('fair') (i.e. distributed around the average of grade 3.5) and no one judged himself as potentially failing (grade less than 4/fair).

[3]That effect was not investigated any further as it was not stable and rather subtle (only one participant mentioned it). It could be result from the fact that lines offer two gradients that causes the sub-cutaneous cells to react when the finger moves laterally over the two discontinuities. Edges of filled rectangles only afford one discontinuity when stroked laterally.

The subjective opinions were confirmed by the tactual acuity test that all participants passed with an error rate of (far) less than 10% with a limited training of 20 minutes beforehand.

There were indications that the progress of tactile map understanding is sub-divided into different phases. Most map-readers first explored the position and size of the map in relation to their bodies. This behaviour was independent of any instruction with that information provided beforehand. Then, exploration began. Two participants explained that they tried to get acquainted with the distribution of objects available in the map as a rough overview. As a last step all participants deliberately read the whole map in detail to memorize it. The first phase was characterised by searching the limits of the map and by following the edges around the map. In the second phase, map-readers exhibited sweeping arm movements over the whole map maintaining only light contact with the fingers, often both hands beside each other. In the last phase, the forearms were at rest and only the hands and fingers moved over the surface from one tactile object to the next, sometimes forth and back, sometimes both hands in the same area of the map, sometimes in different areas, exploring every detail. Asked about the information they gained in each of the phases, I developed the following categorization of map-reading activities into three phases:

Anchoring : anchoring the tactile map in the map-reader's peripersonal space, trying to establish a frame of reference for the map in relation to the egocentric reference frame to be able to integrate the spatial information incoming during the following phases;

Over-viewing : building up a coarse overview of the map with information about the distribution of items over the map, and scanning for recognisable signatures in combination with recalling what each means,

Detailing : decoding the meaning of all signatures either from memory or with the help of the legend, and integrating single elements into one spatial structure.

During the studies several results were produced that can be interpreted as supporting the idea of spatial knowledge acquisition being facilitated the more schematic the tactile orientation maps used for learning is. Concerning exploration times, all four participants spent either about the same time with the different types of maps (see participant MN or HH in 5.3) or a lot more time with the low-abstract map (see participants AR and JM in 5.3). This can be interpreted as indication that non-abstract maps impose a higher cognitive burden to (some) map-readers. Research about *cognitive load* points to such a relation between cognitive effort and time for learning (Sweller et al., 2011). That is, the more time taken, the greater the cognitive load or effort imposed for the task. Applied to the comparison of differently constructed tactile maps it could either mean that the one map is harder to learn than the other. Or the recall of the facts from the one map is harder than from the other. In map-learning for navigation tasks, an increased cognitive effort is important, as there are other cognitive operations to be done. So adding load in map-reading is going to have detrimental

Map-type	**AR**	**MN**	**HH**	**JM**
Non-abstract	12:20	15:00	01:45	10:04
Low-Abstract	05:50	17:00	02:10	02:00
High-Abstract	06:27	16:00	01:39	05:10

Table 5.3.: Total times for map-reading by map-types and by participants

Case	**First Map**	**Second Map**	**Third Map**
AR	12:20	06:27	05:50
MN	17:00	16:00	15:00
HH	02:10	01:39	01:45
JM	10:04	05:10	02:00

Table 5.4.: Total times for map-reading by order of maps and by participants

effects on those other operations, or map-reading is suffering from the other operations. Both consequences are not advantageous.

A second fact can be read off from the data given in 5.4. In each case, the first map was the one which the map-readers spent the most time with, regardless of the map-type. Again in two cases (MN & HH) the extra time needed for non-abstract was minimal, but in the other two cases the differences were huge (12:20 vs. 5:50 and 10:04 vs. 2:00, see 5.4).

Comparing the quality of the route directions and the quality of the descriptions of structure in each of the conditions brought no differences. All participants were fairly good in recalling the spatial organisation of the environment. Specifying the approximate progress of the main streets was no problem at all, often the distribution of minor streets was described as well. The positions of single landmarks and the relation of two landmarks were reconstructed only with minor errors, for example, with a correct bearing ('to the north-west') but with a incorrect distance ('far away' instead of 'close by'). Apparently, one strategy used to memorise the spatial positions of landmarks was to hierarchically organise them, i.e. people learn that object A is close to object B (most often a bigger or more important object) and then they learn how object B is itself positioned in the map space. When asked for the position of object A it seems they recall the position by reconstructing a reference hierarchy: the position of object A is found in the standard reference frame F (most likely body-centred, as found in many tactile exploration experiments), then F is translated such that its origin is co-located with A, that translated F constitutes a second reference frame F', and the position of object B is found in F'. Hints to such a strategy can be found in participants' answers to questions about the positions of single landmarks (not relations of landmarks!):

> 'The book store is beneath the sports ground.' in conjunction with 'The sports ground is in the north-east.'

> 'The sport shop is left from the sports ground.' in conjunction with 'The sports ground is in the north-west.'

The description of routes from memory was the most demanding task for all participants. They all succeeded on very different levels. One big source of error was mixing up landmarks in the reconstruction of the map such that wrong routes were described. The error clearly happened during recall as the landmarks asked for were (in almost all cases) correctly identified during map reading.

Because only one participant (MN) could draw sketch maps, they were not included in the evaluation but can be found in Appendix 8.3.7.3. The other genuine situation was with the congenitally blind participant (AR). In the study it became clear that he was not aware of certain cartographic concepts such as a legend showing the meaning of signatures. After those concept were established in the tactile training, he performed at the same level as the late-blind participants in terms of assigning conceptual meaning to tactile sensations.

Concerning similarities between the maps one participant noticed a structural similarity in that park and sport ground were always quite central and that there were always only some main streets and more secondary streets. A second participant was not sure but believed that there was always a main street in the north or south. All agreed that the different map-types were similar in terms of signatures used, i.e. the existence of two different types of street representations, and the re-occurrence of the same landmarks. But this fact was told them before in the instructions. One can conclude that participants did not know or assume that the maps were similar to each other in terms of street network. Unwanted carry-over effects or position effects that could have flawed the study were unlikely.

The subjective ranking of the map-types regarding the ease-of-use to get an overview of an unknown environment showed a preference: the high-abstract TOMs were liked the most and the non-abstract TOMs the least. There was one exception to this preference: one participant (HH) assumed another use case than introduced to him in the scenario. Instead of pre-journey usage to gain some level of understanding before starting to walk, he reasoned about the usage of the TOM as in-journey tool, too. When using a tactile map as in-journey tool navigators probably want to be able to find their positions' representation in the map. They have to establish a correspondence between map and environment. For this task it would be good to have details of streets represented in the map, for example bends. That would ease tracking and establishing a position in the map. Therefore the participant's expectations which details a map should provide were not met. Exactly those details were schematised in the low abstract and high abstract maps. Consequently he favoured the non-abstract map type. But he agreed that tactile orientation are generally a helpful means to "know what is out there and how objects are distributed over the area".

The approach to convey spatial meaning by schematised TOM was equivocally welcomed and valued. The intent for usage was high. The intend to recommend it to friends was high

	MN	HH	JM
Similarity of map types	3	3	3 (medium)
Best map type	High-Abstract	Non-abstract, as bends and curves provide helpful details when walking the streets	High-Abstract
Worst map type	Non-abstract	High-Abstract	Non-abstract
Intent to use	yes, both types!	yes, best would be as close too reality as possible	yes, for an overview in the same way as with a city map, might by helpful and advantageous
Intent to recommend	yes	yes, to ease navigation, to have a survey, to know what's out there & how objects are dispersed over the area, to schedule a trip to different targets, to facilitate route finding	yes, to have a graphical depiction as support that provides hints (for navigation)

Table 5.5.: The paraphrased answers in the interviews after the trials.

as well. Specific tasks, users and contexts were not suggested. All results from the post-trial interviews can be found in Table 5.5.

5.4. Discussion & Recommendations for Schematisation Principles

5.4.1. Displacement and Distortion in Map Schematisation

As in most representations of the geographical world onto a realm of a map, there are always some distortions involved. The surface of the earth as a three-dimensional object of ellipsoid shape has to be projected onto some two-dimensional piece of paper. Each projection used to produce maps has its own advantages and disadvantages. Some maintain the relative sizes of the depicted areas, others maintain the angles. Yet other projections maintain directions. The Mercator projection that preserves angles but not directions nor fidelity to area is used by most commercial and open source distributors of maps, for example OpenStreetMap, Google Maps, Bing Maps or Yahoo Maps[4]. The important point is that there is no such thing

[4]Frederik Ramm, Jochen Topf: OpenStreetMap: Die freie Weltkarte nutzen und mitgestalten, ISBN 978-3-86541-375-8

as a projection that could maintain all three qualities, i.e. area, angle and direction, at the same time[5].

When developing schematisation rules for tactile orientation maps, one needs to consider such properties as well because some schematisations of local details can result in distortions of the whole map. Let us assume that all curved lines should be abstracted to straight ones under the preservation of the absolute position of the intersections or endpoints. The size of the map will not change, but the relative direction from one street segment to the other at some intersection could change. This is because the direction of each segment incident to some intersection changes a little. In extreme cases, it could happen that the direction from one element to the other was, for example, 'straight' before and 'to the right' after schematisation. In such cases the nature of the intersection was changed qualitatively because of schematisation. To avoid this, one could argue for schematisation that preserve relative directions at intersections. Under such a policy, aiming for straight lines would mean that the positions of endpoints of streets running out from the respective intersection must be changed accordingly. As the policy is then applied to all intersections, the network becomes more and more distorted and will probably run into inconsistencies. It can be relaxed by giving up some constraints as minor displacements of tactile entities from the exact geometric position cannot not be felt. Minor local relaxations at different parts of the map might account enough to allow for some flexibility. Which constraints and how much they might be relaxed is beyond the scope of this thesis and should be investigated separately.

5.4.2. Limitations & Possible Extensions of the Study Setup

5.4.2.1. Wrong Expectations Limit the Perceived Utility of Tactile Orientation Maps

Concerning the ranking of the map-types it turned out in the interview after the trials that one participant assumed another use case than introduced to him in the scenario for the study. The unfortunate situation with that participant motivates a rather high-level recommendation: it should always made clear to the map-users which information the material can provide and for which task is was made. Without being aware of that, map-users might get disappointed and maybe lost if they mis-use a map for a task that it is not intended for.

5.4.2.2. Possible Extension of the Study

The study checked for two factors as source of cognitive complexity: schematisation of intersection shapes and schematisation of segment shapes (for a systematic overview see Table 5.6).

[5]see `http://de.wikipedia.org/wiki/Winkelverzerrung`

	Non-abstract Segments	**Abstract Segments**
Non-abstract Intersections	Non-abstract maps	Low-abstract maps
Abstract Intersections	*not-tested*	High-abstract maps

Table 5.6.: Overview of the schematisation of intersections and segments in the different types of the tactile orientation maps.

One factor combination was not tested. The map-type that would be composed from abstract intersection (see Figure 3.8 and Figure 3.9) and segments of arbitrary shape (like in the non-abstract map type). Line following and the subsequent cognitive simplification of line shapes would be as demanding as with none-abstract maps. But recognizing and learning the intersections would be eased in the same way as with the high-abstract maps. The investigation into that fourth map-type could disentangle the influence of segment shape and intersection shape on readability of a map. From the findings of the studies so far I will reason which factor is likely rule over the other.

As the exploration of the free-form segments would introduce high demand for attention, I expected that the map readers would need about the same time for such a map than for a non-abstract map. Further, I expected that the schematisation of the intersections could be helpful in remembering the directions to adjacent segments. But there could be a problem in connecting abstract intersections and non-abstract segments: The shape of the segment needs to be distorted to preserve continuity with the shape of the intersection, as the shape is aligned to the up-direction of the map. For a better fit between abstract intersection and non-abstract segments it could be a solution to align the shapes of the intersection to the actual direction of the (a street representation. That is, imposing the schematisation of intersections to the local structure but with rotation allowed. An example: Let's assume a main street is displayed almost horizontally, thus a default X-intersection with a minor street is almost vertical. In the case discussed above the intersection would aligned to the global vertical and horizontal axis and the connection to the non-abstract street representation need to be rebuild. Under the new policy, the intersection is not abstracted but preserved by aligning the intersection model to the local situation, i.e. rotating it such that the up-direction points in the direction of one street, maybe the main street. Then this slightly rotated intersection model is imposed onto all incident segments. The advance: the local changes in street presentations are minimized and thus the total distortion over the whole map as well.

The recommendations for schematisation is to adapt the level of simplification to the structure and geometry of the base tactile orientation map. An equilibrium between the effort needed to cope with artefacts introduced through the abstraction and the advantages gained through abstraction would be the best solution. The automatic calculation of this equilibrium will need more research into the cognitive reality of tactile map understanding. It will need to take into account the spatial context, for example along the lines of the *spatial context model* TEAR proposed by Freksa et al. (2007)[6].

5.4.3. Cognitive Considerations about Schematised Tactile Maps

Analysing the whole-map level, the original north-to-south order and west-to-east order of intersection have changed. When analysing single intersections, some have changed their characteristics too, for example from turning slightly right to sharp right. More serious changes include:

- Global ordering of vertices might change, thus the direction from one node to the next is different between map and environment (compare the vertical street in the centre or on the right between Condition Non-abstract vs. Condition High-abstract)

- Local geometric characteristics might chance under schematisation such that the map represents local direction incorrectly (compare the two intersections of the vertical street in the centre between Condition Non-abstract vs. Condition High-abstract)

- Adaptation of Schematisation: Relax relative distance rule according where the segment is located, for example, a segment adjacent to the frame of the map could be became shorter than it should be to make room for other elements. There are two reasons: First, the outer zone of the map is not explored that carefully and hence the elements there are more likely to be of minor importance for the map-reader. Second, the exact relative length of such segment might not be interesting anyway as the function of such segment is to hint to some adjacent other map. Existence is important, length is not.

- Cognitive Advantage through appropriate sensory design: The style of lines could be adapted to reflect some property of the underground, for example, some zickzack lines that signify an uneven pathways are hard to tactually follow. In the same direction were participants' explanations why they liked iconography in symbols and surface patterns that were similar to the represented area, for example, parks as uneven structure (because there are different trees, patches of grass, sometimes lakes etc.) and sport grounds as even (because they have a uniform surface made of grass).

The participants' self-ratings were supported by their low error rate in the tactual acuity test. That can be interpreted in three ways:

[6] TEAR model covers the task, the environment, the user, and the tactile map as representational medium. The rather high-level model defines processes on those constituents (for a more detailed introduction to TEAR, see Schmid, 2010)

1. Each tactile signature developed in the pre-studies is distinct enough to be recognized and to be told apart from the others.

2. The tactile signatures fit the sensory and cognitive abilities of the participants.

3. The tactile training that preceded the test was exhaustive.

5.4.4. Recommendation: Ease Map Understanding By Avoiding Oblique Street Representations

In the case that the geographic environment to be displayed is structured similarly to what is sometimes labelled Manhattan city block structure (a set of parallel streets is perpendicular crossed by another set of parallel streets) one might think about aligning the representations of the streets such that they coincide with the vertical and horizontal axes of the map. That would, having vertical and horizontal lines only, result in lower frequency sensory information and in lower map cognitive complexity compared to a map with oblique lines, given that lines in both maps are straight.

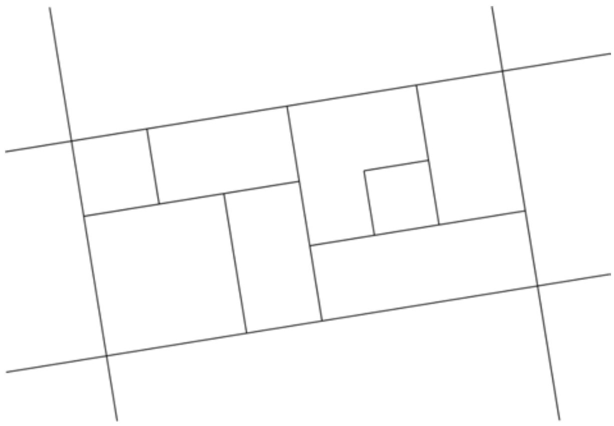

Figure 5.4.: A map of an artificial street network that shows straight, but oblique lines.

One example could be the city of Barcelona: In constructing a tactile orientation map for the district Diagonal, see Figure 5.6, it would be advisable to print the map such that the direction of parallel streets is aligned to the printing direction, i.e. left-right or top-down. Other districts, for example Barceloneta (see Figure 5.7), have not got such a systematic Manhattan city block structure.

Constructing a TOM without oblique streets for the Barceloneta district seems unlikely. If the map is schematised in a less rigid form, for example, by allowing oblique streets, even

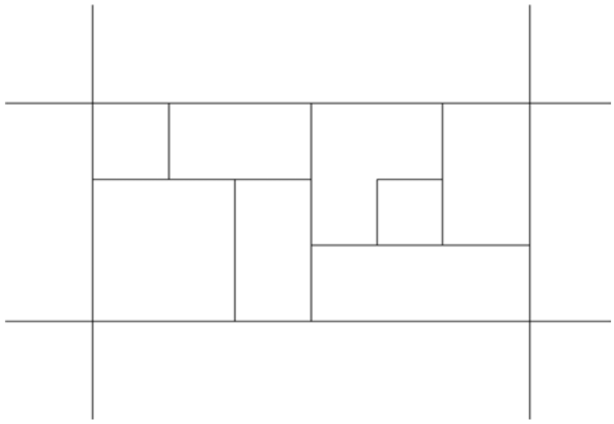

Figure 5.5.: The map is tilted such that the straight lines run perfectly vertical or horizontal.

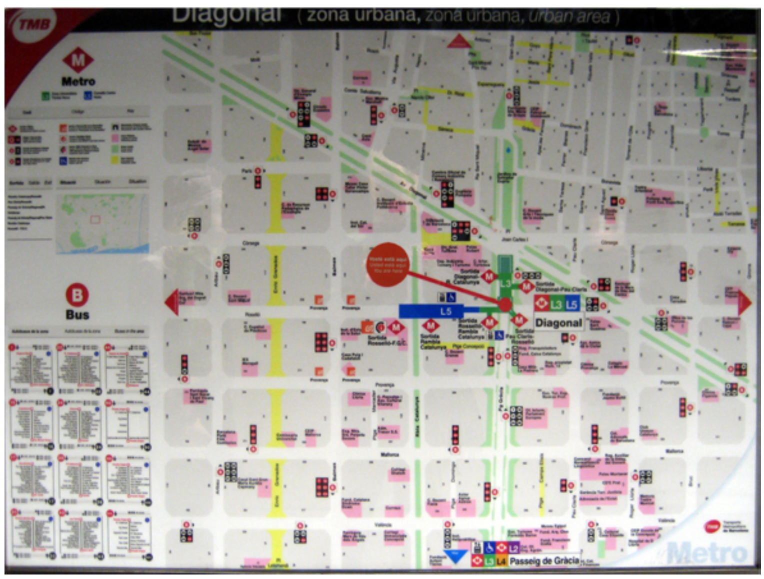

Figure 5.6.: A map of Diagonal, one district of Barcelona, showing almost perfectly alligned horizontal and vertical streets that together form a repetitive, rectilinear structure like on checker boards. Compare this to Figure 5.7.

Figure 5.7.: A map of Barceloneta, another part of Barcelona, that shows a historically grown arbitrary structure of streets connecting in many different ways, angles and configurations. Compare this to Figure 5.6.

the neighbourhood of Barceloneta could be turned into a schematised form. Key for such success is the relaxation of properties based on metrics, for example, shape of streets, such that the whole map can be distorted.

5.5. Summary

This chapter showed that the schematisation of tactile orientation maps through 1) straightening segments between vertices and 2) displacing vertices such that any two segments only coincide in predefined angles can help decreasing cognitive complexity while save-guarding the usefulness of the maps for the reader.

Given the performance in the spatial tasks, I regard TOMs constructed in the detailed way as a promising means to introduce people to the coarse structure of some geographic environment. When contrasting the average self-rating prior to executing the spatial task and the non-the-less good performance, one can argue that other inexperienced map-users might underestimate their performance too. Thus, the fact that someone has never used a tactile map before should not be overrated. Albeit it would need an intensive training to be acquainted with map concepts such maps can be interpreted correctly[7].

The findings in this study suggest several results:

1. The conceptual abstraction of intersection representations and the geometric abstraction of street representations is a feasible approach to schematise a tactile orientation map.
2. It is feasible to abstract tactile orientation maps algorithmically but, most probably, there is no general solution to it. Algorithms need to be adapted to the given input data and the required output map-types.
3. Schematised TOMs with abstract street representation and abstract intersection representation may have an advantage over traditional TOMs. Map-users need less time to learn schematised TOMs and they often prefer it over a non-abstract TOM. They are able to successfully use the acquired spatial knowledge from an abstract TOM in the same way as from a non-abstract TOM.

It was discussed how both types of schematisation contribute to the usability of tactile orientation maps. Reducing the perceptual complexity will likely also increase the map's interpretability, learning, and overall cognitive coherence. That is, when there is no abstraction or schematisation, the map is essentially too crowded to be useful or meaningful, so it is likely to add frustration and cognitive dissonance between what map-readers think should be there and what they actually perceive. Thus, the effect transcends use of one particular

[7] For a review which concepts might be relevant consult the literature on developmental psychology applied to tactile cartography, see Aldrich et al. (2002), Hegarty (2010), Taylor (2005).

map. It increases the likelihood that people will use maps as they have good experiences that they are helpful and improve spatial awareness, instead of causing frustration, confusion, and angst.

Chapter 6.

Localisation Support for Better Tactile Map Usage

This chapter provides insights for how the usage of tactile orientation maps could be eased by providing effective indicators to a specific position, for example, as indicated by the You-Are-Here symbol in a You-Are-Here map. In a physical map such an indicator is permanently present and might hinder the tactile exploration after the specific position was found. Therefore it was investigated how each type of tactile indicator in a tactile map impairs the exploration of the tactile orientation map. Three different indicator types were compared: a guiding line from the frame to the target position, two marks at the frame indicating the x and y coordinate of the target position, and a grid allowing to specify coordinates of the target position. Quantitative and qualitative research results are presented before factors that could have influenced the findings will be discussed. Recommendations are given and future research that could shed more light onto the usability of tactile orientation maps are proposed.

6.1. Motivation & Research Questions

Tactile orientation maps which facilitate access to some geographic environment are generic tools for wayfinding. In chapter 3.1.2 three prominent wayfinding tasks that should be supported by tactile orientation maps were identified, among them was localisation. In localisation the map user wants to pin down a specific position in the map.

One special class of orientation maps is the class of You-Are-Here (YAH) maps (Klippel et al., 2010, Levine, 1982). In a YAH map at least one position is made very explicit: the YAH point, i.e. the representation of the map reader's position in the map. Very distinct and unique entities are used to set the YAH symbol apart from the others symbols. Thus the entity and the encoded concept are brought to the foreground of the user's attention.

In the following, I focused on the special class of YAH maps to investigate which support is usable to find a specific location while not impairing the acquisition of survey knowledge through map exploration.

To find the You-Are-Here symbol in a tactile YAH map, the map user—in the worst case—has to manually explore the whole map. To avoid this, one solution could be to employ indicators that guides the map readers to the positions of interest. Three different types of guides and pointers were motivated for localisation support in a computer-generated tactile maps in chapter 3, subsection 3.2.2: Indicator Line (IL), Frame Indicator (FI), and Grid Indicator (GI). I investigated how effective each type of indicator is to locate a certain position in a computer-generated tactile orientation map, i.e. "Effectiveness", and how much each type of indicator subjectively and objectively impairs the process of map exploration, i.e. "Usability".

After having reviewed the different indicator types and the usage processes that take place during their usage in chapter 3, the research questions to evaluate the indicator types are as follows:

Q1 : Which type of indicator out of the three proposed is most effective for finding the YAH location in a computer-generated tactile orientation map[1]?

When exploration takes places, all map entities that do not benefit the exploration can potentially impede the acquisition of spatial knowledge from the map. Thus the research question is as follows.

Q2 : Which type of indicator out of the three proposed most impedes the acquisition of spatial knowledge from a computer-generated tactile orientation map?

6.2. Participants

The test subjects in all studies reported here were 12 sighted, blind-folded individuals (all students with a computer science background), 4 male & 8 female, aged between 22 and 56 (average age: 26.7) with no impairment to the visual, tactile or motor system and no experience in solving tasks solely with their tactual sense (i.e. without visual feedback).

6.3. Procedure

There were three maps that differed in how finding the YAH point was supported. The maps were of uniform scale and presented an artificial world with three landmarks: one represented the YAH point and the others two distinct buildings (one rectangular, the other one round). Having the same topology of the street system, the placement of the landmarks was different in all conditions. All tactile objects on these maps had the same geometric properties, in terms of surface structure and in terms of elevation.

Condition IL : A map with an *indicator line* to the YAH symbol is provided, see Figure 3.3.

[1] In principle, the indicators could be applied in manually produced tactile maps as well. But as the evaluation of the indicators in traditional maps is beyond the scope of this thesis, I limit the context of the research question to computer-generated TOMs. If a benchmark between the scan performance in traditional and computer-generated maps showed no difference, the findings to this question could be extended to traditional tactile maps.

Condition FI : A map with *frame marks* at the position of the YAH symbol is provided, see Figure 3.4.

Condition GI : A map with a *grid* as coordinate system and the position of the YAH symbol in this coordinate system is provided, see Figure 3.5.

The study was conducted according to the general description in Appendix 8.3.7.3. Tactile training with the sighted participants was done for about half an hour such that the participants got used to reading tactile materials.

In the run, each subject explored the map legend and the corresponding map. The first task in each map was to find the YAH point (i.e. the position of the YAH symbol) as fast as possible. They were not told what kind of strategy they had to use to find the YAH symbol in a certain map. Instead, test subjects were informed implicitly about the type of map through reading the key to the map before they were exposed to the map itself.

The second task was to gain an understanding of the entire area. For this, the test subjects were asked to explore the map in such way that they could explain the structure and routes in the area later on. No time limit was set and no target route was being announced before the map was read (c.f. Brambring & Weber, 1981). After the exploration of one map, the test subject was asked two questions concerning the spatial properties of the area represented in the map to check their basic understanding of it: How many buildings are located in the area? How are the buildings distributed over the area? Then, the test subject had to solve two wayfinding tasks to check if they could infer some route knowledge from the map. Test subjects had to describe how they would walk between two landmarks. They could choose whatever route they wanted but they were not allowed to consult the map again. After the description, test subjects had to solve one sketch task: They were asked to produce a copy of the map as completely as possible on a graphic tablet to test their survey knowledge (following the methodology of Ungar et al. 1997).

In summary, test subjects had to perform four tasks for each condition and two final tasks after all conditions had been tested. These tasks define the different phases of the study. In the following overview, phase names are in brackets. They are followed by a translation of the instruction that was given to the test subjects for the task to be executed.

Usage Tasks (with the map at hand)

1. **FindYAHpoint** :"Find the YAH Point as fast as possible!"

2. **ExploreMap** : “Explore the map until you are confident in knowing the area so that you could explain the structure of the environment and routes between objects!”

Spatial Tasks (without the map)

3. **ExplainRoutes** : “Explain two routes between landmarks: From A to B and from B to C!”

4. **DrawMap** : “Draw a map of the area!”

Evaluation Tasks (without the map)

5. **RankRefFind** : “Rank the indicator types according to how helpful they were for you in finding the YAH point!”

6. **RankRefExplore** : “Rank the indicator types according to how impeding they were for you in the exploration of the map!”

During the different usage tasks, qualitative and quantitative measures were recorded to make an evaluation possible.

Quantitative measures:

1. The time test subjects needed to finish the FindYAHpoint phase (in seconds), more specifically, the time from starting to look for the YAH symbol (first touch of the map) and correctly locating the YAH point was taken by the experimenter with a stopwatch.
2. The time test subjects needed to finish the ExploreMap phase (in seconds), mores specifically the time from having located the YAH point until the test subject declared to have been acquainted with the map content in a satisfying way was taken.

Qualitative measures:

3. Assessments of the test subjects’ externalized route knowledge in the ExplainRoute phase via verbal descriptions.

4. Assessments of the test subjects' externalized survey knowledge in the DrawMap phase via sketches.

5. The subjective ranking by test subjects in the RankRefFind phase.

6. The subjective rankings by test subjects in the RankRefExplore phase.

This study does not aim to proof that one specific location indicator is best for computer-generated tactile maps. Rather, it aims at providing initial arguments for inclusion of usable location indicators. Even if some of those arguments result from quantitative data they should not be seen as last arguments.

The quantitative measures were subject to a standard statistical analysis, which can show whether any statistical significant difference in times needed to find the YAH point or to explore the map can be found between the conditions. The subjective ratings were analysed in the same fashion to find out whether there is a preference or tendency in choosing an indicator type for either finding the YAH position or exploring the tactile map.

To operationalise the research questions, we compared the three types of indicators "Indicator Line", "Frame Indicator" and "Grid Indicator" as conditions in the search for the YAH point and in the following map exploration. After the exploration, descriptions of the scene, and route verbalizations were asked and sketch drawing performed. The routes that were asked for were varied but kept comparable in complexity (i.e. routes had the same number of turns). The first route was always from the YAH point to one of the other two landmarks.

During the FindYAHpoint phase and the ExploreMap phase test subjects produced verbal route directions and sketch maps. For an algorithmic matching of the human-made artefacts to the given stimuli, i.e. the tactile maps, an intermediate format that allows for comparison between the different representational modalities (Habel & Graf, 2008) of the material, i.e. visual-spatial vs. serial language. Encoding maps and routes into an abstract propositional form is one candidate. The human-made artefacts (a sketch map) are external representations of the human's internal cognitive models in a specific representational modality. Propositional encoding converts the original representational modality into another representational modality, i.e. propositions. Thus, the semantic information captured in different representational modalities, which were not compatible before, is converted into an *intermediate* format and can be compared in this format. It can represent the concepts that before were represented in maps and route directions. To gain such an intermediate format, transformations had to be performed:

1. Tactile maps and sketch maps have to be serialized and abstracted such that the topological characteristics and selected geometric characteristics (e.g. the position of landmarks) of the map are preserved.

2. Verbal route directions have to be abstracted to such a form that the important content about directions is preserved. All individual artefacts produced by the subjects and

all stimuli used to evoke those artefacts can be turned into abstract propositional for. Then a matching between tactile maps and sketch maps respectively tactile maps and route directions is possible. For a schematic view of this approach see Figure 6.1.

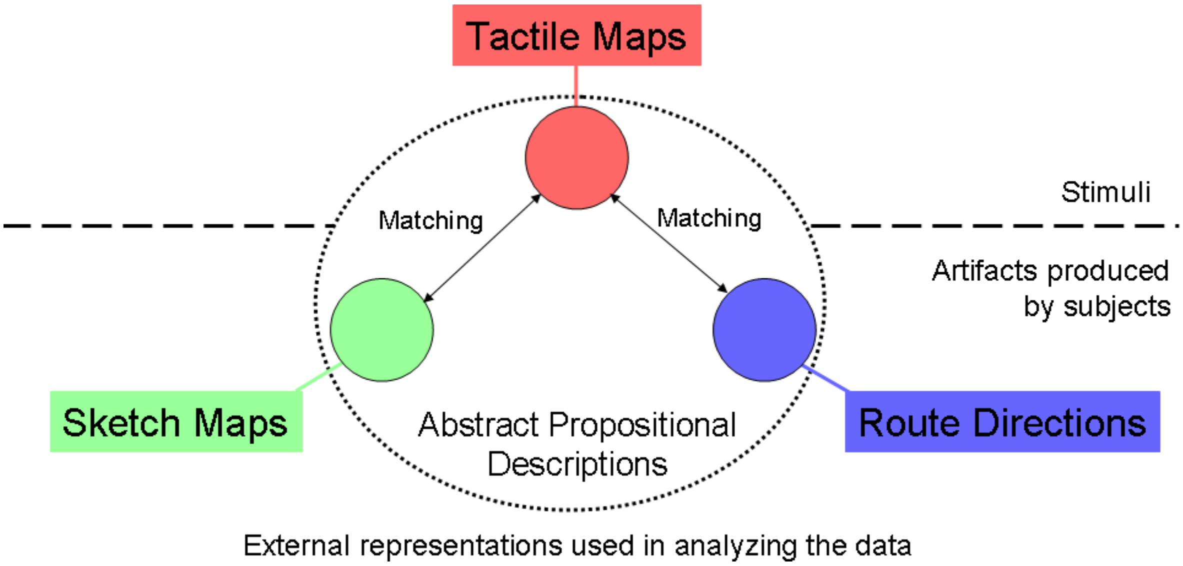

Figure 6.1.: Schematic visualization of the approach on how to match route directions and sketch maps with corresponding tactile maps.

For details about the assessments of the subjects' externalized knowledge see Appendix Appendix 8.3.7.3.

6.3.1. Verbal Route Directions

All types of routes described by test subjects are represented in Figure 6.2, Figure 6.3, and Figure 6.4. In those figures, the outer thick black lines indicate the frame of the map; thin black lines indicate streets segments; the broken line connects the frame marks with the YAH symbol in the map. The round and the rectangular shapes in black represent buildings; the YAH point is symbolised by an upward arrow with a flat roof above it. Different colours indicate different routes that were included in route descriptions by subjects for different start–destination tasks. Green lines indicate route segments that were reproduced when describing routes from the YAH point to the rectangular building (or the other way around), orange indicates segments for routes from the rectangular to the round building (or the other was around), and blue indicates routes segments for routes from the YAH point to the round building (or the other way around). Letters label different route alternatives that were described by different test subjects for a given start to destination task. The shortest routes between buildings had the same number of turns but different length in terms of segments (named 'A' for the length-optimal route and 'B' for the second to length-optimal route).

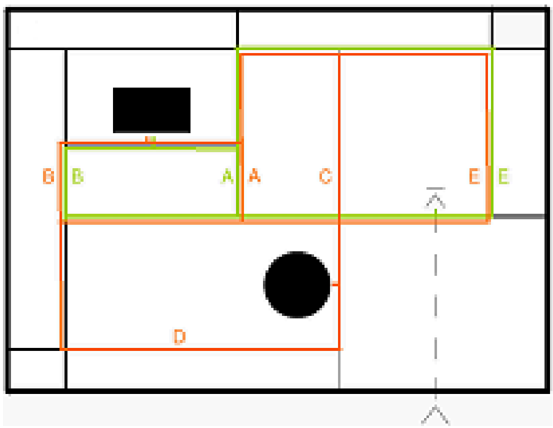

Figure 6.2.: Graphical depiction of all types of route directions produced in the indicator line condition. Colour codes and meaning of letters are described in the text.

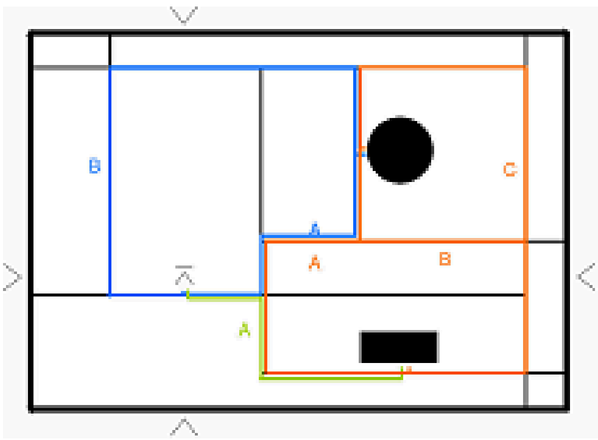

Figure 6.3.: Routes described in the frame marks condition. Colour codes and meaning of letters are described in the text.

Before beginning the systematic analysis of route descriptions, the naive approach was to subjectively rate the route description. Two human raters read the transcribed route instruction and tried to execute it on the corresponding map. A grade from 1 (very good) to 6 (in no way useful) was assigned, with no further differentiation. The more relevant information was given, for example to enable (re-) orientation to correct some error in spatial updating, the better such a description was rated.

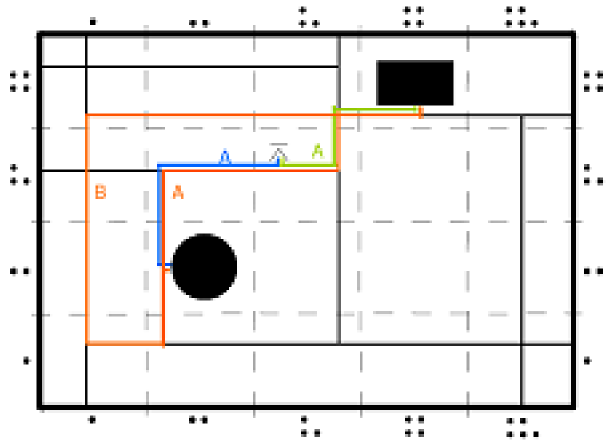

Figure 6.4.: Routes described in the grid condition. Colour codes and meaning of letters are described in the text.

For the systematic analysis of route descriptions each route that was virtually walked was encoded in its propositional form (see Appendix 8.3.7.3) to make some matching possible.

One observation in both, the subjective and the analytic evaluation, was that test persons sometimes exchanged the start landmark for the destination landmark. Thus they described the questioned route in the opposite direction. This was handled in two ways, yielding two separate analysis results:

1. "No correction": With the failure to locate the landmarks correctly, the test-person has demonstrated that she is lacking correct knowledge about the positions of landmarks. This can be seen as indicator of limited survey knowledge, which we are interested, and which is evaluated through the mental construction of different routes. Thus mixing up landmarks is accounted for by assigning the lowest rating (6) for the quality of route description.

2. "Correction": We did not consider mixing up start and destination landmark a failure but interpreted it as if the described route had been asked for. The rational is that the 'without correction' approach discards all the route information that is given in the route description, which might show that the test subject does have an idea of the structure of the area even if she has mixed up the landmarks initially.

6.3.2. Sketch Maps

Before beginning a systematic analysis of sketches, the naive approach was to subjectively rate a map regarding its correspondence with a given map. Two human raters analysed the sketch maps regarding the questions how well the maps resemble to the given maps. The raters assigned a grade from 1 (very good) to 6 (in no way useful) with no further differentiation. In the end, the average of both ratings was computed and a statistics made how often they gave the same grade.

For the analytic evaluation the sketch maps were abstracted and transcoded to the propositional form (see Appendix 8.3.7.3. Applying the four different schemes that are discussed there, one score could be found for each sketch map.

6.4. Results from Observation, Verbal Protocols, and Task Evaluation

The whole study (including the training) lasted about 2 hours (M = 2:02:55h, SD = 15:06min). In the initial self-assessment, the test subjects showed a reasonably high self-confidence in their abilities to read maps (M = .72, SD = .17) and to successfully solve tasks with maps (M = .79, SD = .07). No one failed the final test for recognition of tactile entities.

6.4.1. Performance of the Test Subjects in Finding the YAH Point

The efficiency of the different (tactile) indicators to the You-Are-Here point was assessed through the measurement of search times for the YAH symbol. All respondents except for one in the FI condition found the YAH symbol. This resulted in a total of 35 valid runs (12 in the IL condition and GI condition, 11 in the FI condition). In the FI condition, map user find the YAH symbol the fastest (M = 19.36s, SD = 10.51s), in the GI condition it takes the most time (M= 144.92s, SD = 96.78s). An one-way repeated measures ANOVA test revealed that for searching the YAH point there was a highly significant difference ($F(2, 31) = 15.12$, $p < .05$). A two-tailed t-test between the IL and FI condition revealed no statistically significant effect between them ($t(10) = 1.46$, $p > .05$). The strong increase in search time in the GI condition appeared to account for the observec difference (see Table 6.1). A pairwise t-check supports this assumption (FI&GI: $t(10) = -5.0$, $p < .05$; IL&GI: $t(10) = -4.16$, $p < .05$). One value had to be excluded from each dataset as being an outlier[2]. In the end, the FI condition and the IL condition cannot be said to be different, but the GI condition is significantly different to both of them.

6.4.2. Performance of the Test Subjects in Exploring the Tactile map

It should be assessed how impeding the different (tactile) indicators to the You-Are-Here point might be in exploring the map and thus developing a mental model. This was done by measuring the test subjects' exploration times to make themselves acquainted with the map. All respondents concluded the task. This resulted in a total of 36 valid runs (12 in each condition). In the IL condition map user explore the map the fastest (M = 256.58s, SD

[2] According to Moore & McCabe (1999), an outlier as a point which falls more than 1.5 times of the interquartile range above the third quartile or below the first quartile.

	Mean time to find the YAH point (in s)	**Mean time for exploring the map (in s)**
IL	27.09	256.58
FI	19.36	328.50
GI	144.92	491.25

Table 6.1.: Mean times of successful finishing the two tasks in the study: finding the YAH point and exploring the whole map.

= 108.01s). The most time was taken in the GI condition (M = 491.25s, SD = 187.55). An one-way repeated measures ANOVA test revealed that for searching the YAH symbol the conditions differ highly significantly ($F(2, 33) = 7.23$, $p < .05$). A two-tailed t-test between the IL and FI condition revealed no significant effect between them ($t(11) = -1.74$, $p > .05$). The strong increase in exploration time in the GI condition appeared to make the whole difference (see Table 6.1). A pairwise t-check supports this assumption (FI&GI: $t(11) = -3.31$, $p < .05$; IL&GI: $t(11) = -3.59$, $p < .05$). Thus, the FI condition and the IL condition cannot be rejected to be the same. But that undistinguishable performance does mean that they are the same. In contrast, the GI condition differs statistically significantly from both of them. A descriptive analysis of search times and exploration times is given in Table 6.1 below.

6.4.3. Externalized Route Knowledge: The Route Descriptions

In total test subjects produced 66 descriptions (2 routes per map x 3 maps x 11 test subjects, one test subject's verbalizations could not be analysed due to voice recording problems). In each condition, one test subject failed to describe one questioned route (in each condition it was a different test subject). Thus some interpretation could be made from 95.5% of all given answers. Only in the GI condition test subjects mixed up landmarks and thus described 4 routes in just the other direction (from B to A instead from A to B). This was approximately 18 % of all GI routes.

Quality-wise, the contents of the route instructions differed to a great extent: some contained only a succession of projective directions without naming any landmarks, in others each action to change direction was bound to landmarks and in some every decision point was named (even if no turn occurred).

Even if it was not explicitly demanded for, test subjects described a route from the start to the destination that was length-optimal (i.e. shortest route possible) most of the times (73% of all interpretable routes) and at the same time turn-optimal (i.e. the lowest number of turns possible). The length-optimal and turn-optimal route was labelled 'A' in each map (see Figure 6.2–Figure 6.4)[3]. Other turn-optimal but not length-optimal routes (labelled 'B',

[3] During debriefing it showed that no subject knew that they were optimising on those factors

’C’ or ’D’ in the maps) were chosen in 24% of the cases. In total, participants described turn-optimal routes in more than 96% of all cases. Other, longer routes with more turns were only described in the IL condition (labelled ’E’ in the maps). The length optimal route was often placed through the centre of the map. Some not optimal routes included segments that were placed at the outer region of the map (see route ’E’ for task YAH point to rectangular building in the IL condition, or route ’B’ or the task round building to rectangular building in the GI condition). Asked about their strategies to build up a route to successfully reach the destination, test subjects that took non-optimal routes emphasized that they felt an advantage in remembering and recalling a sequence of long segments in comparison to having a succession of short segments. From comments during the tasks it could be concluded that some subjects realized that it is not the shortest route. The strategy to include successive segments to form long straight parts of a route could be observed in both the turn-optimal and turn-suboptimal routes but not in length-optimal routes.

6.4.3.1. Subjective Rating of Route Quality

Comparing the results produced in the particular conditions without consideration of routes with mixed up landmarks (see “Without Correction” in chapter Evaluation) showed that route descriptions produced from the IL condition were rated best (M = 2.43, SD = 1.16), from the FI condition second (M = 2.57, SD = 1.22), and from the GI condition third (M = 3.11, SD = 1.89). When being interested in the knowledge about the area that is capture in routes with mixed up start or destination landmark, the analysis “with correction” yielded a different result: then, the description from the GI condition was second (M = 2.51, SD = 1.32), slightly ahead of the ratings of the descriptions from the FI condition. This could be due to the longer exploration times. The hypothesis that all conditions show statistically similar results could not be rejected, because an ANOVA test yielded no significant difference, neither with the results from the “Without Correction” analysis ($F(2, 63) = 1.08$, $p > .05$) nor with the results from the “With Correction” analysis ($F(2, 63) = .07$, $p > .05$).

6.4.3.2. Objective Analysis of Route Quality

Analysing the routes with the methodology proposed in chapter 3 supported the ideas that were drawn from the first, subjective assessment to some extent. Nonetheless it was not possible with any of the analytic schemes to yield a statistically significant difference between the conditions. My interpretation is that no conditions stands out from the others, they seem to be all alike.

As none of the analytic schemes could show any statistically significant intra-scheme difference (i.e. between the conditions), I tested if the schemes might actually measure the same things, i.e. the inter-scheme difference over all test cases is not statistically significant. This hypothesis had to be rejected ($p < .000008$, $F(3,40) > 2.8$). Therefore we might assume that the analytic results provided through the different schemes differ not only from chance but systematically.

To summarize, the evaluation of route descriptions showed that test subjects were able (in most cases) to construct routes that were not announced to them beforehand from their mental representation of the spatial configuration. On the one hand, this can be seen as indicator for the existence of some kind of survey knowledge, as the routes had to be constructed mentally. On the other hand, it is unclear if test subjects unconsciously or consciously prepared for the externalization of route knowledge as they could be observed to explore the area between landmarks more frequently than the outer regions of the maps. This was especially true after the in the second and third run when they noticed that the questions were always about routes between landmarks.

6.4.4. Externalized Survey Knowledge: The Sketches

In total test subjects produced 3x12=36 sketches. In total 6 sketches were rated with a grade 1 or 2, 26 with a grade 3 or 4, and only 4 were insufficient or failed completely. Together 32 sketches ($>$ 88%) were of sufficient quality or better. Sufficient in this context means that is the raters were convinced that navigators could extract routes between the three landmarks if they correctly interpreted the sketch maps. The quality of the sketch maps is regarded as another positive answer to the general interest of research question no. 2, i.e. if the test subject did build up an internal spatial representation of the spatial configuration represented through computer-generated tactile orientation maps.

6.4.4.1. Subjective Rating of Sketch Map Quality

An analysis of the sketches with respect to concepts that can be seen as an indicator of survey knowledge (e.g. a network of lines, or neighbourhood of regions) respectively route knowledge (e.g. single lines which starts at a landmark and ends at another) was performed. Two raters equivocally regarded 8 out of 36 sketches (22%) as showing route characteristics rather than survey characteristics. As these route sketches displayed very sparse detail of the whole area, they were not very useful as maps conveying survey knowledge. None of these sketches was considered to be better than grade 4, six of them were rated insufficient (4.5 or worse). Route sketches were produced in the GI condition most of the time ($\frac{5}{8}$ = 62.5%). In the IL and FI condition only 2 respectively 1 sketch with route characteristics could be observed. Only one test subject drew route sketches in all conditions. It seems that test subjects retreated to route maps when the complexity of a map and thus the content to be remembered becomes unmanageable.

Comparing the differences between the ratings produced in each condition shows that sketches produced in the FI condition were rated with the best grades and ratings showed the lowest standard deviation (M = 3.08; SD = .77). This could be interpreted as results being

Task	Searching the YAH Point			Exploring the map		
Condition	IL	FI	GI	IL	FI	GI
Average Rank	1.50	1.25	3.00	2.00	1.00	3.00

Table 6.2.: Respondents ranked the types of indicators when used in different tasks.

Condition	IL	FI	GI
Average Rank	1.75	1.125	3.00

Table 6.3.: Average ranking of the indicator methods.

the least controversial among the raters. The average rating for sketches produced in the IL condition was 3.21 (*SD* = 1.11) and for sketches produced in the FI condition 4.13 (*SD* = .87). With an average rating of more than 4 there is a tendency that sketches from the GI condition were seen as being at most sufficient on a very low level. Sketches from the other conditions were rated almost one magnitude better. This descriptive analysis was support by a formal one-side repeated measure ANOVA. The hypothesis that ratings in all conditions are the same had to be rejected ($F(2,33) = 4.24$, $p < .05$). The significant difference in variance was further investigated with post-hoc pairwise *t*-tests between the conditions. The results from the FI condition and IL condition do not differ significantly ($t(11) = .61$, $p > .05$), but results from the FI and GI conditions ($t(11) = -5.00$, $p < .05$) and from the IL and GI conditions ($t(11) = -4.00$, $p < .05$) differ significantly. If one excludes sketches that show route map characteristics (see paragraph above) from the analysis then the ANOVA no longer yields no significant difference between the conditions ($F(2, 25) = 1.51$, $p > .05$).

6.4.5. Subjective Ratings of Indicator Quality

The frame marks were ranked first for both tasks, the indicator line is second and the grid is third. The ranks for the indicator types in the two tasks can be found in Table 6.4.5.

Frame marks were clearly the method of choice when the exploration of a map should not be disturbed. This indicator type was favourable when searching for the YAH point as well, but not as distinctly as in the exploration task. The grid was considered worst in all tasks. This agrees with the quantitative results (GI condition is always worst) but not in all cases (people can objectively handle the IL faster than FI but they subjectively rank it lower). Combining the figures from both tasks linearly and projecting it into the range of $[1, 3]$ results in what is shown in Table 6.4.5. Without recurring to a specific task, test subjects clearly disliked the grid and voted in favour of the frame marks and the indicator line. The indicator line was rated best in total (see Table 6.4.5).

6.4.6. Comparing Route Description and Sketches

Comparing the results from the DrawMap phase and the DescribeRoute phase, sketches were rated lower (M = 3.47; SD = 1.08) than route descriptions: with corrections M = 2.51; SD = 1.24, without correction M = 2.70; SD = 1.49. The correlation between the ratings was r = .6 respectively r = .58. There is a moderate positive correlation between the means of the ratings of the route descriptions and means of the ratings of the sketches. When comparing the data with corrections being made with the pure data, the correlation only differs by .02. One interpretation is that sketch maps and route descriptions were formed on the basis of different types of spatial knowledge, respectively survey knowledge and route knowledge, and that during encoding time these knowledge bases were filled differently. During the course of the study subjects might have noticed that during recall there were several questions to describe routes but only one task for drawing a map. Consciously or subconsciously they might have adopted there memory strategy to account for the questions about routes.

6.4.7. Other Findings

Having demonstrated that the conditions have a strong effect on search time as well as a moderate effect on exploration time it was investigated if there was any difference between the conditions in the times needed to sketch a map (average times for IL: 87s, for FI: 83s, for GI: 97s). No such statistical effect was found.

We could observe that test subjects reported tactile illusions, namely shortening of lines when comparing horizontal and vertical lines, e.g., at a T-junction shape (c.f. Millar & Al-Attar, 2001). That length-distorting effect resembles the Müller-Lyer illusion in vision and was reported before for congenitally blind people (Heller, 2002). In this study, test subjects were not blind (but blind-folded) but showed similar effects to the previous work.

Map-users seemed to often explore the centre of the maps space more thoroughly than the outer perimeter. This could hint to the idea to represent less objects (only the important ones) at the perimeter as they are notice with less chance anyway. With more complex tactile maps, which put high cognitive load on the reader, such maps could suite map-readers who employ strategies to focus on the important part of the map, i.e. the centre area. Another interpretation could be that map-readers have certain pre-conceptions of how a map is structured. That is, they assumed or checked with a quick swift of their hands where the YAH symbol is located. If they find it in a more central area (often this is the case in YAH maps to enable a survey into all directions) that area will naturally be more important to them as near objects are more important than distant objects. Therefore, near object receive more attention and the objects at the perimeter less attention. One could conclude that if maps have important things to show at the perimeter there should be some note for the map-reader in the map description or the legend. Or there should be multiple maps that show different

Cond-ition	Finding the YAH point	Exploration of the map	Test Route Knowledge	Test Survey Knowledge	Subjective Ranking	TOTAL
IL	0.14	0.24	0.30 / 0.33	0.31 / 0.29	0.30	**0.256**
FI	0.10	0.31	0.31 / 0.35	0.30 / 0.31	0.19	**0.241**
GI	0.76	0.46	0.39 / 0.32	0.40 / 0.40	0.51	**0.502**

Table 6.4.: The table shows a condensed view of the normalized results from the tests outlined in the text. The smaller the numbers the better the performance in that particular condition compared to the other two conditions. The route knowledge and survey knowledge test have two figures: the first is from the subjective rating, the second from the analysis.

parts of the original map but with the important details in their centre. How such a set of related maps could be constructed to not loose the relation between the single maps, see the discussion of future work in chapter 8.3.

6.4.8. Review of Results

To gain an immediate overview over the results reported so far, and to allow for a comparison of how test subjects performed in the various conditions, I have put all the results together in a normalized form in Table 6.4 .

We can learn from this overview that there is evidence for limited acquisition of spatial knowledge from maps that have a grid on their surface (at least in comparison to maps with frame marks or an indicator line). An ANOVA test on the quasi-objective (it is not objective as it stems from human judgements) data (i.e. the results from the route knowledge and the survey knowledge tests) rejected the assumption that all conditions are the same ($F(2, 9) = 5.39$, $p = .029 < .05$). Including the subjective rankings of the user survey (i.e. the rankings from task 5 & 6) yield the same result but in an even more pronounced way ($F(2, 12) = 8.88$, $p = .004 < .05$). To look precisely into the differences of the conditions, a one-tailed t-test comparing the group statistics from the GI condition with the group statistics from the IL condition revealed a higher statistical chance that they are the same than that from the FI condition (GI&IL: $t(4) = -4.26$, $p = .012$; GI&FI: $t(4) = -2.94$, $p = .030$). As these last figures are based on very few data points, the interpretation is not sound but can give a direction.

Both the behavioural data (from the Phase FindYAHpoint and Phase ExploreMap) as well as the data from cognitively orientated phases (ExplainRoutes and DrawMap) indicate that using an indicator line or frame marks might be a cognitively adequate solution to the problem of indicating the YAH point haptically. The results from the survey about what users find more useful and least impeding support the objective findings as test subjects show a strong tendency to not favour the grid and prefer the frame marks to the indicator line. The dismissal of a grid when other linear features are present is in line with earlier findings about tactile line tracing (Barth, 1983). In comparison with the indicator line and the frame marks, the grid offers the opportunity to indicate the approximate positions of many objects when using a x, y-tuple as grid coordinates. This opportunity was discussed and acknowledged by the participants, but regarded as a theoretical question. They could not imagine whether a solution with line indicators, frame mark, or grid would prove to be better when many objects had to be indicated. Such questions should be dealt with in further studies.

6.5. Discussion & Recommendations for Schematisation Principles

6.5.1. Route Descriptions

Choices for verbalizations might be influenced by factors of chunking, e.g. only right turns (see route 'B' for task round building to rectangular building in the GI condition), or by having uniform pattern (see route 'B' for task rectangle building to round building in the FI condition). Recall of long segments or successions of segments without a turn in route descriptions could be an effect of easier encoding of these segments. There is more time to represent these entities mentally during the exploration compared to the quick succession of short segments. During the tactile exploration the interpretation of continuous serial tactile sensation involves integration of new concepts into the existing mental model. Especially in the case of tactual stimuli this takes high cognitive effort. Thus, the time gained in exploring long segments in comparison to short segments might help to cope with the effort of integration. That could be one reason why test subjects in some cases chose the long routes that were either not length-optimal or not turn-optimal.

6.5.2. Difference to the Results of Denis

Denis (1997) reported a high percentage of wayfinding actions being bound to landmarks. In contrast I have found most actions to be verbalized without a indicator to a landmark. This is probably due to the very limited number of object landmarks (in contrast to the landmarks that are induced by the network of tracks, like intersections). Among others, Michon & Denis (2001) labelled these landmarks with the term "3d landmarks", the other type "2d landmarks". In the absence of prominent 3d landmarks, the test subjects in this study only relied on 2d landmarks and verbalized it.

6.5.3. Limitations in the Material

By some unfortunate accident, one segment was missing from one of the maps. This missing segment resulted in one missing region in that map and a change of +1 in the cardinality of one region (see Figure 6.5, left).

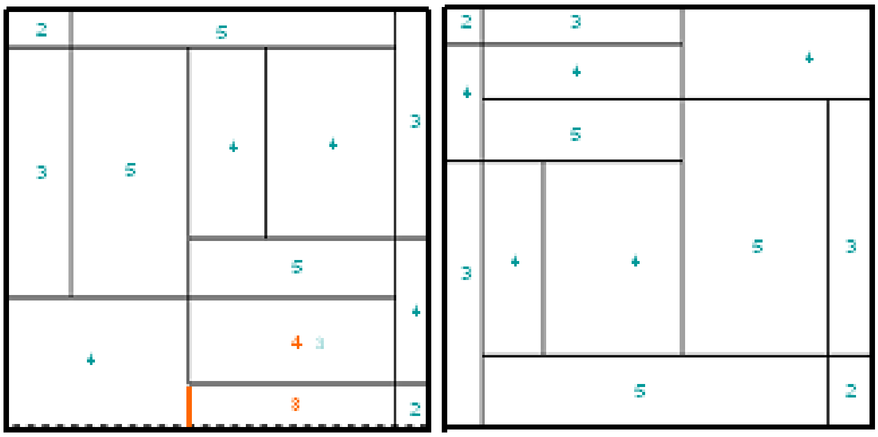

Figure 6.5.: Left: The (distorted) map for the RM condition. The orange segment was accidentally missing in the stimulus material. That caused some (unwanted) changes in the neighbourhood relation such that the cardinality of two regions changed (orange text). With the segment in place this map would have been topologically equivalent to the others. Right: the GI map rotated 180ĉirc to show that it is structurally equal to the (corrected) map in RM condition.

In how far this has effected the complexity of the map is questionable as the place where the segment should have been was in the 'outskirts' of the map, i.e. not in the centre. And it led to the "border" of the map, i.e. a region that seems to be of little interest if we take into account the exploration strategies we could observe even if all segments were present.

In an inter-condition comparison, shortest routes from the YAH point to some other landmark did not have the same complexity (in terms of turns) in all maps. In the IL and the GI conditions the route to the rectangular building takes one turn, and to the second two turns. In contrast, in the FI condition the route to the first building takes two turns and to the second three turns. Additionally for the task of walking from the YAH point to the circular building in the GI condition, there was no second shortest route with the same complexity as the shortest routes. In all other conditions this second option with the same number of turns was always present. These factors might have had an influence on the cognitive processing of the map, but they were not accounted for so far in the evaluation.

In an intra-condition comparison, each map except for the one in the GI condition afforded two routes from the YAH point to some second landmark having the same number of turns but different length. For the task of walking from the YAH point to the circular building the shortest route has one turn, the second shortest has three turns. Thus, test subjects could not choose an alternative for this route but had the chance in other tasks on the same map. Additionally, the complexity (in number of turns) of routes from the YAH point to the rectangular building and the route from the YAH point to the circular building differed in the GI and IL conditions. These factors might have had an influence on the cognitive processing of the

Map	Task	Route	Turns
IL	YAH – Rectangle	Shortest (A)	2
		Alternative (B)	2
	YAH – Circle $*$	Shortest	1
		Alternative	3
FI	YAH – Rectangle	Shortest (A)	2
		Alternative	2
	YAH - Circle	Shortest (A)	3
		Alternative (B)	3
GI	YAH – Rectangle	Shortest (A)	2
		Alternative	2
	YAH - Circle	Shortest (A)	1
		Alternative	3

Table 6.5.: Characteristics of the shortest route and its alternative for each map and task. Letters in brackets behind the route indicate that test subjects described this route at least one time. The specific letter labels the route as displayed in Figure 13. An '$*$' denotes that this route was not asked for, the details in this table are only for the sake of completeness.

map. As some test subjects were asked about the one route and some were asked about the other route their results are not easily comparable.

These factors might have had an influence on the cognitive processing of the map, but they were not accounted for in the evaluation. For details of the mentioned characteristics of routes see Table 6.5. It is hard to know if they might have caused noise in the data or not. By counterbalancing the maps, the difference was distributed across conditions. Thus, any cognitive differences was equally distributed.

Some improvement in the modelling of the maps might be needed. For some test subjects it was obviously not clear where to enter a building (they were told in the instructions, but that sometimes did not help much). Definite exits of and entries to buildings to emphasize the movement in and out of them should be thought of. Extra decision points in front of buildings to separate the segment that runs along buildings in two distinct parts might be good to avoid confusion.

Three landmarks were too few for a map that should somehow resemble a common situation in the world. The complexity was not realistic enough but higher complexity would certainly mean more training for the participants. The displayed network of straight streets with perpendicular intersections of three streets maximum are very limited in the expressiveness. Such networks can be found in some parts of the geographic world, for example in North America, but they are atypical for Europe, for example. It should be extended to networks with more elaborate geometry and topology. This could be done by investigating intersections that are qualitatively and quantitatively more complex, i.e. allowing for more types of intersection with more streets and different angles (not just increments of 90°). For example, allowing increments of 30° or 45° would give the opportunity for far more types of intersections and thus more variations in the map. Increasing the number of incoming streets would also increase the variations but also the expressiveness of the maps. At the some time the complexity of such map is likely to be higher that what was tested for in this study.

6.5.4. Limitation in the choice of test subjects

Testing sighted people instead of blind people in these studies might be questioned. Colloquial wisdoms favours the impression that blind people were so much better than sighted when asked to solve tactile tasks. But on the sensory level, blind and sighted people depend on the same bodily sensor system. For example, for judgements of smoothness, Heller (1989b) found no differences by sighted and blind respondents, neither for passive touch (in which a stimulus is applied to a static skin surface) nor for active touch (in which a stimulus is engaged with by a moving skin surface). Jehoel et al. (2005) reassessed those findings and concluded that there are mostly preference differences in both the blind as well as the sighted people when it comes to touch. When it comes to basic cognitive tasks like object matching, blindfolded sighted people learn quicker in repeated tasks than blind people but blind people are still better in shape recognition and comparison (Postma et al., 2007). It seems that haptic experience increases the speed of identification of simple shapes, but blind people do not perform as well when active elaboration is required (Vecchi, 1998). In contrast to sensing and object matching, the study reported here depends more on higher cognitive abilities that demand the tacit and procedural knowledge how to interpret a map. But several works support the similar performance of sighted and blind people in pictorial based task, such as haptic and visual map updating (Giudice et al., 2011) and haptic graph reading and pattern recognition (Giudice et al., 2012). Nonetheless, conducting field studies or studies with blind people could foster the ecological validity of the findings reported here. Especially the performance of congenitally blind people could be interesting because the ability to understand maps might depend on how well the concept of maps as 2d abstract representations of the 3d world can be communicated.

6.5.5. Generalisation of the Results

In this study tactile YAH maps were taken as exemplary type of maps in which the indication of a position is needed. With the results found for that special type one could ask whether a transfer to other types of maps or a generalisation to all similar types of maps might be feasible. Two questions arise:

1. Do the characteristics of tactile YAH maps render them incomparable to other types of maps such that a successful transfer is unlikely?

2. If not, which types of maps could be similar such that a successful transfer is likely.

The special characteristic of each YAH map—regardless whether it is a visual map or a tactile map—is the salient YAH symbol that is prominently displayed. In a hardcopy tactile map produced with a tactile printer, the realisation of that signifier is limited to only very few dimensions to produce a tactile pop-out effect. First, the elevation above the base level is a good discriminator in traditional tactile maps. If a map-maker wants one particular map element to pop-out it can be done by employing the maximum elevation possible. Then the map reader will notice that particular element by a swift scan in low altitude over the map. But the elevation dimension is only of limited use to catch the user attention as the min-max contrast in hardcopy tactile maps is not distinct enough (see chapter 4). Second, catching the user's attention by extreme size is limited as well because space is rare in tactile maps. As a result, the pop-out effect cannot be as strong in hardcopy tactile maps as it could be in traditional tactile maps. Thus, the stark accentuation of the location indicator and the YAH symbol that is so characteristic for visual YAH maps is only of limited use in hardcopy tactile YAH maps. As a consequence the YAH symbol in tactile maps is more similar to the other symbols than in visual YAH maps. In tactile maps, the YAH symbol is a special symbol among others. That is, the tactile YAH symbol does not—in contrast to good visual YAH maps—capture the map-readers' attention in a quick scan of the map.

As the YAH symbol is a special symbol among others, one could ask whether the guides and pointers could be used to notify the map user of the existence and position of other map objects as well. The types of maps that could benefit from a transfer of the findings presented here could be probably found when looking into the context of use that was supported. This includes user characteristics, task characteristics and characteristics of the map. Looking back into the scenario (see chapter 1) the user was characterised as being blind, not familiar with the environment depicted in the map and interested to know more about it.

The tasks that a tactile orientation map should support were characterised in chapter 3 as being mainly localisation and survey mapping, and to a small extent route finding. The TOM was characterised as a survey map that (potentially) displays lots of information. Thus I reckon that especially survey maps could benefit as they are more populated than route maps and because in route maps the start location and end location could be easily found by following the route (the route has a function like an indicator line). And, the indicators reviewed in this research might support in a usage context in which positions need to be indicated in a tactile map of a formerly unknown environment (if it was known, the map-users could simply explore a bit of the area they know and find the positions by correspondence with their cognitive map).

One factor in the consideration of which indicator to use is the total number of indicators needed and the size of the map. Using the indicator line is fast and can support usage when finding one particular position is time critical. The indicator line might become unusable if more than two symbols should be brought to the foreground. Then the extra lines in the map space (which have no geographic meaning) contribute to the clutter in the map and the map-reader might be more confused than supported, at least in the exploration task. The frame marks could be a suitable solution if there are only a few positions to be shown and the map is already filled with symbols. Then having more lines in the map space would not be a good idea. If too many positions were to be shown the symbols at the frame margin would be too many – cluttering at the frame margin would hinder the discrimination. In such a situation, i.e. if there is the need to specify the positions of many objects, it would be a good idea to use the grid, especially if the map space is big and cannot be handled easily. For example, in tactile orientation maps that exceed the size of 20x30cm, a grid could be a good idea. The rather huge search space would then be subdivided into smaller handy parts.

Another solution could be to develop interactive tactile maps that offer dynamic updating of the map contents. In such a way, objects and symbols could be shown whenever needed and customized to the task at hand, the users' knowledge and abilities, and the complexity of the map. Then, in the progression of the interaction between the user and the (interactive) map, the computer could dynamically decide which of the indicator types is the most appropriate to highlight certain objects in the situation at hand (for references, see Giudice et al., 2012).

6.6. Summary

The study investigated the usability of three different types of location indicators in a hard-copy tactile orientation map: frame marks, indicator line and grid. From the study the following statements can be supported.

1. There is considerable variance in the times needed to find an unknown position in a tactile map. This depends on the type of location indicators it is equipped with.
2. If the map is used only to show one particular position (and maybe its immediate surroundings), the best way to support the map user is by displaying a indicator line to that position.
3. If map exploration constitutes a big part of the map-usage task then the frame marks are better suited than the others.
4. The participants judged these two indicators as overall superior than the grid.

The study provided new evidence for the superiority of the frame marks and an indicator line over the grid in terms of effectiveness, efficiency, and satisfaction. Aside from the objective data the subjective rankings for the usability of each means in exploring the map support those findings. Some conceptual considerations about the impact of map topology and map geometry on human wayfinding abilities were brought to a status from which further studies might start.

Part III.

Cognitively-Adequate Schematisation as a Construction Principle for Tactile Maps

Chapter 7.

The Generation of Schematised Tactile Environment Maps

In this chapter I will review the studies and the findings generated (chapters 4–6), discuss the limits and to which extent they are generalizable. First, in section 7.1 I will discuss the findings from the studies and how they can be employed together in individual map-construction so that map-users obtain maximum benefit. Then, in section 7.2, I will discuss the limits of schematisation. Specifically, I discuss the role of location indicators as clutter that impair map-reading, the misunderstandings that could result as consequences of schematisation, and the influence individual differences might have in understanding TOMs. Last, in section 7.3, I will argue that the schematisation principles identified in this thesis are not only valid for the specific matrix-based tactile printer used but for a whole class of matrix-based display technologies, including dynamic tactile displays. Further, I will discuss the generalisation and transfer of schematisation principles to other types of maps and production technologies that are not matrix-based.

7.1. Discussion of the Findings from the Studies

The theoretical review in chapter 2 and the concept for tactile orientation maps (TOMs) in chapter 3 has shown that the challenge of creating perceptible and understandable TOMs with a tactile printer is not trivial. The studies described in chapter 4 to chapter 6 were set up to clarify most of the challenging aspects, namely

- the user requirements that have to be met when developing tactile orientation maps for the use of potential users,
- the opportunities and constraints in production technologies used, namely dot matrix embossers, and
- the schematisation principles that facilitate map learning, according to the above mentioned requirements and constraints.

In the following subsections I will briefly recap the findings elaborated in the previous individual chapters, discuss their overall meaning for the challenge of creating tactile orientation maps, and deliberate how they relate to one another.

7.1.1. User-Requirements about Tactile Orientation Maps

A main finding that has resulted from the thesis studies has been that potential users expressed a great need and interest for obtaining access to tactile orientation maps. As assumed beforehand the availability of digital wayfinding tools, like navigation systems, does not render the classical print map obsolete. This is especially true with tactile maps, owing to the reasons summed up in the following list (distilled from the literature review in chapter 2 and findings in the studies in chapter 4–6):

- Non-visual navigation relies heavily on experience in the geographic environment, whether direct or indirect experience. Tactile orientation maps are regarded as an opportunity find out how a geographical environment is structured before actually arriving in that environment. The spatial knowledge acquired from such maps is essential to build up a survey-type representation (such as cognitive maps), even if it was coarse and distorted. These are properties that can be found in spatial representations derived from any input (c.f. Siegel & White, 1975, p. 21).

- The navigation systems available are often only suitable for route-related spatial tasks, like path-finding. They are not made to provide a survey-view of the environment. A combination of survey-oriented navigation tools and route-oriented tools could be the solution of choice for blind individuals' independent navigation.

- Special purpose high-tech navigation systems, adapted to visually impaired persons' needs, are a lot more expensive than the common systems for visually able people. Therefore, an inexpensive low-tech alternative, accessible to the blind, would be highly welcomed, especially if that alternative is able to provide access to environments that are usually not represented in other low-tech materials, such as a tactile atlas.

- With reference to the questionable reliability of GPS-driven navigation systems in closed spaces, for example between tall skyscrapers (imagine the streets of New York), stationary solutions that do not rely on GPS signals were regarded as more reliable and sufficient for the task of preparing for a trip by the study participants.

The interviews (see chapter 4) have shown that people would probably use maps as wayfinding aids if they offered an advantage over personal communication and GPS-driven digital navigation systems and if they allow to maintain independence and foster wayfinding competence. The interviewees required the maps not only to be accessible but also to quickly understand them (30 minutes at the most to understand an DIN A4 map; the average time for exploration of a complex tactile map was about 17 minutes, see chapter 6). Especially maps for unknown or unfamiliar environments were demanded in the interviews. Generally, the individual construction of tactile maps that are customized to personal needs was one of the main requirements. And, tactile orientation maps were only regarded as being a support if they could be made available within a short time frame (if instant production at home is not feasible, one day of production and delivery would be accepted).

Comparing GPS-based travel aids with tactile maps could be misleading. The latter is not a low-tech alternative to the first, as they serve different purposes in wayfinding. At best, both could complement one another. On the one hand, GPS-based travel aids can help the traveller to build up a route-based spatial representation that allows for path-following on a turn-by-turn basis once navigators are in the environment. On the other hand, maps allow for cognitive map development that is allocentric and not route-based. During travel preparation, a robust and flexible overview of the environment can develop, i.e. as a cognitive map. This enables shortcuts, spatial inference, knowledge of inter-object relations, and a lot of off-route knowledge that is hard or impossible to achieve from simple route-based representation or route-guidance technologies (c.f. Long & Giudice, 2010). Once in the environment, travellers can improve self-localisation in relation to principal landmarks and to the whole area. Additionally, travellers can use wayfinding strategies that are not possible without survey knowledge, for example, pleasure walks, informed searches or planning a path (see subsection 2.1.1). Thus, tactile maps should play a greater role in the lives of blind people and support survey knowledge acquisition, increased independent navigation, and access to spatial behaviours and cognitive strategies that were inaccessible before.

7.1.2. Constraints in the Production of Tactile Maps with Matrix Printers

Throughout the studies presented in chapter 4 to 6, one may notice that a main constraint for the production of tactile materials with tactile printers is the limited possibilities to differentiate surface patterns and shapes on the results. First, the maximum elevation above the base level of the paper is very limited and only two elevation levels can clearly be distinguished (plus the flat level, i.e. no elevation at all). Due to these constraints, a usable thermoform terrain map like Figure 7.1 cannot be reproduced with the ViewPlus Emprint – it needs clearer, more distinguishable elevation levels to represent altitudes. Nevertheless, using the Emprint, even if with its limited levels, is the best computer based solution there currently is. Most tactile graphics produced from standard Braille embossers only have one level and blank (compare the printers by Index), so the Emprint actually gives more levels of gradation, which is just not enough. Second, low-details of geometry, such as short straight edges, small symbolic entities, or slightly curved parts can be produced to some extent. But even the details that can be displayed are hard to recognise during map exploration – too easily are they missed. Production of high-detail maps, as in thermoform maps like Figure 7.3, is not possible at all with tactile printing. Third, highly heterogeneous surfaces, like those produced with thermoforming (see Figure 7.2), cannot be reproduced in hardcopies. The variables for printing tactile surfaces are far too limited. In hardcopies, comparably big geometric entities are needed to enable the map reader to detect shape, elevation and surface patterns and discriminate two entities. Further even larger entities are needed to allow for recognition.

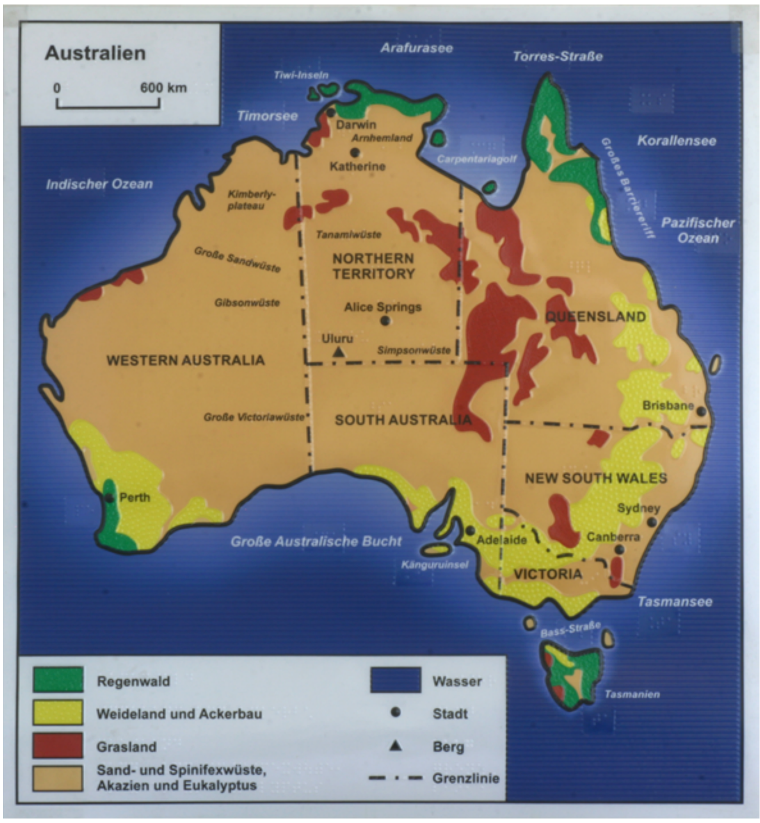

Figure 7.1.: A traditional tactile thematic map of Australia with additional colour codes. Map © by Deutsche Zentralbücherei für Blinde, Leipzig, Photo © by the author.

Altogether this means that only basic geometric shapes can be represented, preferably with straight edges, and not many different surface patterns can be realised. Compared to traditional tactile maps the 'vocabulary' to display tactile entities, whether symbols, lines, or areas, is relatively low. Therefore the possibility to encode different meaning through shapes, elevation, and surface patterns is limited. For maps. as illustrated in Figure 7.3, Figure 7.1, and Figure 7.2 this is not enough. However, other types of maps are more adaptable. Maps that do not need high variance in elevation with several clearly discriminable signatures can be produced. Orientation maps that only display streets and important landmarks are one example.

To make orientation maps a suitable application area for printing technologies, some factors have to be considered to make them usable. Telling two tactile entities apart is essential

Figure 7.2.: Detail from the map in Figure 7.1: the tactile signatures become distinguishable, for example, raised and stippled areas denote montain ranges, and hatched areas denote water. Map © by Deutsche Zentralbücherei für Blinde, Leipzig, Photo © by the author.

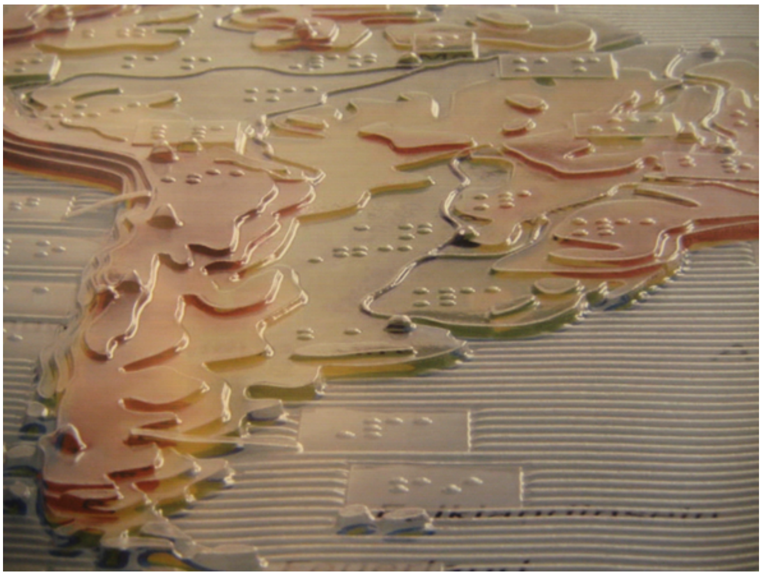

Figure 7.3.: Detail from a traditional tactile topographic map of South America: different levels of flat areas mean different elevation levels. Map © by Deutsche Zentralbücherei für Blinde, Leipzig, Photo © by the author.

when two conceptual entities need to be clearly discriminated; let us imagine a street (represented by a line) that runs along a park (represented by an 2d shape).

- As shown in the studies (see section 4), noticing the separation between two conceptual entities is facilitated by introducing a gap between their geometric counterparts. However, the gap should not be too big as their relation should be obvious (for example, it should be obvious that the street RUNS ALONG the park). 2.5 to 3.7 mm space between entities (two or three taxels with the Emprint embosser) has proven to be a suitable distance and the ideal measure to be distinguished and yet considered related. The distance may be small (2.5mm or 2 taxels) if the two edges are straight and in a strict vertical or horizontal line. More space (3.7mm or 3 taxels) is needed in all other cases, especially if uneven lines are involved.

- Filling a small area (below 25mm x 25mm) with a tactile structure often results in lacking adequate recognition during map-reading. Such small patches do not carry enough taxels to display the characteristics of certain structure even if it is coarse. With these small patches the usage of filled shapes in contrast to outlines (i.e. non-filled shapes) is recommended. If the areas are larger, simple symbols can be added to the interior to assign meaning through the legend. Symbols should be at least 14mm (11 taxels on the Emprint) wide. Separation between symbols and other tactile entities should be at least 3.7mm (3 taxels). If larger areas are filled, simple areal signatures are easiest to recognise: repeating line patterns such as stripes are recommended.

- Small directional changes of 45° of straight lines (i.e. an intersection of two streets with an angle 135°) have to be longer than about two centimetres to be detectable. If any smaller, such setup can lose its unique features and instead give the impression of being 'round'. When abstracting the shape of regions this must also be taken into account.

- Representation of extended objects by symbols is feasible and in line with the experience of knowledgeable blind people. However, it impairs the opportunity to get an impression of the size of the object. For buildings this might not be an issue as usually, the location of the building and its entrance are essential to successfully executed wayfinding tasks. For parks and parking lots that serve as audio landmarks schematisation might be detrimental as their shape give an impression of the spatial extension.

The characteristics of the printing technologies investigated nicely fit to the application area that was investigated. A tactile printer that produces print-outs with discrete entities arranged in a fixed matrix can well produce maps that mainly show the line features of two different kinds: a small set of symbols (max. 7 in the studies reported), and a few different surface signatures (max. two). Some more differentiations of the dimensions are possible, for example, introducing broken lines to represent another street type or more symbols to represent other landmarks. However, it is an open question whether these extra signatures actually help to understand maps or whether they would be regarded as clutter. It might help to establish certain conventional symbols. Once their meaning is learnt they can be applied in every map.

7.1.3. Schematisation to Enable Map-Usage and Map-Understanding

As shown in this thesis, certain constraints become clear through printing technologies when producing tactile maps. These constraints are essential factors to be considered when constructing tactile maps. The low resolution of hardcopies is adapted to computer-generated tactile orientation maps by schematising intersections, line geometries and symbol characteristics.

Being aware of certain user-requirements and the constraints of printing technologies have provided the foundation for the subsequent investigations into schematisation principles for TOMs, see chapter 5 and chapter 6. I will first discuss the concepts for localisation in tactile orientation maps that were investigated in chapter 5. Then I will look into the conceptual basis of the schematisation investigated in chapter 6. At the end of this section I will discuss factors that need to be taken into account when adapting the schematisation principles to the situation at hand to enable usage and understanding.

7.1.3.1. Concepts for Localisation Support in Tactile Orientation Maps

As shown in the studies reported in chapter 6 location indicators on tactile orientation maps can be a useful and practical support in handling tactile maps. Directing attention through location indicators seems to facilitate the usage of the map compared to the standard situation without indicators.

The cognitive function of localisation indicators was based on providing 'short-cuts' to the targets on the map. By omitting most of the map space the search space is smaller and user-searches end faster. Two classes of short-cuts were described and tested in a pilot study: pointers and guides. Both work similarly but each affords different degrees of support in localisation (for details, see chapter 3). For a schematic visualisation of the search spaces with the different localisation methods, see Figure 7.4.

One factor when considering which indicator to use is the total amount of indicators needed and the size of the map. As indicated through the results of the studies in chapter 6, using the indicator line is fast and can support map-usage when localising one particular position is urgent. The purpose of the indicator line might be diminished if more than two are used. Then the extra lines (that have no spatial meaning) contribute to the clutter in the map and the map-reader might feel more confused than supported. If there is the need to

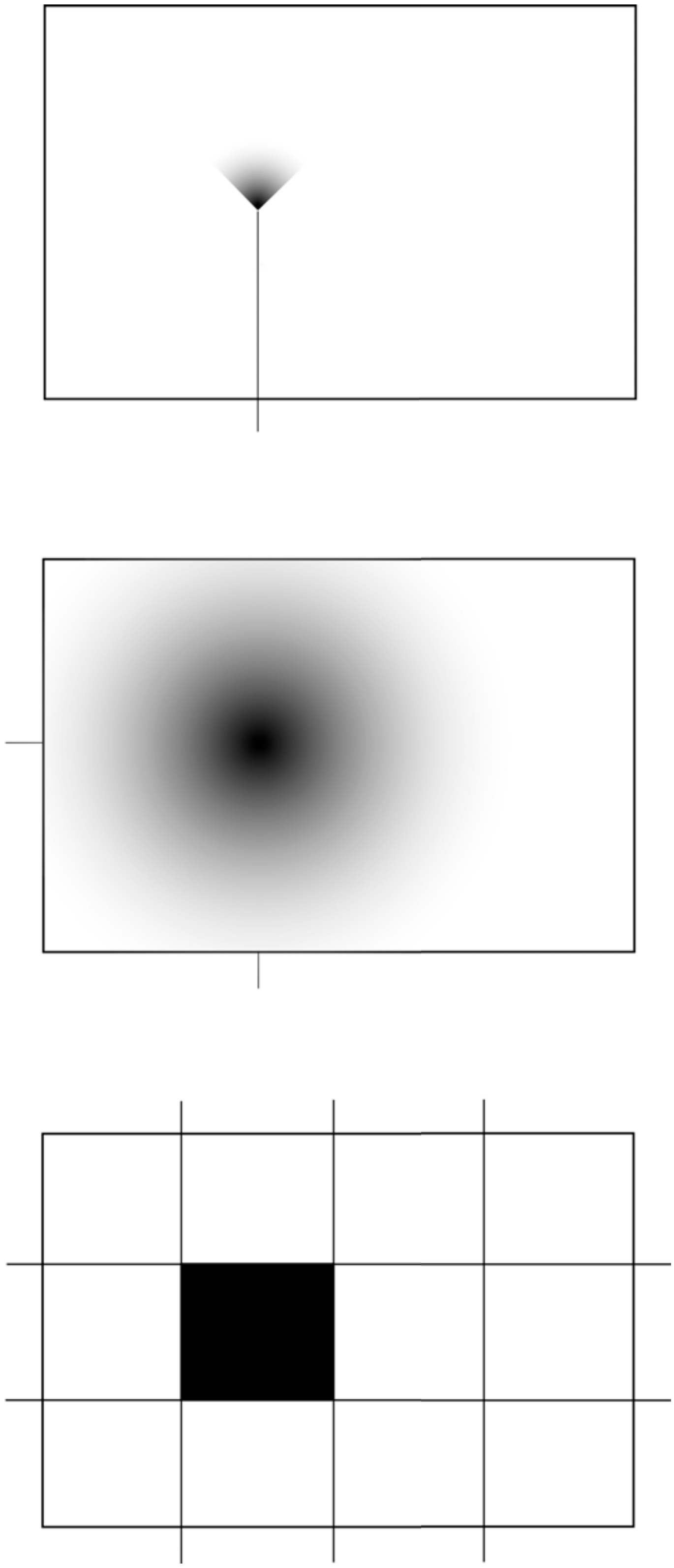

Figure 7.4.: Schematic illustration showing different potential search spaces when localisation short-cuts are used (likelihood is encoded in grey tones): (top) Line Indicator (center) Frame Indicator (bottom) Grid Indicator.

specify the positions of several objects it is a good idea to use the grid, especially if the map space is extensive. For example, in tactile orientation maps that exceed the size of format A4 (29.7mm*21mm), a grid could be a good idea. The rather extensive search space is then subdivided into smaller functional parts. If the map is already filled with symbols, introducing more symbols to the map space is not a very good idea. In order to accommodate this situation, the frame marks could be a suitable solution, albeit limited to indicating only few positions.

In summary, localisation support in tactile orientation maps can be helpful. Tactile map-usage becomes less cognitively demanding with indicators because the search space is reduced. One can argue that the less complex the map-usage is, the better the usability of tactile orientation maps. But the discussion has shown that not each indicator type is helpful in each context of use.

7.1.3.2. Concepts for Facilitating Survey Knowledge Acquisition with Tactile Orientation Maps

Position indicators are auxiliaries to facilitate map-understanding because they provide fast access to one or more reference entities. A clearly indicated reference entity could make it easier to build relations to other map entities. To build relations between spatially distributed objects has been defined as one form of spatial knowledge (i.e. location knowledge) (Kuipers, 1978). Learning the locations and relations of landmarks is a good start for subsequently learning routes and eventually acquiring survey knowledge.

As shown in chapter 5, schematisation of intersections and schematisation of street representations can contribute to the usability of a tactile map. During integration of spatial information, cognitive demand is limited by reducing sensory ambiguity and instead providing categorical information. In less abstract maps the map-reader is forced to differentiate between many individual shapes of intersections that might only have subtle differences. The process of recognizing each angular setup for each intersection can take a lot of time and attention. In a schematised map, the schematised intersection only gives categorical information. These characteristics need to be communicated so that map-readers do not treat them as exact geometric representations. Subsequently, map readers only need to recognise a few prototypes of intersections instead of memorising every single one. As demonstrated in chapter 5 this means less effort and therefore building accurate spatial mental representations is facilitated.

The findings from chapter 5 can be interpreted in yet another way: Besides reducing sensory clutter, communication of spatial concepts is improved the more the maps are schematised. On the downside, individual details about streets and intersection are missing. And, as by definition, a schematised map is highly abstracted from reality, it costs more effort aligning it to the geography of physical reality. Distances might not be to scale and shapes of streets in the geographic world might be different to the ones perceived from rendering the map . As a result, shapes of regions could be different in the geographic world than inferred from the map. These are artefacts of the schematisation process applied to the street network. And surely, there must have been more salient objects in the environment that catch attention than on a corresponding TOM, where only buildings, parks or zoos were highlighted. Thus, before reading a TOM, the effects of schematisation and the conventions used should be communicated, for example, by an accompagning instruction sheet. If such maps became popular, orientation and mobility instructors could be suitable multipliers. Otherwise a TOM could be severely misinterpreted, for example when considered being metric.

Beside the peculiarities of map-interpretations, there are the benefits of schematised representation of the world: mental operations could become easier, for example in routing. As Klippel (2003) have shown, the use of wayfinding choremes (schematised turning instructions) helped people to plan, describe and find their way. With schematised survey maps the inference of routes along a schematised path might become easier as the studies reported in this thesis indicate. This could be experimentally investigated in future research.

7.1.3.3. Conditions for Schematisation

The scenario introduced in chapter 1 – namely the survey on learning about a formerly unknown environment to allow for independent orientation and wayfinding – motivated specific wayfinding activities, discussed in chapter 2. Beside this specific scenario, tactile orientation maps could be used in other wayfinding situations as well. Some of the interviewees, reported in chapter 4, mentioned these situations (for example, that the map-reader already knows part of the environment) as desirable to be supported by an individual wayfinding aid such as tactile maps. Motivated by the outcome of the interviews and based on my studies and existing literature, I will analyse and discuss factors that characterise different wayfinding situations in which tactile maps could be supportive.

1. Goal of usage: the type of spatial knowledge that is primarily learned, categorised by Kuipers (1978).
    a) Location knowledge: the location of spatial entities is learned to get an idea of where the main landmarks are located and how they are directionally related to one another. To specify this information, a location map is used, i.e. a map with symbolised landmarks. If there are main streets to give context information, only the shape of streets should be schematised (not the intersections!). Subsequently schematisation does not introduce distortions for the positions of landmarks. This preserves the veridicality of the displayed positions.
    b) Route knowledge: A route from a starting point to a destination is sought: special route maps are recommended, that is a different type of map for other options of

schematisation (for a review of that schematisation see Graf & Schmid, 2010).

c) Survey knowledge: the standard case discussed in this thesis. The characterised tactile orientation maps are suggested for map developers as a concept to convey spatial meaning, for individual navigators as spatial learning tools, and for mobility trainers as tools for communicating spaces.

2. Existence of prior knowledge: the quality of spatial knowledge of the environment before starting to read the map.

   a) None: everything must be learned, especially location knowledge and survey knowledge: as shown in classic texts about spatial learning, location knowledge should be learned first, followed by route, and eventually survey knowledge (Siegel & White, 1975).

   b) Limited to one part ('home zone'): the existing knowledge should be extended to cover all parts of the environment : learning the areas outside the home zone and connecting to existing knowledge must be supported, e.g. by showing only main reference structures/landmarks in the home zone and detailing the unfamiliar parts with major landmarks and structures so that landmark knowledge about the unknown parts, and subsequently route and survey knowledge, can be established.

   c) Limited to *n* unconnected parts ('known zones'): the existing fragments of knowledge must be related to one another so that an integrated model can develop; then the gaps in the model have to be filled; relating the known zones to one another, e.g. in direction and distance, could occur by simply displaying the main reference structure/landmark in the known zones. As soon as these known zones are related, the gaps in-between can be filled the way described in case 1.2.

   d) All known: the users should be reassured regarding the main spatial structures and encouraged to learn background details that have possibly been forgotten, for example, by making them more prominent.

3. Timeliness: the relation between point of time of knowledge acquisition and point of time of knowledge use.

   a) Before travelling (preparation): the standard case discussed in this thesis, i.e. the tactile orientation map, is consulted before a journey starts. When re-interpreting Wiener et al. (2009)'s taxonomy one can identify several strategies that are not only applied when on site, but also in mental wayfinding, for example, Informed Search, Path Search and Path Planning.

   b) During travelling (on-route): tactile orientation maps can be taken along. However, they are not made for this particular use. As they are not dynamic and cannot be updated, it is not possible to display the current position. In this case Path Following GPS enabled route planners would most probably be a better support. They monitor locomotion and give directions appropriate to situations. Nevertheless, in certain cases a tactile orientation map can support on-route navigation. They could serve as a reference map and support orientation querying configuration of landmarks.

c) After travelling (reflection): after travelling the tactile orientation map can be used to disambiguate contradictory impressions gathered during travels, for example to clarify directions, or it could be used to foster the spatial knowledge collected during environmental mapping.

These characteristics define the dimensions (goal of usage, existence of prior knowledge, and time of usage) for map-usage scenarios. Valid realisations are listed for each dimension. A specific scenario is defined by selecting one realisation per dimension, i.e. a 3-tuple. Each tuple stands for a specific scenario. Additionally each scenario needs specific schematisation and results in a specific type of tactile map[1]. The three dimensions with their respective realisations (goal of usage: 3, existence of prior knowledge: 4, and time of usage: 3) result in $3 * 4 * 3 = 36$ different scenarios. Tactile maps could be adjusted to each one.

The concept of tactile orientation maps as discussed in chapter 3 was only targeted at one of these usage scenarios: acquiring survey knowledge / without having prior knowledge / before the travel starts. But during research, particularly during the interviews (see chapter 4), it became clear that tactile orientation maps will also be used in other ways. Even if most of the characterised scenarios have not been studied in this thesis, many of the findings can probably be applied to other scenarios. For example, a tactile map for travel preparation could probably look similar to a tactile map that supports survey knowledge acquisition after exploration when the traveller had already gained some knowledge. The difference between the two is that the level of detail in the second map is not uniform any more. Unknown areas can be visualised in more detail than already known areas. But the rest is probably the same. Thus, guidelines that were primarily targeted at one specific usage scenario could then also be used to inform the construction of another type of map. In contrast, a tactile map that serves to acquire route knowledge against the background of prior knowledge for an on-route support would be very different. However, even for this extremely different type of map, many design factors investigated in this thesis are similar – and independent of their use. Especially the technological constraints and usability requirements of hardcopies presented in chapter 4 and the findings about localisation support for better tactile map-usage presented in chapter 6 could be very informative for realising other types of maps using the same production technique.

[1] That does not mean that the types of maps must be all different. Two or more scenarios may result in the same map design, i.e. the mapping from scenario to map design is assumed to be surjective.

7.2. The Limits of Schematisation

Up to this section the focus has been about the possibilities and advantages schematisation offers or could potentially introduce to understanding tactile maps. In this section I will cast some light on the question whether schematisation approaches possibly impair the usefulness of the map they are applied to. In certain cases the cognitive advantage of schematisation, both the reduced geometric details and highlighted conceptual details, may be regarded as a disadvantage. For example, details that convey potentially important spatial details can accidentally be abstracted. I will question whether schematisation actually supports or impairs the understanding of tactile maps regarding certain conditions that arose in the course of this research project.

7.2.1. Localisation Indicators as Clutter

As shown in chapter 6, localisation indicators can help to quickly find certain positions on a map. This advantage comes with a price: the tactile entities introduced to the map do not bear any geographic meaning. The indicators simply have auxiliary features. After the map-readers have used them to locate an entity on the map they might obstruct further acquisition of spatial knowledge through exploration of the map – quite contrary to their actual purpose. The three location indicators investigated in this thesis have different characteristics, especially regarding their presence on map space. The grid causes significant interferences as many lines have to be displayed. The frame marks are only slightly invasive as there is no tactile entity displayed on the map space but only at the map margin. However, if too many positions are occupied by symbols at the frame margin, cluttering hinders discrimination. Thus, it is necessary to find a balance between the amount of indicators and to what extent they actually support or potentially distract when using the map. A balance can be found considering the principal objective of map-usage: if there it is necessary to determine objects and the relation of their positions in the first place (to learn about locations), a location indicator for each object can be a good idea. Introducing further indicators will eventually clutter and occupy the margin of the map, regardless to the type of indicator used. If acquiring survey knowledge, i.e. exploring of the map, is the principal objective, then just a few indicators should be used. There is no strict rule as to number and type of indicator applicable for numerous objects – it depends on the communicative function and the context of use of the map.

7.2.2. Misunderstandings as Consequence of Schematisation

Especially the local details that are omitted in TOMs can be helpful in situations other than preparing a trip to an unknown environment. If a TOM is taken on a trip to provide support while moving in an environment, they might miss essential information. The map does not display the level of details navigators would probably like to be provided with. One example are small side-streets that are missing as they were not selected for display in a survey view. Nevertheless, when on site the information on how many streets need to be cross before turning is essential. It is important to know that these maps are for learning the structure of an environment and in which ways places are connected. They are comparable to underground plans, such as the London Tube Map (see Figure 7.5). No one would ever use these maps to estimate distances, at least not a walking distance. Therefore it is essential to set the right expectations before people begin to use a map, especially if it is highly specialised like a TOM.

What could happen if the purpose and the characteristics of such maps are not clear to the reader can be observed in one of the studies in chapter 5. One participant misinterpreted the purpose of a TOM and selected the most veridical map when he was asked to choose the 'best' map. In the interview after the test, the participant explained that his intention was to take the TOM into the field to facilitate his orientation and to use it as an additional wayfinding option. In such cases severe misunderstandings can be the consequence of schematisation. The map would possibly display insufficient environmental detail to self-monitor the progression in the environment. Special purpose route navigation systems based on GPS are much better support tools for locomotion, although they were shown to impair spatial knowledge acquisition (as noted in chapter 1).

There can be situations in which enforcing schematisation of each intersection and each street shape could result in global inconsistency, i.e. the displayed street network is not topological correct any more. In such situation constraints for schematisation have to be relaxed, for example, by allowing for small variations in the angles of intersections or by connecting intersections with not-straight lines. In other situations, there are intersections that have several streets in the same sector. These streets would be all schematised into the same one line. The information that there are two streets running into the approximately same direction would be lost. Whether those street representations are to be discriminated is limited by the minimum detectable increments in angles as well. Displaying two streets falling into the same sector has not be dealt with in this work. It is an open question to future research. Some concepts how to deal with such problems can be found in Klippel (2003) albeit for route maps that usually need to preserve fewer relations than a survey map.

7.2.3. Accounting for Individual Differences

With regard to tools for preparing individual trips to unknown or unfamiliar environments, the studies and discussion have neglected one essential part: the human being. Individually produced maps in particular can be tailored to the individual's requirements. People have different (spatial) abilities, different prior knowledge, different needs for support, different

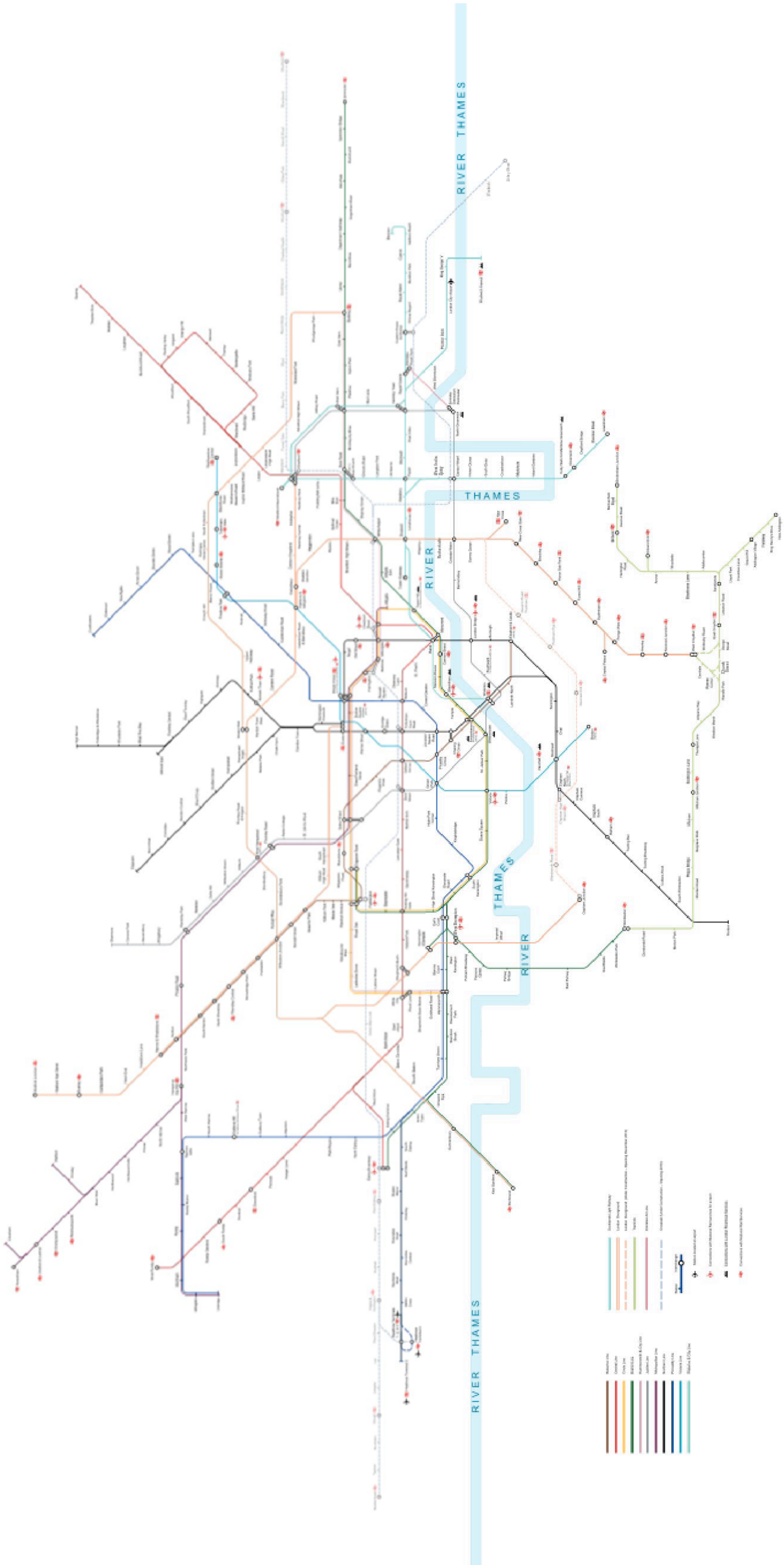

Figure 7.5.: A topological map of the railway system in London operated by Transport for London. Map is up-to-date as of August 2012. © Metthewedwards, licensed under GNU Free Documentation License, Version 1.2

interests and different goals. Hardcopy tactile maps produced with a tactile embosser can be personalised and adapted to the individual needs and wishes of the future map-reader. This is a great chance to really have personalised tactile maps – adapted to prior knowledge, the task at hand, and the sensory and cognitive abilities of the reader. It is prerequisite to know the map reader well. Defining and introducing these characteristics was not the aim of this research, although it could be a follow-up. It would provide an opportunity to have individual profiles carrying the information needed to adapt the principles of schematisation to TOMs. According to the information stored on the profile, a map for an elderly individual A could have larger symbols representing landmarks and with a more prominent separation between two signatures as the tactile acuity of her fingers is weakening. Other blind individuals might feel more safe to navigate the environment only using distinct acoustic guidelines[2]. The profiles could be collected by a service provider who then makes the maps for these customers. Besides more persistent characteristics stored in a profile, the represented categories of objects could be customised to the corresponding task at hand, so that person A would get a TOM with all the shoe shops and person B would get a TOM with all the electronics shops in an environment.

7.3. Outlook to Potential Future Developments

The basic idea to reduce cognitive demand during map exploration by introducing task-relevant schematisation is not confined to tactile orientation maps. When thinking about the principles for schematisation proposed in this thesis, we might ask ourselves whether they can be transferred to other map types, i.e. other usage contexts (different tasks, different environments, different users). In this section I will discuss two options: whether schematisation principles can be transferred to other map types and under which circumstances the transfer is valid if production technologies change.

7.3.1. Transfer of Schematisation Principles to Other Types of Maps

During the pilot studies reported in chapters 4–6 there was evidence for geometric abstraction : that straight lines are superior to geometric, veridical curved lines. For learning a whole environment, it is better to display schematised intersections than veridical intersections in survey maps produced with a tactile printer. Now I will discuss which of the findings produced in this thesis can be transferred to other types of tactile maps produced with an embosser.

In the pilot studies evidence was found that maps produced with tactile printers and made of discrete entities, such as physical taxels, have limitations in their ability to display a wide

[2]The computation of these acoustic guidelines should be possible with modern GIS that often provide information on the fronts of buildings that face the streets: distance to the street, number of floors, whether there are several entrances, etc.

heterogeneity of surfaces. Due to these limitations, only the signatures that are very probable to be distinguished, should be used.

During the studies, it was observed that the texture of surfaces has be very different so that it can be discriminated and identified as a further conceptual entity. This is due to both the sensory limitations of touch and to the technologies creating tactile stimuli. Elevation of taxels can vary between seven grades with the production technologies used. However, people were only able to discriminate three levels when direct comparison was offered. Recognition without comparison was even worse. This shows that in certain circumstances, technology is not the limiting factor but rather the sensory abilities of users interacting with this special form of discrete tactile surfaces[3]. Some characteristics of lines were hard to discriminate for the participants, for example, line width (see section 4.2). This was especially true when lines had an oblique orientation. Other line characteristics were noticed easily regardless of orientation; for example, continuous lines versus broken lines. Symbols were best identified if they were small (ideally only as big as a finger tip, 9 taxels or 11.5mm), or angular with distinct corners (for example, a triangle or a rectangle, not a circle), and of simple structure (for example, only am outline, no filling). Special caution should be taken if round edges are used to distinguish symbols: they can only be identified if the symbols are sufficiently large (at least 13 taxels or 16.5 mm, bigger is even better).

These examples show that not all dimensions of tactile signatures produced with tactile printers are equally suitable for variations. Thus, maps that require a many different signatures need a further step of reduction because the tactile resolution of the output and detectability during encoding is not high. Otherwise, map readers will most certainly be confused about the multitude of different symbols – and ultimately only grasp a small part of the spatial meaning. An example will clarify how some of the results from this thesis could be used by others. Let us assume that a *thematic map* showing the different types of land use (see Figure 7.1 and Figure 7.2) is reproduced as a hardcopy. The different types of land use are encoded by different colours in the visual original. The colours can be converted to a brightness value so that different shadings encode different meanings. This is what the device driver of the ViewPlus Emprint does automatically. When this map is directly printed, the different shadings will be encoded to different elevations of taxels. As ascertained in the first study (see chapter 4), the difference between the regions and their borders, or between two regions, cannot be detected very well if there are no discontinuities ('white spaces') in the tactile sensation. Additionally, hardcopy tactile maps do not serve to build rich surfaces. Surfaces can possibly be made more distinguishable by introducing individually structures like stripes and dots that are separated through sufficient space. However, this possibility is limited as filled elements must be at least 11.5mm (9 taxels) in diameter to be able to carry a recognisable structure (if they are round, then at least 20 mm). The minimum size depends

[3] I am not interested in the physiology of touch or how the receptor's physiology effects perception. The attentive reader will find more details in Loomis & Lederman (1986).

on the complexity of the pattern. Complexity depends on the shape of the pattern elements used; also on repetitiveness, and on the amount of empty space required between pattern elements. To clearly distinguish between any tactile elements, it is a good idea to introduce spacing of 2.5–3.8 mm (2–3 taxels) between elements. Existing separations are hereby highlighted – the structure of a pattern is clarified, and regions are clearly separated. Introducing such an extra spacing for filling regions means that the minimum size of a region with a tactile pattern (see above) must increase.

The minimum size of a geometric object in a thematic map produced as a hardcopy should be calculated as follows: the shape of the region in Figure 7.1 is somewhat round (i.e. of irregular shape), thus the minimum diameter of a hardcopy must be 20 mm. It should have a detectable continuous surface structure (i.e. no pattern), and have a diameter of at least 11.5 mm (this is less than the first requirement so it can be neglected). To discriminate this region from another, a white space of 3.75 mm is needed. Altogether this amounts to about 24 mm in diameter as the minimum size necessary for a round structure in a thematic map. If the region was more complex in shape or needed a special surface structure to be recognised, the minimum size would quickly grow to sizes between 50 and 100mm. If the map should additionally have well more than 5 surfaces needing to be discriminated it would become increasingly more difficult to define appropriate tactile signatures.

All these limitations show that it is probably better to produce a thematic map with any of the traditional approaches, such as thermoforming. First, thermoforming provides the possibilities of displaying rich surface structures and makes encoding many areas that have to be distinguished easier. Second, thermoforming facilitates the use of a third dimension for encoding. Neighbouring regions can simply be at different elevation levels so that an extra separation at the borders is not necessary. A natural edge is formed because of the elevation discrepancy. Less obvious regions may be smaller. Thermoforming does not only benefit thematic maps that display many regions and need to encode different meanings for each region, but also topographic maps (see Figure 7.3). With matrix-based tactile printers there is no way of producing a meaningful topographic map as it demands clearly distinguishable levels of elevation – a characteristic that hardcopies cannot offer.

Traditionally produced thermoform maps suffer from a time-consuming, expensive production process (see chapter 2 for details on the drawbacks of traditional tactile map-making). Nonetheless, traditional thermoform tactile maps can benefit from the findings in this thesis: map-makers should also consider the benefits schematisation has to offer, even though it is not mandatory for the traditional production technologies. For example, the rich details in Figure 7.1 (details in Figure 7.2) might have not only positive impact on the conceptualisation of the map. If the task at hand does not afford such high details, it could be considered as clutter. Even if, for example, shape of the isolines is hard to reconstruct from memory. Map-readers could improve their understanding of maps if the shapes of the isolines were hugely abstracted, i.e. the level of geometric details were decreased, and the textual information in Braille labels was transferred to a second map. By the division of labour between two maps, the level of conceptual details could be decreased. Alternatively, the levels of elevations could be reduced from five to three to reduce conceptual information further.

Another type of maps that could benefit from the findings are those that support tasks of localisation, overview, or both, for example, You-Are-Here maps. They can benefit from the schematisation investigated in this thesis. In contrast to the scenario laid out in motivation report (see chapter 1), YAH maps are usually co-located to the environment they depict. Typically they are installed outdoors; they are static and designed for long-term use by various different people. Nevertheless, the adaptation of schematisation principles to individual YAH maps could advance travellers' possibilities to learn the prospective environment beforehand and prepare for the trip.

As the schematisation principles discussed in this thesis were developed and investigated for maps of large-scale outdoor environments, it is questionable to what extent they actually apply to maps of indoor environments. There is evidence that certain principles of indoor navigation can also be found in outdoor navigation. The *longest-leg-first strategy*, for example, selects a route that has the longest straight leg that needs no turning operations and is expected to cover the largest distance to the selected destination (Golledge, 1995a). However, these results were first found by testing sighted fully-oriented individuals and not blind people. Therefore the question is, whether blind people navigate large-scale in the same way after they have read a tactile map, i.e. a small-scale representation.

Indoor environments have certain challenges that are not met outdoors, essentially different floors, one above the other. This poses unique challenges, for example, correctly identifying and remembering transition points to change floors (Giudice & Li, 2012). The multilevel challenge is out of reach for outdoor TOMs. The principles of reducing geometric complexity by straightening streets may not be of use for indoor maps as most of the corridors in buildings are straight anyway. A corridor that is not straight would probably be a very salient feature. This kind of feature should probably not be abstracted as it can function as landmark and might facilitate orientation. The principle to abstract the geometry of linear features can be counterproductive for the usage of maps in indoor environments.

There may be principles of schematisation that are applicable to indoor maps, for example, the schematisation of intersections. Research has shown that the confined environment of corridors can impair environmental mapping (Darken & Sibert, 1996). This fact can be seen as an opportunity to highlight the characteristics of an intersection by exaggeration without risking that the navigator recognises the metric distortions and weak metric matches between map and environment. Research with virtual environments indicates that people are not good at recognising global distortions or inconsistency when they engage in environmental mapping (Marsh et al., 2012). But again, those cited results were done with sighted people. It might by that blind people are better in spatial updating and might recognized inconsistencies. This is another open question to be investigated in the future.

One class of maps that could be appropriate for hardcopies with applied schematisation are possibly certain route maps, for example, strip maps (MacEachren, 1986), and *route aware maps* (Schmid et al., 2010b) – see chapter 3 for schematisation principles used for route maps on small displays analysed as a starting point for schematisation of tactile maps.

Despite the chance to apply some schematisation principles to two (or more) map types, some constraints in production technologies could be too restrictive to produce certain map-types in the first place, see the case of topographic maps discussed at the beginning of this section. However, tactile matrix printers can be reported to be a suitable production technology for tactile orientation maps and can be expected to be suitable for other types, too.

This short discussion shows that the same way specific schematisation principles were found for tactile orientation maps, schematisation of other types of maps can also customised. However, the requirements for differentiation in order to realise a certain map type should match the constraints resulting from technology and schematisation.

7.3.2. Transfer of Schematisation Principles to Other Technologies

When considering the application of the identified principles of schematisation to other types of production technologies, I will distinguish two approaches. First, there are technologies that are able produce discrete tactile external representations similar to the ones produced with a dot-matrix tactile printer. Then, there are technologies that work similar to plotters, however in 3d, i.e. they can produce continuous small-scale 3d models of the world.

7.3.2.1. Transfer to Other Discrete Tactile Technologies

The tactile printer used for this thesis is a fairly recent product on the assistance technology market (the company ViewPlus was founded 1996). Over the period of this research project there has been an ongoing development of novel technologies that can be used to realise tactile maps. The following list is not necessarily complete but it provides an impression of the different technologies that similarly use a dot-matrix approach and could be enhanced with the schematisation concepts developed in this thesis.

The US patent 'Method and apparatus for multi-touch tactile touch panel actuator mechanisms' (Christopher, 2009) claims different kind of technologies in a context of applying a tactile touch display with input and output capabilities. The realisation described is composed from layers with different features, properties, and materials on top of one another. A matrix that is applied to all layers forms independent haptic cells. These haptic cells can be activated by adding electric current to micro-electro-mechanical systems (MEMS) so that deformation is caused. One type of the MEMS is a piezo bender (bent strip of bi-metal) that elongates when the current is applied. The patent is a rather comprehensive description of an approach to touch-panels that work as two-way communication devices: as displays and as sensors. It also describes a typical approach to a computer-driven display that is well-known from the visual area as well as from tactile printers: partitioning the continuous phenomena of tactile and haptic surfaces into discrete elements. All the following approaches have that characteristic in common.

The European project TACMON (2008–2011) aimed to 'increase SME[4] competitive advantage in the special needs sector by offering an innovative and cost-effective technology to help the visually impaired to have access to graphical and text-oriented information' (TACMON Consortium, 2008, p. 1). The consortium wanted to develop 'innovative technology targeting an interactive graphical tactile display and user interface for the visually impaired to access electronic information' (TACMON Consortium, 2008, p. 1). Complete information about the final results of the development are missing due to a transfer of intellectual property rights to a commercial entity and a pending patent application (TACMON Consortium, 2010). It can be only assumed from the website tacmon.org and from the newsletters that the tactile display they developed is based on mechanically raising pins that are arranged in a matrix larger than the common Braille modules that have 2 by 3 pins. A similar device was first developed by the consortium partner METEC AG in 1985 under the name 'Tawis' (TACMON Consortium, 2008, p. 3). The website states that the final tactile display was sized 80 by 120 pins, which makes 9600 pins on a surface of approximately format DIN A5 (21 by 15 cm). The pins are activated by micro-electro-mechanical systems (MEMS), i.e. if a current is applied, the attached pin moves up. No information is provided as to whether and when the technology, software, and training material developed will be available to the public.

The project HYPERBRAILLE (2008–2010), funded by the German government, further developed the initial prototype Tawis of METEC (TACMON Consortium, 2008, p. 3). While Tawis was working with pneumatics to activate pins, the newly developed HYPERBRAILLE Display 7200 works with MEMS. Vertically mounted MEMS raise the pins above the plate by 0.7mm if a current is applied[5]. The display is 410x300x60mm in dimension, approximately a DIN A4 format (300x210 mm). It has 7200 pins (60 rows by 120 columns). The pins only need a fraction of a second to fully raise or lower (no gradual elevation possible). Each one can be activated independently from the others. There are also 1440 touch sensors. In this way the position of the fingers can be determined. With these capabilities the HYPERBRAILLE can also work as input device. This affords interactive scenarios that are investigated by the project partners in the Human-Computer-Interaction research group at

[4]SME = Small and Medium Enterprises

[5]For technical specifications see `http://www.metec-ag.de/Display%207200.pdf`, latest access August 25, 2012.

the University of Dresden, Institute of Applied Computer Science (c.f. Zeng & Weber, 2010, 2012) and the Institute for Visualisation and Interactive Systems at the University of Stuttgart (c.f. Schmitz & Ertl, 2012). By 2012, the device was commercially available as bundle with a PC for € 49,000 (Baden-Württembergischer Genossenschaftsverband e.V, 2012). Mass production has not started (and probably never will, due to the small market) and thus the hefty price tag may persist – hardly affordable for private households and even a massive investment for community centres or organisations that would like to equip blind people with tactile maps. Nevertheless, another project to develop accessible mobility maps has been initiated in 2011. The publications about the project (Zeng & Weber, 2011) and the official blog (`http://www.mobility-projekt.de`) indicate that it may be a good place to apply the concepts developed in this thesis for the display users' cognitive benefit.

The EU funded project NOMS (2010–2012) set out to realise tactile displays with Nano opto-mechanical systems (Campo et al., 2011): The display area is covered with a polymer. Underneath the polymer diodes are placed in a matrix arrangement. When one diode is lit, the polymer in the cell above reacts with expansion, and the surface protrudes above base level such that one can feel a bump. The general applicability of the approach was proven with a prototype system, size 10 by 10 elements[6]. As of 2012, the polymer only reacted to a high energy intake [7]. Therefore, the light diodes need to be very powerful. This causes a huge energy concentration in a small space. So, to date diodes cannot yet be placed that closely. The whole display can still not be built as large as intended. The right polymer that reacts to low energy light still has to be found. Then diodes could be placed beside one another in half of the Braille spacing (1.25 mm) and the projected size of the display (80 by 80 elements) would be reached[8]. Once this display technology would be ready, the concepts developed in this thesis would become applicable to some extent. One aspect that needs some consideration is the finer resolution. It could afford to reduce some minimum distance thresholds and angle thresholds. For example, it would be reasonable to test whether angles less than 45° can be recognised with high precision on that new tactile display.

Similar to the last approach the patent application 'Light-Induced Shape-Memory Polymer Display Screen' (Kikin-Gil, 2009) describes a method working with light and different layers of materials. Different wavelengths of ultra-violet light cause a polymer to have different properties: from being stiff to being soft. The patent claim that by modulating wavelengths texture can be created when a piece of otherwise flat material is covered with the polymer. As the approach works with a matrix it can be assumed that resulting figures are composed from discrete tactile elements much in the same way as with the other approaches based

[6]See presentation 'NOMS - Towards Smart Tactile Tablets for the Visually Impaired Persons' by Jaume Esteve, `http://goo.gl/9ZNpQ`, last access July 09, 2013.

[7]Personal communication with Patrick Bruns, a researcher for one of the consortium members, August 27, 2012.

[8]See presentation 'NOMS - Towards Smart Tactile Tablets for the Visually Impaired Persons' by Jaume Esteve, `http://goo.gl/9ZNpQ`, last access July 09, 2013.

on discrete tactile elements. Interactivity is not proposed in the patent[9]. Light activated polymers have the advantage that the single elements can be packed side-by-side, very close to one another and densely, as diodes only occupy little space. The mechanical approaches, whether electro-sensitive polymers or pneumatics, cannot be packed so densely because the mechanics need a certain space and electric current may spill-over if the elements are too close. The consequence is that light-activated approaches could realise a higher resolution in displays. Such displays could be produced easily and have much larger dimensions than those based on MEMS or mechanics. The principles discussed in this thesis could be an advantage to displays that are based on light-induced shape-memory polymers, MEMS or mechanical displays.

An approach that has not yet been used to construct rich tactile displays is using magneto-rheological fluids (Lee & Jang, 2011). This fluid reacts to a magnetic field that alters its material properties. Depending on the strength and polarity of the magnetic field it exerts different forces against moving objects so that tactual and haptic sensation is created. It is primarily targeted at supporting the tactual sensation of roughness and the haptic sensation of object solidity during the exploration of virtual objects and materials. Parametrizing the approach is yet limited, i.e. only a few objects can be simulated as the ability to form magnetic fields in arbitrary shapes with high detail is yet limited. Besides the technologies presented here, there are other possibilities to implement tactile displays (for a review see Chouvardas et al., 2008).

In contrast to these discrete display technologies, the technologies discussed next produce continuous surfaces.

7.3.2.2. Transfer to Continuous Tactile Production Methods

I will briefly summarise the main characteristics of production technologies from the rapid prototyping area along the lines of Mellis (2011), Voženílek et al. (2009). First, production methods can be distinguished the by the way physical results are obtained, either subtractive, additive, or transforming. With subtractive methods small portions of material are iteratively cut away from an initial solid piece of material until the remaining material constitutes the desired result. Additive methods iteratively add material to build the shape. See Appendix 8.3.7.3 for a review of additive methods (for example, fused deposition modelling [FDM]) and subtractive methods (for example, laser cutting).

I consider additive production technologies as particularly useful if the background in the model (i.e. the void areas without material) takes up more space than the foreground (i.e. areas with entities that need to be printed). As the material is solid the method gives sustainable results. With professional manufacturers the resolution is high and high-detailed

[9] A similar approach but with a different mechanism is proposed in patent application US 2011/0018813: the chemical effect of osmosis is activated by a current to pump liquid into cells. The result is—as with the other techniques—a surface displacement that can be felt as tactual bumps, (for details see Kruglick, 2011).

products can be formed. Professional services that offer production on demand with similarly professional machines are often only affordable for commercial applications, not for home-use or for individual production.

Tactile graphics and tactile maps could be produced with the FDM approach. However, the small production table limits the potential usage of the Thing-o-Matic to tactile maps that are only $\frac{1}{6}$ sized DIN A4. This format has proved to be an appropriate size for tactile maps in studies. The inability of printing fine details with sub-millimetre resolution would limit the usage of FDM produced maps to haptic representations, i.e. the usage of tactile surface variation to encode different semantics would most likely be of little help. That and the limited size might be why the FDM printing method has not yet been extensively used to produce tactile maps.

The fundamental difference between tactile displays and tactile printers is that no persistent physical artefact is produced and that physical artefacts have continuous surfaces, i.e. there is no typical dot-structure as in physical tactile displays. Instead a digital artefact is shown on a volatile dot-matrix tactile display. The communication of the information to be represented is more immediate with displays but it is discrete. Often these displays have built-in sensors and the artefact can be manipulated directly while being displayed. This enables a reaction to the touch and hence interaction between the user and the artefact is possible. On the other hand, physical artefacts make it easier to be taken on travels or other places. Users could discuss the hardcopy with others that are not present in the moment of interaction with the display.

There are approaches to other types of tactile interaction. These do not produce continuous tactile surfaces but cause a similar sensation to touch on the human skin. These vibrotactile displays are a promising direction for research as they require no additional hardware and can be used with standard smartphones or tablets, and are commercially available to users (c.f. Giudice et al., 2012). These displays probably have similar or even worse resolution problems as hardcopies. Thus, some recommendations formulated in this thesis can possibly be transferred. However, investigating the transfer is beyond the scope of this thesis and left for future work.

The drawback of some of the envisioned display systems is that some might never leave the stage of research prototypes (for example, TACMON), and some are licensed to a commercial vendor targeting the business market and not the consumer market (for example, HYPERBRAILLE). It is uncertain whether tactile display technologies, developed in the second decade of the third millennium, will really hit the consumer market in future and at what point. The core of the ViewPlus printer technology was developed in the 1990s (ViewPlus Technologies, Inc., 2012) whereas currently developed technologies might need another 10 years to be available and affordable for personal use. And even if they were available immediately, the acceptance of tactile displays could suffer from the prejudice against electronic products, as expressed by blind users in the studies reported in section 4.3. Nevertheless, the efforts to bring dynamic, interactive tactile displays to market could only be welcomed. They offer great potentials for the inclusion of blind people especially if augmented with technology that optimizes the understanding of the displayed information.

This short discussion shows that the schematisation of maps should be adapted to the machinery in use for map production. In the same way as specific schematisation principles were found for tactile orientation maps, the schematisation of other types of maps can also be customised.

7.4. Summary of Generating Schematised Tactile Environment Maps

In this chapter I first summarised and discussed the findings from the studies reported in chapters chapter 4–chapter 6. Based on the result of the first study, namely that some blind people would certainly use tactile maps as tools for spatial learning, I discussed the given possibilities of using computer-controlled tactile printers and the constraints that have to be taken into account when using such printers, both sensory and conceptually. Finally, I reviewed the findings from schematisation for hardcopy tactile maps before I discussed why the concepts found to support the task of localisation and the concepts to facilitate survey knowledge acquisition work, and why they are successful. I have depicted their relations, essentially how they can jointly be a basis for usable tactile orientation maps. My findings provide an initial guideline for future developments in the area of tactile map production with tactile printers.

In the second part of this chapter, I discussed whether and how the schematisation principles found in this thesis can be generalised. I argued that the transfer to other types of maps is possible to some extent, especially if the characteristics of these types resemble the characteristics of orientation maps, i.e. if they are survey-oriented and primarily highlight line features (representing streets) with only few symbols. I investigated whether the schematisation principles found for maps produced with tactile printers is also applicable to other production technologies. I named ongoing research projects from recent years that show how eager the research community is to find solutions for dot-based tactile graphics displays. With each of these display technologies, the cognitively driven approach to schematise graphics will most likely outperform the abstraction through filters in terms of learning the displayed network structure. References to external findings augmented my argumentation.

At the end of this chapter, I balanced the possibilities schematisation can provide to understanding tactile maps with certain potential drawbacks. One of these are misunderstandings as a consequence of schematisation that is introduced without levelling expectations as to the spatial aspects tactile maps can display and which not. This is why TOMs probably better display street networks than thematic land use information (a typical field of use for traditional tactile maps and their rich surface patterns).

Besides these conceptual limitations there are also methodological limitations. The differences in individual performances with maps were not investigated as factors in this thesis. For example, using indicators in a TOM introduces additional clutter that could prevent map-users from acquiring appropriate mental representation on a very individual basis. Previous training, knowledge of similar environments, and other factors can affect the individual success of learning. This aspect was not targeted in the thesis and could be considered for future research.

Balancing the level of schematisation to facilitate map-understanding and the level of richness that supports the purpose of a map is a difficult task. I would like to close by with a well-known saying from the Bauhaus period: One can state that the abstraction that forms the map, follows its function, i.e. the intended purpose of that map.

Chapter 8.

Conclusions and Future Work

This chapter summarises what has been achieved in this thesis: which questions that have remained unanswered and which future research subjects are motivated by its results. It argues that cognitively motivated simplification should not only be a principle of construction for computer-generated tactile orientation maps in order to support their use and comprehension.

The summary in section 8.1 establishes the condensed recommendations that were supported by this thesis about principles of generating tactile orientation maps.

In section 8.2 I elaborate the contributions of this thesis by abstracting recommendations for the generation of schematised tactile orientation maps collected and discussed in chapter 7. Then I illustrate how to adapt schematisation principles to other types of maps, previous knowledge of the map reader, and the context of map-usage.

Closing the dissertation, in section 8.3 I provide an insight into its confines and deductions and finish with a prospective view to future research areas.

8.1. Summary of Work

In the introduction of this thesis (see chapter 1) I motivated the need for survey knowledge acquisition through tactile maps for the blind. In times of GPS-driven wayfinding systems that help to find and follow routes, the remaining challenge for blind people is to develop an understanding of the geographic environment from a survey perspective. Simplified tactile survey maps that only show main landmarks and certain streets (labelled Tactile Orientation maps) were motivated as tools in at least one use-case: as means of acquiring some survey knowledge before travel begins. Standard You-Are-Here maps that are typically installed in the environment they depict, may provide *in-situ* the required information. It may also happen that map-users explore the structure of environments they are not co-located with, i.e. *ex-situ*. In both cases, Tactile Orientation maps provide orientation support for map-users and help to clarify questions of spatial cognition, for example, with regard to the existence of objects ('Which objects are geographically meaningful objects and can be used for orientation?', 'Which are the main streets and which landmarks are contained?'), survey perspective of the environment ('In which directions are geographically meaningful objects situated ?', 'How does the overall distribution of objects looks like?'), or orientation and wayfinding concerns ('Where am I in relation to important landmarks?', 'How are the streets or/and landmarks connected?').

Tactile maps that have to be tediously explored through touch. They complicate the process of attaining a first impression or a survey perspective. In chapter 2 I discussed how orientation maps can help to get an overview of the environment, regardless of certain sensory and cognitive limitations in tactile map-reading. I argue that tactile survey maps are still necessary. The spatial knowledge blind people acquire from survey maps is important for navigation tasks, for example, to plan routes prior to certain trips or visits, to keep track of their movements while moving around in the environment, and in situations assisted navigation fails. In any of these cases navigators could fall back on a cognitive model of the space. By using tactile survey maps, blind navigators are empowered – they become independent again (see section 2.1). In order to be used in the first place, maps need to show the depicted reality in a simplified form to ensure legibility and to ease comprehension. Both approaches of how to facilitate (visual) map design successfully are reviewed (see section 2.2) and later, certain deductions are extracted from that prior work. Then, the production of tactile maps is reviewed in section 2.3, both for traditional handmade and deep-drawn tactile maps and for digitally produced hardcopy tactile maps.

In chapter 3, I discussed the options of how schematisation of tactile maps can facilitate learning about spatial environment. First, in section 3.1, I described digitally produced hardcopy Tactile Orientation Maps. They are made of discrete tactile elements (taxels) and unimodal (in the sense that they do not contain labels or other language-related elements). One main characteristic is their stark simplification from the environment they depict. Simplification is essential for any tactile map, even more so than in other maps. It can be achieved by selecting a limited number from all map elements available. Simplification through schematisation may present an additional option to simplification through selection. Tactile Orientation maps are the result of two consecutive processes of simplification. The first step is *abstraction*, i.e. the number of elements in the map is greatly reduced, so that only the important streets and a maximum number of 10 landmarks representing three-dimensional objects remain. Following, *schematisation* takes place, i.e. the geometry is changed for cognitive reasons to render map learning easier. For that purpose, the maps are restricted to having only straight street representations and only certain types of shapes for intersections. The thesis focussed on how schematisation influences usage and comprehension so that the acquired spatial knowledge can be employed to successfully solve qualitative spatial reasoning tasks – particularly (self-)localisation, and survey mapping.

In section 3.2 I discussed the challenges resulting from production of schematised tactile orientation maps. The initial observation of this dissertation states that only very little information is actually transported through tactile maps owing to the coarse resolution of tactual senses and the cognitive effort involved in the serial exploration of tactile maps.

However, the differences between computer-generated, embossed tactile maps and manufactured, deep-drawn tactile maps are significant. Therefore the possibilities and confines of communicating information through tactile maps produced with embossers was a primary area of research. Before this dissertation it was largely unknown under which conditions fine variations in map construction translate into tactual realisation of the corresponding tactile map. I reviewed schematisation strategies found in mobile maps on smartphones, discussed in chapter 2.2, and analyse whether they are entities of quantitative or qualitative abstraction and which cognitive advantage they offer. The constraints of schematisation to ensure legibility or to ease comprehension of hardcopy tactile maps were identified: minimum separation, minimum size, unique signatures, minimum angle, topological veridicality, static outbound streets, prototypical intersections, prototypical relations of objects, and prototypical orientations of streets. After investigating the basis of interpreting tactual stimuli produced with the embosser, I proposed to investigate two approaches that promise to improve the usage of tactile orientation maps (details presented in chapter 5 and chapter 6) .

1. Schematisation of streets, i.e. simplification of geometry of line segments in the maps in connection to the schematisation of intersections, i.e. the simplification of geometry of line intersections in the map.

2. Guides and pointers as aids that could facilitate the map readers' options to discover certain objects on the map quickly and without possessing a complete overview.

The following paragraphs summarise the results of the motivated studies.

1. The studies presented in chapter 4 showed the technological constraints of producing tactile maps and the sensory challenges of reading the hardcopies. It informed about the further construction of usable tactile orientation maps with a technology that produces discrete spatial representation. We learn that there are at least two sources of requirements that must be considered when producing hardcopy tactile maps: A) the prospective context of use, including task, user, and support tool, i.e. the tactile map; and B) the technology that is used to print the tactile map. The interviews conducted with six potentially approved map-users verified that, with regards to the prospective context of use, these blind, active people welcomed the opportunity to learn more about unknown environments by using tactile orientation map. They gave insight into their style of navigation and confirmed that even simple tactile maps only showing streets and major landmarks, are sufficient to acquire a first survey perspective. They enable to recall the existence and direction of salient landmarks (for example, central buildings, sights, transportation hubs), and the rough street network with its main streets, intersections, and embedded landmarks. Regarding the design of such maps, tactile iconographic symbols are actually better than symbols introduced by conventions. With respect to the technology used for printing we learn that users participat-

ing in the study were satisfied with the readability of tactile hardcopies. The sensation of discrete taxels in hardcopy tactile maps was not noticed by most users. Instead—as the studies showed—most people interpreted the sensations as representing continuous objects. The readability of tactile hardcopies made with the ViewPlus Tiger technology was found to depend on several parameters. The study showed that discrimination and recognition of objects on a hardcopy are influenced by shape, distance, orientation, size, texture, and elevation. Elevation was the dimension found to play a major role for legibility. Some of these parameters did not always reveal deterministic interaction, which most notable in the automatic anti-aliasing activated by the driver when printing with the Windows API. Differences in the width of two oblique lines have to be very prominent if they are to be discriminated (for details see chapter 4). Other parameters that need adjusting are separating between objects and filling areas and symbols so that the map-user can easily discriminate them. All these adjustments increase the usability of tactile materials produced with the ViewPlus Emprint.

2. The study presented in chapter 5 brought forward first evidence that tactile map understanding is facilitated by schematisation. Rather than further reducing the number of displayed objects, the investigation concentrated on how the representation of different forms of streets (natural vs. straightened) and junctions (natural vs. prototypical) affects the transfer of knowledge. The study showed that the schematic tactile orientation maps with 1) straight segments between vertices and 2) prototypical representations of junctions help to remember the tactile orientation map and, at the same time, ensure the usefulness of maps for readers. The findings in this study suggest that the conceptual abstraction of intersections representations and the geometric abstraction of street representations is a feasible approach to schematise a tactile orientation map. Schematised TOMs with abstract street representation and abstract intersection representation may have an advantage over traditional TOMs. Map-users need less time to learn schematised TOMs and they often prefer it to a non-abstract TOM. They are able to successfully use the acquired spatial knowledge gained from an abstract TOM the same way as from a non-abstract TOM. Although feasible, there is most probably no general solution to schematising tactile maps algorithmically. Algorithms need to be adapted to the supplied input data and the required output of map-types. The study established that qualitative simplification of tactile orientation maps through schematisation enhances their usability and makes them easier to understand than maps that have not been schematised. It demonstrated that simplifying street forms and limiting them to prototypical junctions does not only accelerate map exploration but also has a beneficial influence on retention performance. The majority of participants that took part in the study selected a combination of both as their preferred display option. Reducing the perceptual complexity is also likely to increase the map's interpretabil-

ity, learning, and overall cognitive coherence. This means that, without simplification, the map is essentially too overloaded with details to be useful or meaningful. So it is likely to add frustration and cognitive dissonance between what map-readers think should be there and what they actually perceive. Schematisation increases the likelihood that people will use maps, because they have had positive experiences and know they are helpful. Instead of causing frustration, confusion, and angst they improve spatial awareness.

3. In chapter 6 three types of map-usage aids were examined: frame marks, indicator lines and grid. The study showed that these types can be produced by tactile printers. The study provided first evidence that frame marks and indicator lines are superior to grid in terms of effectiveness, efficiency, and satisfaction. Beside the objective data, subjective rankings for usability support these findings. Considerable variance of time is needed to locate a position in a tactile map depending on the type of location indicators. If the map is only used to show one particular position in its embedding, and subsequent exploration of the whole map is only a minor task, the best way to support the map user is by displaying an indicator line for that position. Although an indicator line proves to be fast in size A4 tactile maps containing only one target object and few distracting objects, the line also impedes further exploration of the map (similar to the grid). If map exploration is a major part of map-usage, frame marks are better suited than other options as map exploration is least impeded. Participants judged that frame marks and line indicators are generally preferable to grid. Some conceptual consideration about the impact of map topology and map geometry on human wayfinding abilities with tactile maps were brought to a status that might initiate further studies.

The details for the qualitative studies can be found in chapter 4, chapter 5, and chapter 6.

8.2. Contributions

This thesis contributed to the body of research about the schematisation of maps to improve the comprehension of the represented spatial concepts. After a thorough state-of-the-art review about the acquisition of spatial knowledge with (tactile) maps, a review about the role of simplification in map-use and a review about the production of tactile maps the thesis brought about the following contributions.

1. This thesis was able to demonstrate that hardcopy tactile maps are technological feasible alternatives to traditionally manufactured deep-drawn tactile maps if simplified networks with a few embedded symbols need to be displayed. Their disadvantage is the limited richness of the tactual surface. Their great advantage is fast and individual production and (apart from the initial procurement costs for the printer) low price,

accessibility and easy understanding after only a short period of training. Regarding the context of use, interviews revealed that potential users would accept maps produced with embossers for in-advance survey knowledge acquisition even if they have disadvantages.

2. The readability of tactile hardcopies made with the ViewPlus Tiger technology was found to depend on several parameters that constrain the construction of tactile map in several ways. To cope with these constraints when producing a hardcopy tactile map, tests about the influence of placement, orientation, and expressiveness of tactile objects were done and recommendations drawn. These recommendations are not specific for tactile orientation map but specific for the ViewPlus Emprint Spot Dot printer being used. Thus the recommendations can be re-used by others who want to produce other tactile graphics with that printer.

3. Schematisation concepts were investigated for applicability in tactile orientation maps. Comparable to the findings about cognitively motivated schematisation of route maps on small display mobile devices, this thesis shows that schematisation can help to use tactile orientation maps. It was possible to identify principles of schematisation that contribute to better comprehension of tactile survey maps produced with a tactile printer.

4. Schematisation concepts customised to map production with a tactile printer were proposed, tested and reviewed. Acknowledging the constraints of the printing technology (see above), the thesis proposed schematisation concepts for simplified tactile survey maps that only contain street representations and a few landmarks (under 10 in total) but that can be produced swiftly and with good ergonomic properties. The contributed concepts were for two tasks typically performed with tactile orientation maps.

   a) For the task of localising a position in a tactile map three concepts were compared: the indicator line, the frame marks, and the grid. The discussion showed that for assessing the usability of the indicators it is essential to test them not only in the target activity (locating a point in the map) but how they might impede other activities performed with the map (for example, map exploration).

   b) For the task of survey mapping of a tactile orientation maps two concepts were proposed and compared to a 'baseline' conditions. Schematisation was two-fold: The representation of intersection were connected by straight lines and any intersection with 3 or 4 legs is represented by one of 13 simplified shapes (see Figure 3.8 and Figure 3.9). Although the geometry of the network changed when schematised, the schematisation contributed to the understanding of the maps.

The tactile maps investigated in this thesis are a result of both abstraction and schematisation. The level of abstraction was kept static, i.e. there was no variation between different types of tactile maps. Thus, no effect observed could be contributed to abstraction. Instead schematisation has systematically been varied. The focus was on factors that contribute to what was characterised as qualitative simplification. From the result one can learn that variation that one could regard as minor have a great influence on tactile map comprehension.

Transferring the principles would not be limited to survey maps as many of the results could be probably used for other map types as well, for example, the minimum distances for tactual legibility of tactile objects. The findings about the pointers in maps would probably hold in route maps as well because. Pointers might not be necessary for the start and the end in route maps as they can be found relatively easily. Although, other objects that need to be found quickly could be brought to the attention of the map-user by pointers.

The research has shown that schematisation not only offers a potential for comprehensible hardcopy tactile orientation maps but that several constraints have to be maintained to be successful in that challenge. The following list does not imply a relevance order of the concepts.

Unique Signatures : To ease detection, discrimination, and recognition of map entities a set of tactile symbols, lines and textures was proposed and used in the tests. Each map entity has a unique texture, shape, and size. Shapes was found to be the best discriminator, size variations and texture variations are often too subtle. Minimum size of symbols is 9 mm, depending on the shape. Broken lines are best to distinguish line types. For details see chapter 4.

Minimum Separation : Each map entity must be spatially separated from any other entity. Displacement must be introduced if necessary. The minimum separation is 4 mm but depends on the geometries and the orientation of the involved entities. For details see chapter 4.

Minimum Angle : Intersecting lines should at least enclose an angle of 30° to be detected on the hardcopy. For high recognition rates angles of at least 45° should be used.

Topological Veridicality : The topology, i.e. the neighbourhood relations of regions, the adjacencies of vertices, the containment relations (landmark in region). If distortion is necessary it should be kept minimal. Distortions of the geometry, i.e. changes in length or angle, are less critical.

Static Outbound Streets : The existence of streets that connect the depicted area with other areas off-map must prevail. Those outbound streets should persist on the original side of the map to ensure the transition from one schematised map to the adjacent one.

Simplified Intersections : The shape of intersections should be simplified to a 8-sector model. Minor deviations of some degrees from the mathematically exact shapes are not problem as the minimum detectable angle is much larger.

Directional Relations : Relations between spatial objects should prevail, whether on the 'local' level (for example, a landmark adjacent to an intersection/a street) or on a 'global' level (for example, the prototypical directions between landmarks on the whole map).

Orientations of Streets : The qualitative directions of streets should not change, i.e. the orientation of a street in a schematised map should fall into the same sector of the 8-sector model as its original.

On the one hand these constraints set limits in realising tactile orientation maps. On the other hand the can be interpreted as recommendations or prerequisites for realising successful tactile orientation maps with tactile embossers.

The results of this thesis are beneficial for all manufacturers of tactile maps who have tactile embossers. The manufacturers could use the findings for setting up a optimised production pipeline for tactile maps. A field test with tactile orientation maps that were constructed following the findings in this thesis showed very promising results. People who before had never used tactile maps, neither traditional nor hardcopy, described the experience with the maps as 'revealing' and 'intriguing' (Graf et al., pear).

With this basis about how tactile orientation maps should be constructed, human-made map design could potentially be turned into computer-driven map construction. With the availability of tactile printers the whole map making process has the potential to be transformed. The infrastructure with single specialised institutions that are widely dispersed could change to an infrastructure of locally established organisations near to the homes of blind people, those who want to make use of tactile maps. Independence of human expert knowledge for construction, only depending on print technology for production, and targeting at good usability could open new possibilities for wider distribution and acceptance of tactile maps. Given that most blind people are well older than 60 years and often sceptic about digital appliances, hardcopy tactile maps have the advantage that they are completely analogue. This research could contribute to the life of all the 39 million blind people worldwide if it is coupled with technology that will probably hit the mass market soon (see the discussion in chapter 7) and extended (see next section).

8.3. Future Work

During the course of this thesis several assumptions had to be made. On the one hand they focus the work, however, on the other hand they limit its scope. These limitations are a good foundation to broaden the work initialised in this thesis. Besides, some of the work presented in the preceding chapters motivate new ideas for further studies. In the following, I will discuss issues that result from the limitations set for the studies presented. Then I will propose ideas for future work about hardcopy tactile maps. Further research is needed in the directions indicated.

8.3.1. The Generalization of the Results

The results obtained in the studies (see chapter 4, chapter 5, and chapter 6) cannot be generalised as the number of subjects was too limited and therefore not representative. The results should be considered as first indications for measurable effects of schematisation in tactile maps and need to be checked for their statistical significance. If statistical significance is proven, the results may be more convincing for readers from the ares of psychology or human-computer interaction.

8.3.2. Automatic Generation of Schematised Maps

Being set in the subject of computer-science, it would be great if this thesis could contribute to make a complete system of hardware and software that automatically generates schematised tactile maps. The thesis did not set off to reach that goal, but with the results obtained in this thesis are a good basis. Starting from that basis, the automatic generation of a map is a challenging multi-criterion optimisation problem[1]. There will be situation when not each criterion can be met and thus constraints need to be relaxed. For an example, see Appendix 'Algorithm to Generate a High-abstract Map': There is an oblique street that cannot be schematised to a vertical one because that would introduce an intersection that did not exist in the original map. Aside from that, the vertical street would not be 'right' because the street must exit the map at the same side as in the original to contain distortion. Otherwise the distortion would be propagated to other maps. Monitoring and controlling the accumulated distortion could become a problem that need solutions.

Considerable work on general constraint-based reasoning and constraint relaxation was done before and might be useful (for an overview see Guesgen et al., 1992). For automatic orthogonal or octi-linear schematisation of networks, Brandes & Pampel (2009), Dong et al. (2008), Nöllenburg & Wolff (2006), Stott et al. (2011), Wolff (2007) discuss algorithmic solutions and approximations, among others *Simulated Annealing* and the *Douglas-Peucker algorithm*. Barkowsky et al. (2000b) proposed *Discrete Curve Evolution* to simplify whole shapes. On the one hand, the prior work will be helpful for implementing the cognitively motivated construction principles for schematic hardcopy tactile maps. On the other hand, the problem of global non-linear optimisation of a network with embedded landmarks could serve

[1] Such a non-linear optimisation can be a difficult mathematically problem with computational complexity of NP-hard or NP-complete (Gass & Harris, 2000).

as test-bed and benchmark for existing optimizer libraries and new implementations of optimisation algorithms.

8.3.3. From Mental Navigation to Real Navigation

An aspect that could not be adequately mimicked in the studies presented is the time period between learning the map and using the spatial knowledge acquired. In the studies presented (see chapter 4, chapter 5, and chapter 6) evaluations of tactile orientation maps performed through mental navigation: after having some time to learn the map, different *virtual* navigation tasks were tested. This means that navigation was not performed in the actual geographic space but an entirely imagined performance. Reason for this mental navigation was that it frees from the contingencies of the geographic world (for example, that maps need to have a certain structure to maintain the comparability between conditions).

In the scenario described in chapter 1, Hannah reads the tactile map at home to be able to use the learned spatial knowledge later, 'in the field'. This is very different to actually being in a situation and immediately recalling the map after reading. In the time between learning and usage, other cognitive tasks may interfere with memory traces that represent the structure of the map. Although the extended time between learning and using spatial information may have its disadvantages, Lobben & Lawrence (2012, p. 107) conclude that real-world navigation tasks after map learning are more beneficial compared to only studying the map.

> '[A]lthough users of tactile navigation maps can study a map and develop an understanding of the spatial layout [...], the actual USE of the map for real-world navigation tasks facilitated a more complete mental map of the same environment.'

For forthcoming studies the extension to real navigation tasks would signify a major advantage for the applicability of results, as map usage in general is not only intended to learn the map but also to use the acquired knowledge in wayfinding activities, such as (self-)localisation or survey mapping when in the geographic environment, as discussed in subsection 3.1.2.

Thus, studies with a realistic study setup (time differences between learning and using the spatial knowledge and usage in the actual geographic environment) will yield additional insights into the principles of schematisation and contribute to improving schematisation principles for tactile orientation maps that are still recalled after a (extended) period of time.

8.3.4. From Uni-Modal to Multi-modal Maps

A further factor to understand tactile maps could be to distribute spatial information through various sensory and representational modalities. The research about the conjoint retention hypothesis (for a review, see Verdi & Kulhavy 2002) and the dual coding hypothesis (Paivio, 1986) showed that spatial encoding contributes to the retrieval of propositional information from memory (Winn, 1991). Thus, the approach to base information on spatial encoded representation, such as a map, could be promising. As the TOMs investigated in this thesis are not multi-modal, the approach to multi-modal communication remains a subject for future research.

Once a data model for a tactile map is generated, opportunities other than producing a physical map will open up. Computer technology has been employed to provide blind people with naturalistic and intuitive devices dedicated to the acquisition of spatial knowledge. Virtual reality has been proposed, for example, virtual tactile maps, explored with a computer-controlled, motorised device and monitored manually. When a user virtually touches a virtual object in the simulation space (the virtual world), this device produces a real force against the the user's movement ('force-feedback' or 'force-reflecting'). The impression of a real object being hit is produced. Fundamentally, force feedback interfaces have two basic functions: to measure the positions and contact forces of the user's hand, and to indicate contact forces and positions to the user (Tan et al., 1994). This concept can be used to explore virtual objects as well as virtual tactile maps of real environments (c.f. Golledge et al., 2005).

The virtual haptic maps interaction either takes place haptically or/and auditorially. The interaction with a real object is simulated by the interaction with a computer-controlled device to acquire information (for example shape and surface texture) (see the review by Paneels & Roberts (2010)). The concept of virtual maps was introduced and reviewed from a cartographers perspective by Moellering, 1980, 2007). In the case of virtual haptic maps, a force-feedback device like the PHANTOM (Massie & Salisbury, 1994) renders virtual objects so their shape can be explored (Salisbury & Srinivasan, 1997). The technology required for each user is quite expensive and interaction is often limited to proprioceptive and kinaesthetic cues. The abundance of cutaneous cues is neglected. For these reasons virtual haptic maps have other usage scenarios than hardcopy tactile maps. For example, virtual haptic maps are more often found in the academic research domain.

Virtual tactile maps could be extended to a virtual audio-tactile system that links touch, sound and/or speech. Spatially organised data can be sonified in *virtual sound maps* with sound. Sound labels are, for example, attached to certain points and if these points are virtually touched, the corresponding sound is reproduced. For details see book chapter by Théberge & Taylor (2005) or the article by Belardinelli et al. (2009). Speech can transform spatial data into language descriptions that are reproduced if certain conditions are met, for example, if the user explores an intersection for the first time. Speech is semantically richer than sound. However, it causes a higher cognitive load as language descriptions have to be interpreted. The combination of speech and haptics for multi-modal knowledge transfer was described (for example Habel & Graf, 2008) and demonstrated (Giudice et al., 2012, Lohmann et al., 2010) elsewhere. The combination of audio output and vibro-tactile output that can be found in many mobile phones today. It is a cheap and promising way of establishing audio-tactile systems in the consumer market. A major player among those groups that are actively pursuing research in vibro-audio interfaces is headed by Prof. Nicholas A. Giudice in the VEMI lab at the University of Maine (`http://www.vemilab.org`).

8.3.5. Evaluating the Effect of Symbolisation, Labelling & Explanatory Text

As explained in chapter 4, the symbols used in the studies went through a thorough initial testing phase before they were used as part of the material in the later studies. Other symbols in a more realistic study setup may turn out to be more adequate for conventional use in hardcopy tactile orientation maps than the ones used in the presented studies. Regarding that there has been nearly no research of map symbols on hardcopy tactile maps so far, symbolisation could be a research topic in its own right. Sensory and cognitive aspects need to be taken into account, similar to the work done in chapter 4.

Tactile labels in Braille print were not available in the tactile maps used for the studies presented in this thesis. This was done on purpose in order to exclude one confounding factor of map understanding as people that do not master Braille reading would have a major disadvantage. Braille labels in tactile maps are possible for Individuals that can read Braille. The presence of Braille labels would pose additional problems, especially regarding space, placement, and cluttering. As Braille print is expansive, additional space needed for other purposes would no longer be available . This would mean an additional constraint the construction of tactile orientation maps. It would probably influence the schematisation recommendations. However, Braille can facilitate the explanation of symbols in a legend. Map readers interactions with maps would be independent and there would be no need for an assistant explaining the meaning of symbols by reading out descriptions. For map usage in real world scenarios, labelling maps and communicating instructions and the legend of a map will be challenging. There is a huge percentage of blind people that cannot read Braille (about 70–90% according to estimates, see section 3.1). Other means may be applicable for those who cannot read Braille but will have to be tested:

- Recorded/Generated auditory explanation during exploration can inform about the meaning of features and their relations to other objects. This poses the problem of an appropriate reading speed that has to correspond to the pace of the map-users' tactual exploration. Interactive tactile tablets, like those discussed in subsection 7.3, dynamically adjust reading speed to the user's exploration pace and mitigate the problem. The right timing and appropriate content of supplemented audio descriptions are crucial as map readers may become annoyed by listening to the same description (without any new information) again and again, only because they pass the same location several times. Research on timing and dynamic construction of descriptions in connection with certain exploration behaviour has been initiated (Lohmann et al., 2010) but needs further investigation.

- Appropriate auditory description of the map and its purpose before the explorations starts. This case describes the challenge to present an appropriate amount and the right information that helps the map reader to understand the map and what it intends to communicate. A field test with tactile orientation maps constructed following the recommendations in this thesis showed that an introductory explanation to the map was a crucial part for people who had never used a traditional or hardcopy before (Graf et al., pear). These first results indicate that adjunct text may be helpful to better understand hardcopy tactile orientation maps[2] If each map is individually made for a different purpose, it will have different characteristics and an introductory explanation is very helpful for the map user, as a first field study indicated (Graf et al., pear). In addition, explanations will be especially useful for first time users of hardcopy tactile maps in order to understand the basic contingencies and properties, for example, the discrete printing of continuous objects. Explanations will be helpful to understand the orchestration of multiple maps (see next subsection).

8.3.6. Multipart Maps for Overview & Context

One single tactile map might be to small to display significant parts of the environment. Either the environment is too extended or/and it is too detailed. The use of multipart maps could be a solution for this problem, i.e. a collection of maps that together display the environment in an appropriate scale. Single maps from this collection can be read one-by-one. The problem with the collection of maps is how the map readers could be supported in relating objects that are displayed in different sub-maps. Here, I present initial thoughts on two strategies that are related to the strategies 'Show stable frame of reference' and 'Constrain panning and zooming'. Those strategies were both initially discussed in section 3.1 but dismissed for the application in single tactile orientation maps. In multipart maps such concepts might be helpful.

Using a stable frame of reference to embed a detailed map into a spatial context by referencing a set of fix global landmarks probably will ease establishing relations of each sub-map to the whole environment (see Figure 8.1). This is similar to the strategy 'Show stable frame

[2]Promising findings in this regard have been published by Ungar et al. (2002). The results are often interpreted against the background of the conjoint retention theory (Kulhavy et al., 1985), an extension of the dual coding theory (for a review see Paivio, 1991). Although the effectiveness of conjointly presenting map and text is not undisputed (for example Griffin & Robinson, 2005), it is often explained by encoding and retrieving processes that involve the visuospatial sketchpad component of working memory, postulated by Baddeley (for a review see Baddeley, 2003).

of reference' Now, for multipart maps the strategy 'Show stable frame of reference' and 'Constrain panning and zooming' become helpful and—at best—could be used together.

The transition from one sub-map to the next could be eased by defining a 'zone of transition' where adjacent sub-maps overlap, i.e. they both show the same details. The map-readers than can establish some correspondence between objects that are present in both maps. This might help tracing the transition from one sub-map to the other.

Another challenge is to remember all the information from different sub-maps and integrate them in a coherent cognitive map. The next proposed field of future work could ease this burden.

8.3.7. Adaptation of Schematisation

Research about maps on small displays (for an overview see Schmid, 2010) has motivated one strain of future studies. Instead of regarding schematisation as homogeneous in a map, one can think of having *heterogeneous levels of simplification* (including both, abstraction and schematisation) in different parts of the map. This would mean to abandon details in one part of the map, for example by simplifying the geometry of street representations, while keeping the same details in other parts. This would be an opportunity to abstract map entities of questionable importance in a certain place and not in another. For example, if there are types of elements that have a minor contribution to the map readers' conceptualisation of one part of the map, they could be neglected in this part only instead of leaving them out everywhere. This would result in adaptive schematisation: fewer unnecessary sensory information needs to be read and fewer unnecessary conceptual information needs to be comprehended. However, the heterogeneous level of simplification might confuse map readers, as the rationale behind this display technique is not attainable for them. Research in gains, losses, and trade-offs between both may lead to insights of how map-users can benefit from heterogeneous levels of simplifications in tactile maps. I propose three directions here.

8.3.7.1. Precedence Hierarchy for Feature Selection

Barkowsky & Freksa (1997) and Golledge (1995b) suggest that certain spatial concepts can be derived from a map and that each one conveys specific information (for details, see section 2.1.1, especially regarding subsection 2.1). Both authors propose a hierarchy of their concepts. Table 8.1 shows a proposal of a non-exclusive mapping between elements of the precedence hierarchy suggested by Barkowsky & Freksa and the essential spatial primitives for cognitive maps postulated by Golledge.

Such hierarchies implicitly state the importance of different types of spatial concepts for certain tasks. In the construction of tactile maps such hierarchies could be helpful to control

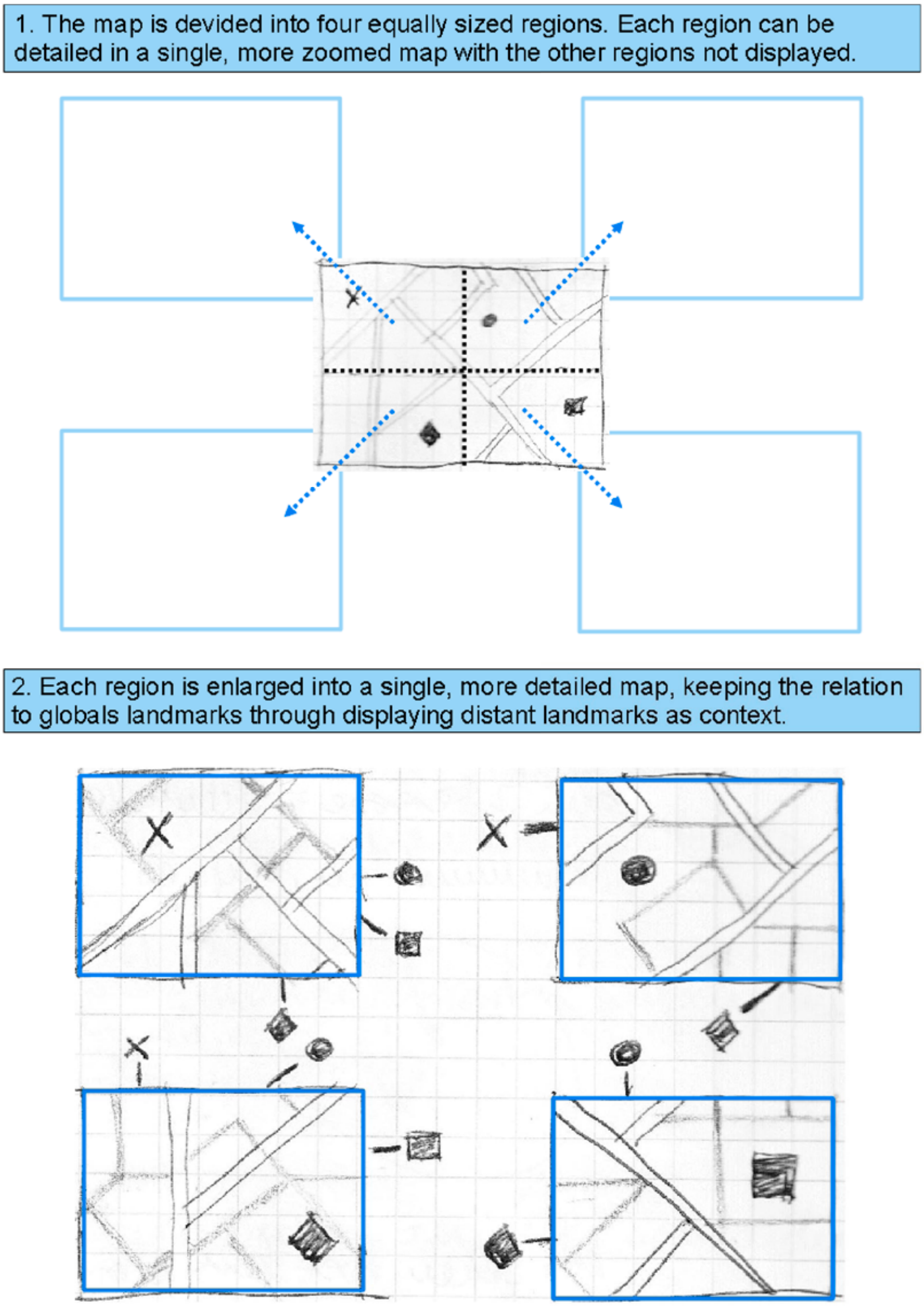

Figure 8.1.: The map has been zoomed out for greater overview. The overview is automatically divided horizontally and vertically so that four equally sized, non-overlapping sub-maps can be selected for more details. When the user chooses to zoom into one, the sub-map shows more details than the overview. In the frame of each sub-map, there are indicators that direct to important 'global' landmarks in other maps to foster the understanding of relations between sub-maps.

Concept from Barkowsky & Freksa	Concept from Golledge
Existence	Identity
Connectedness	Connection, Linkage
Orientation	Angle, Direction
Localization	Location
Distance	Distance
Shape	Pattern, Shape

Table 8.1.: Suggested mapping between concepts in a precedent hierarchy for physical maps and identified concepts in cognitive maps.

a selection strategy, i.e. display of mandatory and optional concepts represented in tactile maps. To develop such a hierarchy it is necessary to closely observe the details navigators use, the types of tasks, from which types of tactile maps they derive, and in which context. Relating the spatial details used to the task solved in a provided context might make it possible to find a hierarchy of concepts for each type of map. Such a precedence hierarchy could be a helpful guideline for relaxing the constraint satisfaction problem, in case it cannot be solved satisfying all constraints.

8.3.7.2. Individual Preferences of Map-users

The observation reported in chapter 6, that peripheral areas of the maps are not as extensively explored as central areas, could be an entity of cognitive economy (Hölscher et al., 2007). To accommodate such learning preferences one strategy could be employ heterogeneous levels of schematisation and leave out details in the periphery while keeping them in the central areas. See the example in Figure 8.2 that has the same level of details all over the map in contrast to Figure 8.3 that has full details in the centre of the map and less details in the periphery. Structuring a map in this way corresponds to a class of visualisation techniques known as *Focus+Context*.

Leaving out landmarks that are not needed (from whatever reason, for example, because they do not highlight decision points in the street network or connection points to adjacent maps) will probably result in both less sensory details and fewer information to remember. A more usable tactile map would probably be the results.

8.3.7.3. The Map-users' Individual Spatial Knowledge and Spatial Abilities

In contrast to the traditional tactile maps available today for learning about the general structure of the world, for example, as part of educational material, the proposed tactile orientation maps are customised wayfinding tools made to support individual tasks in individual

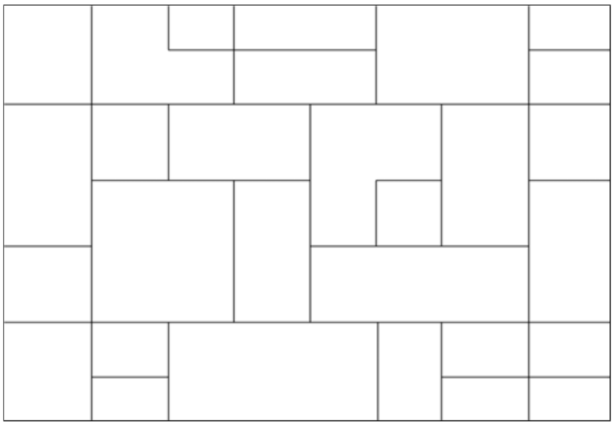

Figure 8.2.: A exemplary basic map (no landmarks, street representations only) with a homogeneous level of simplification. Compare it to the map with heterogeneous levels of simplification in Figure 8.3.

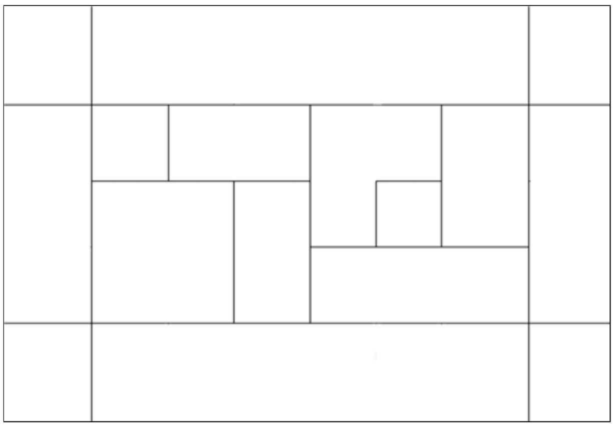

Figure 8.3.: In this variant of the basic map (see Figure 8.2) the periphery is simplified to a much greater extend than the central part, i.e. there are heterogeneous levels of simplification.

contexts. Customising the schematisation of maps, not only to the task but also to the contextual factors, for example, the user's spatial knowledge about the environment, can render especially useful maps adapted to their users. For example, strategies to hide entities based on prior knowledge (see section 3.1) could be used to omit detail that is already known. For example, if navigators know some parts of an environment well and do not know about the other parts, it would be beneficial for them to have a tactile map that highlights the details in-between the known parts.

This thesis set out to contribute to the quality and proliferation of tactile maps because 'if students use a map [...] their spatial and environmental learning could be significantly enhanced' (Lobben & Lawrence, 2012, p. 107). The findings in this thesis strongly support the need for tactile orientation maps that are adapted to the task, the production or display technology, and the individual user with her spatial abilities and existing spatial knowledge. I strongly suggest to evaluate those factors in an integrated research approach to advance the body of knowledge about the construction of tactile maps that are produced swiftly and that are easy to use, including the read. Perspectives from multiple research domains and established theories and methods from one field should be discussed to see how these approaches could provide new insights or design guidance for producing comprehensible tactile maps. The first workshop about *Spatial Knowledge Acquisition with Limited Information Displays* (SKALID 2012) showed that there is a particular interest in that topic (see Graf et al., 2012).

> *The ultimate increase in the availability of high quality, more easily read tactual maps will play an important part in extending the influence of map form to the visually handicapped, helping them to understand spatial patterns and processes in their unseen environment.*
>
> Ogrosky (1975, p. 212)

Bibliography

Agrawala, M. & Stolte, C. (2001). Rendering effective route maps: improving usability through generalization. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (pp. 241–249). New York, NY, USA: ACM.

Aldrich, F., Sheppard, L., & Hindle, Y. (2002). First steps towards a model of tactile graphicacy. *British Journal of Visual Impairment*, 20(2), 62–67.

Amick, N. & Corcoran, J. (1997). Guidelines for design of tactile graphics. Retrieved from `http://www.aph.org/edresearch/guides.htm`, March 23, 2009.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, 4(10), 829–839.

Baden-Württembergischer Genossenschaftsverband e.V (2012). Metec führt Blinde in die Windows-Welt. Retrieved from `http://www.bwgv-info.de/content/702.htm`, August 24, 2012.

Barkowsky, T. & Freksa, C. (1997). Cognitive requirements on making and interpreting maps. In S. C. Hirtle & A. U. Frank (Eds.), *Spatial information theory: A theoretical basis for GIS*, volume 1329 of *Lecture Notes in Computer Science* (pp. 347–361). Berlin, Heidelberg: Springer.

Barkowsky, T., Latecki, L. J., & Richter, K. F. (2000a). Schematizing maps: Simplification of geographic shape by discrete curve evolution. In C. Freksa, C. Habel, W. Brauer, & K. F. Wender (Eds.), *Spatial Cognition II*, volume 1849 of *Lecture Notes in Artificial Intelligence* (pp. 41–53). Berlin, Heidelberg: Springer Berlin Heidelberg.

Barkowsky, T., Latecki, L. J., & Richter, K.-F. (2000b). Schematizing maps: Simplification of geographic shape by discrete curve evolution. In *Spatial Cognition II* (pp. 41–53). Springer.

Barth, J. L. (1983). Factors affecting line tracing in tactile graphs. *Journal of Special Education*, 17(2), 215–226.

Baudisch, P. & Rosenholtz, R. (2003). Halo: a technique for visualizing off-screen objects. In *Proceedings of the SIGCHI conference on Human factors in computing systems (CHI 2003)* (pp. 481–488). New York, NY, USA: ACM.

Belardinelli, M. O., Federici, S., Delogu, F., & Palmiero, M. (2009). Sonification of spatial information: Audio-Tactile exploration strategies by normal and blind subjects. In *Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments*, volume 5615 of *Lecture Notes in Computer Science* (pp. 557–563). Berlin / Heidelberg: Springer.

Berendt, B., Barkowsky, T., Freksa, C., & Kelter, S. (1998). Spatial representation with aspect maps. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial Cognition – An interdisciplinary approach to representing and processing spatial knowledge* (pp. 313–336). Berlin: Springer.

Berlá, E. P. & Butterfield, L. H. (1977). Tactual distinctive features analysis: Training blind students in shape recognition and in locating shapes on a map. *Journal of Special Education*, 11(3), 335–346.

Berlá, E. P. & Murr, M. J. (1975). The effects of noise on the location of point symbols and tracking a line on a tactile pseudomap. *Journal of Special Education*, 9(2), 183–190.

Bertin, J. (1974). *Graphische Semiologie – Diagramme, Netze, Karten*. Berlin, New York: Walter de Gruyter. German translation of Bertin, J. (1973). Sémiologie graphiques, 2nd ed., Monton & Gauthier-Villars: Paris, La Haye.

Blades, M., Ungar, S., & Spencer, C. (1999). Map use by adults with visual impairments. *The Professional Geographer*, 51(4), 539–553.

Blasch, B. B., Wiener, W. R., & Welsh, R. L. (1997). *Foundations of orientation and mobility*. American Foundation for the Blind, 2nd edition.

Brambring, M. & Laufenberg, W. (1979). Construction and complexity of tactual maps for the blind. *Psychological Research*, 40(3), 315–327.

Brambring, M. & Weber, C. (1981). Taktile, verbale und motorische informationen zur geographischen orientierung blinder. *Zeitschrift für experimentelle und angewandte Psychologie*, 28(1), 23–37.

Brandes, U. & Pampel, B. (2009). On the hardness of orthogonal-order preserving graph drawing. In I. G. Tollis & M. Patrignani (Eds.), *Graph Drawing*, volume 5417 of *Lecture Notes in Computer Science* (pp. 266–277). Springer Berlin Heidelberg.

Brassel, K. E. & Weibel, R. (1988). A review and conceptual framework of automated map generalization. *International Journal of Geographical Information Science*, 2(3), 229–244.

Brunyé, T. T. & Taylor, H. A. (2008). Extended experience benefits spatial mental model development with route but not survey descriptions. *Acta Psychologica*, 127(2), 340–354.

Böttger, J., Brandes, U., Deussen, O., & Ziezold, H. (2008). Map warping for the annotation of metro maps. *Computer Graphics and Applications, IEEE*, 28(5), 56 –65.

Buziek, G. (2001). *Eine Konzeption der kartographischen Visualisierung*. Unpublished habilitation treatise, University of Hannover. Retrieved from `http://deposit.ddb.de/cgi-bin/dokserv?idn=969654022`.

Caddeo, P., Fornara, F., Nenci, A. M., & Piroddi, A. (2006). Wayfinding tasks in visually impaired people: the role of tactile maps. *Cognitive Processing*, 7, 168–169.

Campo, E. M., Roig, J., Röder, B., Wenn, D., Mamojka, B., Omastova, M., Terentjev, E. M., & Esteve, J. (2011). Nano opto-mechanical systems (NOMS) as a proposal for tactile displays. In *Proc. SPIE 8107, Nano-Opto-Mechanical Systems (NOMS)* (pp. 81070H–1 – 81070H–10).: Society of Photo-Optical Instrumentation Engineers (SPIE).

Canadian Braille Authority English Braille Standards Committee (2003). Report of tactile graphics sub committee part 3. Retrieved from `http://www.canadianbrailleauthority.ca/docs/Report_Tactile_Graphics_part3.pdf`, December 02, 2009.

Casakin, H., Barkowsky, T., Klippel, A., & Freksa, C. (2000). Schematic maps as wayfinding aids. In *Spatial Cognition II*, volume 1849 of *Lecture Notes in Computer Science* (pp. 54–71). Berlin / Heidelberg: Springer.

Casey, S. M. (1978). Cognitive mapping by the blind. *Journal of Visual Impairment & Blindness*, 72(8), 297–301.

Castner, H. W. (1983). Tactual maps and graphics – some implications for our study of visual cartographic communication. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 20(3), 1–16. doi: 10.3138/L221-K31N-TH17-5273.

Cattaneo, Z. & Vecchi, T. (2011). Spatial cognition in the blind. In *Blind Vision: The Neuroscience of Visual Impairment* (pp. 113–135). Cambridge, Massachusetts & London, England: MIT Press.

Challis, B. P. & Edwards, A. D. N. (2001). Design principles for tactile interaction. In *Haptic Human-Computer Interaction*, volume 2058 of *Lecture Notes in Computer Science* (pp. 17–24). Berlin / Heidelberg: Springer-Verlag.

Chan, C. (2007). *Computer-aided design and manufacturing of tactile maps*. Unpublished master thesis, School of Mechanical Engineering, Hong Kong University. DOI: 10.5353/th_b3789572.

Chang, D., Nesbitt, K. V., & Wilkins, K. (2007). The gestalt principle of continuation applies to both the haptic and visual grouping of elements. In *Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 15–20). Los Alamitos, CA, USA: IEEE Computer Society.

Chen, M.-S., Huang, C.-K., & Wang, C.-N. (2010). Working memory for spatial construction in blind and sighted individuals. *Journal of the Chinese Institute of Industrial Engineers*, 27(3), 199–208.

Chipofya, M., Wang, J., & Schwering, A. (2011). Towards cognitively plausible spatial representations for sketch map alignment. In M. Egenhofer, N. A. Giudice, R. Moratz, & M. Worboys (Eds.), *Spatial Information Theory*, volume 6899 (pp. 20–39). Berlin, Heidelberg: Springer Berlin Heidelberg.

Chouvardas, V. G., Miliou, A. N., & Hatalis, M. K. (2008). Tactile displays: Overview and recent advances. *Displays*, 29(3), 185–194.

Christopher, J. U. (2009). Patent No. US 2009/0002328: Method and apparatus for multi-touch tactile touch panel actuator mechanisms.

Coulson, M. R. C. (1991). Tactile-map output from geographical information systems: the challenge and its importance. *International journal of geographical information systems*, 5(3), 353.

Dacen Nagel, D. L. & Coulson, M. R. C. (1990). Tactual mobility maps / A comparative study. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 27(2), 47–63. doi: 10.3138/D310-6U13-H13J-H414.

Daniel, M.-P. & Denis, M. (1998). Spatial descriptions as navigational aids: A cognitive analysis of route directions. *Kognitionswissenschaft*, 7(1), 45–52.

Darken, R. P. & Sibert, J. L. (1996). Wayfinding strategies and behaviors in large virtual worlds. In *Proceedings of the SIGCHI conference on Human factors in computing systems: common ground*, CHI '96 (pp. 142–149). New York, NY, USA: ACM.

Denis, M. (1997). The description of routes: A cognitive approach to the production of spatial discourse. *Cahiers de Psychologie Cognitive*, 16(4), 409–458.

Denis, M., Pazzaglia, F., Cornoldi, C., & Bertolo, L. (1999). Spatial discourse and navigation: an analysis of route directions in the city of venice. *Applied Cognitive Psychology*, 13(2), 145–174.

DIN EN ISO 9241-12 (2006). *Ergonomische Anforderungen für Bürotätigkeiten mit Bildschirmgeräten. Teil 12: Informationsdarstellung*. Berlin: Beuth Verlag.

Dong, W., Guo, Q., & Liu, J. (2008). Schematic road network map progressive generalization based on multiple constraints. *Geo-spatial Information Science*, 11(3), 215–220.

Douce, J. L. & Gill, J. (1973). Computer-drawn maps for the blind. *Electronics & Power*, August 1973, 331–332.

Downs, R. M. & Stea, D., Eds. (1973). *Image & environment: cognitive mapping and spatial behavior*. Chicago, IL: Aldine Transaction.

Downs, R. M. & Stea, D. (1977). *Maps in Mind: Reflections on cognitive mapping*. New York: Harper and Row.

Downs, R. M. & Stea, D. (2011). Cognitive maps and spatial behaviour: Process and products. In M. Dodge, R. Kitchin, & C. Perkins (Eds.), *The Map Reader: Theories of Mapping Practice and Cartographic Representation* (pp. 312–317). John Wiley & Sons, Ltd.

Dulin, D. (2008). Effects of prior experience in raised line materials and prior visual experience in length estimations by blind people. *British Journal of Visual Impairment*, 26(3), 223 –237.

Dykes, J., Müller-Hannemann, M., & Wolff, A. (2011). *Schematization in Cartography, Visualization, and Computational Geometry*. Technical report, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, Germany, Dagstuhl, Germany.

Edman, P. (1992). *Tactile graphics*. New York, NY: American Foundation for the Blind Press.

Ellsiepen, I. (2005). *Methoden der effizienten Informationsübermittlung durch Bildschirmkarten*. Unpublished dissertation, Institut für Kartographie und Geoinformation, Inversität Bonn. Retrieved from `http://hss.ulb.uni-bonn.de:90/2005/0552/0552-1.pdf`.

Eriksson, Y. (1999). How to make tactile pictures understandable to the blind reader. In *Proceedings of the 65th IFLA Council and General Conference* Bangkok, Thailand: IFLA.

Eriksson, Y., Jansson, G., & Strucel, M. (2003). *Tactile Maps: Guidelines for the Production of Maps for the Visually Impaired*. Enskede, Sweden: The Swedish Braille Authority.

Espinosa, M. A., Ungar, S., Ochaíta, E., Blades, M., & Spencer, C. (1998). Comparing methods for introducing blind and visually impaired people to unfamiliar urban environments. *Journal of Environmental Psychology*, 18(3), 277–287.

Fleming, L. J. (1986). *Scale variation in tactual maps : implications for improved mobility*. Unpublished master thesis, Simon Fraser University, Vancouver, CA. Retrieved from `http://ir.lib.sfu.ca/handle/1892/7673`, June 25, 2013.

Foerster, T., Stoter, J., & Köbben, B. (2007). Towards a formal classification of generalization operators. In *Proceedings of the ICC 2007* Moscow, Russia: ICA.

Fortin, M., Voss, P., Rainville, C., Lassonde, M., & Lepore, F. (2006). Impact of vision on the development of topographical orientation abilities. *NeuroReport*, 17(4), 443–446.

Foulke, E. (1994). Tangible graphic displays. In J. A. Gardner & W. A. Barry (Eds.), *Proceedings of the Symposium on High Resolution Tactile Graphics Held on March 15, 1994 in Los Angeles as part of the 1994 CSUN International Conference on Technology and Persons with Disabilities*. Los Angeles, CA, USA: California State University.

Frank, A. U. (1991). Qualitative spatial reasoning with cardinal directions. In *Proceedings Seventh Austrian Conference on Artificial Intelligence* (pp. 157–167).

Frank, A. U. (1996). Qualitative spatial reasoning: Cardinal directions as an example. *International Journal of Geographical Information Science*, 10(3), 269–290.

Freksa, C. (1991). Qualitative spatial reasoning. In D. M. Mark & A. U. Frank (Eds.), *Cognitive and linguistic aspects of geographic space* (pp. 361–372). Dordrecht: Kluwer.

Freksa, C. (1999). Spatial aspects of task-specific wayfinding maps. In J. Gero & B. Tversky (Eds.), *Visual and Spatial Reasoning in Design* (pp. 15–32). Key Centre of Design Computing and Cognition; University of Sydney.

Freksa, C. & Barkowsky, T. (1999). On the duality and on the integration of propositional and spatial representations. In C. Habel & G. Rickheit (Eds.), *Mental Models in Discourse Processing and Reasoning* (pp. 195–212). Amsterdam, Lausanne, New York: Elsevier.

Freksa, C., Klippel, A., & Winter, S. (2007). A cognitive perspective on spatial context. In A. G. Cohn, C. Freksa, & B. Nebel (Eds.), *Spatial Cognition: Specialization and Integration*, Dagstuhl Seminar Proceedings Dagstuhl, Germany: Internationales Begegnungs- und Forschungszentrum für Informatik (IBFI), Schloss Dagstuhl, Germany.

Friedman, A. & Montello, D. R. (2006). Global-scale location and distance estimates: Common representations and strategies in absolute and relative judgments. *Learning, Memory*, 32(3), 333–346.

Gallagher, B. & Frasch, W. (1998). Tactile acoustic computer interaction system: A new type of graphic access for the blind. In *Technology for Inclusive Design and Equality Inproving the Quality of Life for the European Citizen, Proceedings of the 3rd TIDE Congress, Helsinki, Finland*.

Gardiner, A. & Perkins, C. (2002). Best practice guidelines for the design, production and presentation of vacuum formed tactile maps. Retrieved from `http://www.tactilebooks.org/tactileguidelines/page1.htm`, March 03, 2009.

Gardiner, A. & Perkins, C. (2003). Here is the beech tree! understanding tactile maps in the field. *The Cartographic Journal*, 40, 277–282. doi: 10.1179/000870403225013005.

Gardiner, A. & Perkins, C. (2005). 'It's a sort of echo...': Sensory perception of the environment as an aid to tactile map design. *British Journal of Visual Impairment*, 23(2), 84–91. doi: 10.1177/0264619605054780.

Gardner, J. (2005). Braille, innovations, and Over-Specified standards. In *Proceedings of the 2005 GOTHI (Guidelines on Tactile and Haptic Interactions) Conference* (pp. 26–27). Saskatoon, Canada: University of Saskatoon.

Gardner, J. A. & Bulatov, V. (2004). Directly accessible mainstream graphical information. In *Computers Helping People with Special Needs*, volume 3118 of *Lecture Notes in Computer Science* (pp. 739–744). Berlin / Heidelberg: Springer.

Gass, S. I. & Harris, C. M. (2000). *Encyclopedia of operations research and management science*. Boston: Kluwer Academic, 2 edition.

Gentaz, E. & Hatwell, Y. (2004). Geometrical haptic illusions: The role of exploration in the Muller-Lyer, Vertical-Horizontal, and delboeuf illusions. *Psychonomic Bulletin and Review*, 11(1), 31–40.

Giudice, N. A., Bakdash, J., & Legge, G. (2007). Wayfinding with words: spatial learning and navigation using dynamically updated verbal descriptions. *Psychological Research*, 71(3), 347–358.

Giudice, N. A., Betty, M. R., & Loomis, J. M. (2011). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37(3), 621–634.

Giudice, N. A. & Legge, G. E. (2008). Blind navigation and the role of technology. In A. Helal, M. Mokhtari, & B. Abdulrazak (Eds.), *Engineering handbook of smart technology for aging, disability, and independence* (pp. 479–500). Hoboken, NJ, USA: John Wiley & Sons, Inc.

Giudice, N. A. & Li, H. (2012). The effects of visual granularity on indoor spatial learning assisted by mobile 3D information displays. In C. Stachniss, K. Schill, & D. Uttal (Eds.), *Spatial Cognition VIII*, volume 7463 of *Lecture Notes in Computer Science* (pp. 163–172). Springer Berlin / Heidelberg.

Giudice, N. A., Palani, H. P., Brenner, E., & Kramer, K. M. (2012). Learning non-visual graphical information using a touch-based vibro-audio interface. In *Proceedings of the 14th international ACM SIGACCESS conference on Computers and accessibility*, ASSETS '12 (pp. 103–110). New York, NY, USA: ACM.

Golledge, R. (1995a). Path selection and route preference in human navigation: A progress report. *Spatial Information Theory A Theoretical Basis for GIS*, (pp. 207–222).

Golledge, R., Klatzky, R., & Loomis, J. (1996). Cognitive mapping and wayfinding by adults without vision. In *The Construction of Cognitive Maps*, volume 2 of *GEOJOURNAL LIBRARY* (pp. 215–246). Dordrecht: Springer Netherlands.

Golledge, R. G. (1991). Tactual strip maps as navigational aids. *Journal of Visual Impairment and Blindness*, 85(7), 296–301.

Golledge, R. G. (1995b). Primitives of spatial knowledge. In T. L. Nyerges, D. M. Mark, R. Laurini, & M. J. Egenhofer (Eds.), *Cognitive aspects of human-computer interaction for geographic information systems* (pp. 29–44). Dordrecht, Netherlands: Kluwer Academic Publishers.

Golledge, R. G. (1999). Human wayfinding and cognitive maps. In R. G. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 5–45). Baltimore, MD, USA: Johns Hopkins University Press.

Golledge, R. G., Dougherty, V., & Bell, S. (1995). Acquiring spatial knowledge: Survey versus route-based knowledge in unfamiliar environments. *Annals of the Association of American Geographers*, 85(1), 134–158. `http://www.jstor.org/stable/2564282`.

Golledge, R. G., Rice, M., & Jacobson, R. D. (2005). A commentary on the use of touch for accessing on-screen spatial representations: The process of experiencing haptic maps and graphics. *The Professional Geographer*, 57(3), 339–349.

Gould, P. & White, R. (1974). *Mental Maps*. London, UK: Penguin Books.

Graf, C. (2010). Verbally annotated tactile maps: Challenges and approaches. In *Spatial Cognition VII*, volume 6222 of *Lecture Notes in Computer Science* (pp. 303–318). Mt. Hood / Portland, Oregon: Springer.

Graf, C., Giudice, N. A., & Schmid, F., Eds. (2012). *Spatial Knowledge Acquisition with Limited Information Displays (SKALID 2012), Proceedings*, volume 888 of *CEUR Workshop Proceedings*, Monastery Seeon, Bad Seeon, Germany. `http://ceur-ws.org/Vol-888/`?

Graf, C. & Schmid, F. (2010). From visual schematic to tactile schematic maps. In *Spatial Cognition 2010, Workshop You Are Here 2: 2nd Workshop on Spatial Awareness and Geographic Knowledge Acquisition with Small Mobile Devices, Proceedings* Mt. Hood / Portland, Oregon.

Graf, C., Wippich, F., & Drewes, D. (to appear). Haptomai - an online service for customizable tactile maps.

Griffin, M. & Robinson, D. (2005). Does spatial or visual information in maps facilitate text recall? reconsidering the conjoint retention hypothesis. *Educational Technology Research and Development*, 53(1), 23–36.

Guesgen, H. W., Hertzberg, J., & Siekmann, J. (1992). Constraint relaxation. In *A Perspective of Constraint-Based Reasoning: An Introductory Tutorial*, volume 597 of *Lecture Notes in Artificial Intelligence* (pp. 41–56). Berlin / Heidelberg: Springer.

Gustafson, S., Baudisch, P., Gutwin, C., & Irani, P. (2008). Wedge: Clutter-free visualization of off-screen locations. In *Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems* (pp. 787–796). Florence, Italy: ACM SIGCHI.

Habel, C. & Graf, C. (2008). Towards audio-tactile you-are-here maps: Navigation aids for visually impaired people. In *Workshop Proceedings "You-Are-Here-Maps", Spatial Cognition 2008* (pp. 1–10). Freiburg / Breisgau, Germany: University of Freiburg.

Hamel, J., Michel, R., & Strothotte, T. (1996). Visibility through inaccuracy: Geometric distortion to reduce the cluttering in route maps. In *Proceedings of the Central European Conference on Computer Graphics* (pp. 123–132). Plzen, Czech Republic.

Harrie, L. (2003). Weight-Setting and quality assessment in simultaneous graphic generalization. *The Cartographic Journal*, 40, 221–233. doi: 10.1179/000870403225012925.

Hegarty, M. (2010). Components of spatial intelligence. In *The Psychology of Learning and Motivation*, volume Volume 52 (pp. 265–297). Academic Press.

Heller, M. A. (1989a). Picture and pattern perception in the sighted and the blind: the advantage of the late blind. *Perception*, 18(3), 379–89. PMID: 2798020.

Heller, M. A. (1989b). Texture perception in sighted and blind observers. *Perception & Psychophysics*, 45(1), 49–54.

Heller, M. A. (2002). Tactile picture perception in sighted and blind people. *Behavioural Brain Research*, 135(1-2), 65–68.

Heller, M. A., Brackett, D. D., Scroggs, E., Allen, A. C., & Green, S. (2001). Haptic perception of the horizontal by blind and low-vision individuals. *Perception*, 30(5), 601 – 610.

Heller, M. A., Calcaterra, J. A., Burson, L. L., & Tyler, L. A. (1996). Tactual picture identification by blind and sighted people: effects of providing categorical information. *Perception & Psychophysics*, 58(2), 310–23. PMID: 8838173.

Heller, M. A. & Kennedy, J. M. (1990). Perspective taking, pictures, and the blind. *Perception & Psychophysics*, 48(5), 459–66. PMID: 2247329.

Heller, M. A., Kennedy, J. M., & Joyner, T. D. (1995). Production and interpretation of pictures of houses by blind people. *Perception*, 24(9), 1049–1058.

Hinton, R. (1996). *Tactile Graphics in Education*. Glasgow: Moray House Publications.

Hölscher, C., Büchner, S. J., Brösamle, M., Meilinger, T., & Strube, G. (2007). Signs and maps – cognitive economy in the use of external aids for indoor navigation. In *Proceedings of the 29th Annual Conference of the Cognitive Science Society (CogSci 2007)* (pp. 377–382).

Jacobson, R. D. (1998). Navigating maps with little or no sight: An audio-tactile approach. In *Proceedings of the Workshop on Content Visualization and Intermedia Representations (CVIR)*.

Jansson, G. (1983). Tactile maps as a challenge for perception research. In J. W. Wiedel (Ed.), *Proceedings of the First International Symposium on Maps and Graphics for the Visually Handicapped* (pp. 68–75). Washinghton, D.C.: Association of American Geographers.

Jansson, G., Juhasz, I., & Cammilton, A. (2006). Reading virtual maps with a haptic mouse: Effects of some modifications of the tactile and audio-tactile information. *British Journal of Visual Impairment*, 24(60).

Jehoel, S., McCallum, D., Rowell, J., & Ungar, S. (2006). An empirical approach on the design of tactile maps and diagrams: The cognitive tactualization approach. *British Journal of Visual Impairment*, 24(2), 67–75.

Jehoel, S., Sowden, P. T., Ungar, S., & Sterr, A. (2009). Tactile elevation perception in blind and sighted participants and its implications for tactile map creation. *Human Factors*, 51(2), 208–223.

Jehoel, S., Ungar, S., McCallum, D., & Rowell, J. (2005). An evaluation of substrates for tactile maps and diagrams: Scanning speed and users' preferences. *Journal of Visual Impairment and Blindness*, 99(2), 85–95.

Jentzsch, K. & Kurt, J. (2001). *Anleitung zum Entwerfen taktiler Grafiken für Blinde mit CorelDraw*. Technical report, Institut für Rehabilitationswissenschaften, Abteilung Rehabilitationstechnik und Informatik, Humboldt-Universität zu Berlin.

Kaklanis, N., Votis, K., & Tzovaras, D. (2013). A mobile interactive maps application for a visually impaired audience. In *Proceedings of the 10th International Cross-Disciplinary Conference on Web Accessibility*, W4A '13 (pp. 23:1–23:2). New York, NY, USA: ACM.

Kappers, A. M. (2007). Haptic space processing – allocentric and egocentric reference frames. *Canadian Journal of Experimental Psychology*, 61(3), 208–218. doi: 10.1037/cjep2007022.

Kappers, A. M., Postma, A., & Viergever, R. F. (2008). How robust are the deviations in haptic parallelity? *Acta Psychologica*, 128(1), 15–24.

Kesavan, S. & Giudice, N. A. (2012). Indoor scene knowledge acquisition using a natural language interface. In C. Graf, N. A. Giudice, & F. Schmid (Eds.), *Proceedings of the Workshop on Spatial Knowledge Acquisition with Limited Information Displays 2012*, volume 888 (pp. 1–6). Kloster Seeon, Germany: CEUR Workshop Proceedings.

Kikin-Gil, E. (2009). Patent No. US 2010/0295820: Light-induced shape-memory polymere display screen.

Kinzel, K. (1995). *Untersuchung gestalterischer und technischer Aspekte der Herstellung und Nutzung von Karten für Blinde und Sehschwache*. Unpublished Diplomarbeit, Technische Universität Dresden, Institut für Kartographie, Dresden.

Kitchin, R. & Freundschuh, S. (2000). *Cognitive mapping: past, present and future*. London: Routledge.

Kitchin, R. M. (1994). Cognitive maps: What are they and why study them? *Journal of Environmental Psychology*, 14(1), 1–19.

Klippel, A. (2003). Wayfinding choremes. In W. Kuhn, M. Worboys, & S. Timpf (Eds.), *Spatial Information Theory: Foundations of Geographic Information Science. Conference on Spatial Information Theory (COSIT)*, Lecture Notes in Computer Science (pp. 320–334). Berlin, Heidelberg: Springer.

Klippel, A., Hirtle, S., & Davies, C. (2010). You-Are-Here maps: Creating spatial awareness through map-like representations. *Spatial Cognition & Computation*, 10(2), 83–93.

Klippel, A. & Kulik, L. (2000). Using grids in maps. In M. Anderson, P. Cheng, & V. Haarslev (Eds.), *Proceedings of the First International Conference on Theory and Application of Diagrams*, volume 1889 of *Lecture Notes in Artificial Intelligence* (pp. 486–489). Berlin / Heidelberg: Springer-Verlag.

Klippel, A. & Richter, K.-F. (2004). Chorematic focus maps. In G. Gartner (Ed.), *Location Based Services & Telecartography*, Geowissenschaftliche Mitteilungen (pp. 39–44). Wien: Technische Universitï¿½t Wien.

Klippel, A., Richter, K.-F., Barkowsky, T., & Freksa, C. (2005). The cognitive reality of schematic maps. In L. Meng, A. Zipf, & T. Reichenbacher (Eds.), *Map-based Mobile Services – Theories, Methods and Implementations* (pp. 57–74). Berlin: Springer.

Klippel, A., Tappe, H., & Habel, C. (2003). Pictorial representations of routes: Chunking route segments during comprehension. In C. Freksa, W. Brauer, C. Habel, & K. F. Wender (Eds.), *Spatial Cognition III. Routes and Navigation, Human Memory and Learning, Spatial Representation and Spatial Learning*, number 2685 in Lectures Notes in Artificial Intelligence (pp. 11–33). Berlin / Heidelberg: Springer-Verlag.

König, H., Schneider, J., & Strothotte, T. (2001). Orientation and navigation in virtual Haptic-Only environments. In V. Paelke & S. Volbracht (Eds.), *Proceedings of User Guidance in Virtual Environments. Workshop on Guiding Users through Interactive Experiences: Usability Centred Design and Evaluation of Virtual 3D Environments*, volume 8 of *C.LAB Publication* (pp. 123–134). Aachen: Shaker.

König, V. (1997). *Handbuch über die Blinden- und Sehbehindertengerechte Umwelt- und Verkehrsraumgestaltung*. Bonn, Germany: Deutscher Blindenverband e.V.

Kosslyn, S. M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology*, 3(3), 185–225.

Kraus, M., Völkel, T., & Weber, G. (2008). An Off-Screen model for tactile graphical user interfaces. In *Computers Helping People with Special Needs*, volume 5105 of *Lecture Notes in Computer Science* (pp. 865–872). Berlin / Heidelberg: Springer.

Kruglick, E. (2011). Patent No. US 2011/0018813: Electro-osmotic tactile display.

Kuipers, B. (1978). Modeling spatial knowledge. *Cognitive Science*, 2, 129–153.

Kuipers, B. (1982). The "map in the head" metaphor. *Environment and Behavior*, 14(2), 202.

Kulhavy, R. W., Lee, J. B., & Caterino, L. C. (1985). Conjoint retention of maps and related discourse. *Contemporary Educational Psychology*, 10(1), 28–37.

Kulhavy, R. W. & Stock, W. A. (1996). How cognitive maps are learned and remembered. *Annals of the Association of American Geographers*, 86(1), 123–145.

Kulik, L. & Klippel, A. (1999). Reasoning about cardinal directions using grids as qualitative geographic coordinates. In C. Freksa & D. M. Mark (Eds.), *Spatial Information Theory* (pp. 205–220). Berlin, Heidelberg: Springer.

Lahav, O. & Mioduser, D. (2008). Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-Computer Studies*, 66(1), 23–35.

Lambert, L. & Lederman, S. (1989). An evaluation of the legibility and meaningfulness of potential map symbols. *Journal of Visual Impairment & Blindness*, 83(8), 397–403.

Lawrence, M. M. & Lobben, A. K. (2011). The design of tactile thematic symbols. *Journal of Visual Impairment & Blindness*, 105(10), 681–691.

Lee, C. H. & Jang, M. G. (2011). Virtual surface characteristics of a tactile display using magneto-rheological fluids. *Sensors*, 11(3), 2845–2856.

Levine, M. (1982). You-Are-Here maps: Psychological considerations. *Environment and Behavior*, 14(2), 221–237. doi: 10.1177/0013916584142006.

Liben, L. (1997). Children's understandings of spatial representations of place: Mapping the methodological landscape. In N. Foreman & R. Gillett (Eds.), *Handbook of spatial research paradigms and methodologies. Volume 1: Spatial cognition in the child and adult* (pp. 41–83). East Sussex, U.K.: The Psychology Press (Tayor & Francis Group).

Liben, L. & Downs, R. (1989). Understanding maps as symbols: The development of map concepts in children. In H. Reese (Ed.), *Advances in child development and behavior*, volume 22 (pp. 145–201). San Diego, CA: Academic Press.

Liben, L. & Downs, R. (1993). Understanding person-space-map relations: Cartographic and developmental perspectives. *Developmental Psychology*, 29, 739–752.

Linvill, J. & Bliss, J. (1966). A direct translation reading aid for the blind. *Proceedings of the IEEE*, 54(1), 40–51.

Lobben, A. & Lawrence, M. (2012). The use of environmental features on tactile maps by navigators who are blind. *The Professional Geographer*, 64(1), 95–108.

Lobben, A. K. (2004). Tasks, strategies, and cognitive processes associated with navigational map reading: A review perspective. *The Professional Geographer*, 56(2), 270–281.

Lohmann, K., Kerzel, M., & Habel, C. (2010). Generating verbal assistance for tactile-map explorations. In *Proceedings of the 3rd Workshop on Multimodal Output Generation (MOG 2010)* (pp. 27–35). Dublin, Ireland: Trinity College Dublin.

Long, R. G. & Giudice, N. A. (2010). Establishing and maintaining orientation for mobility. In *Foundations of Orientation and Mobility*, volume Vol. 1: History and Theory (pp. 45–62). New York: American Foundation for the Blind, 3rd edition.

Loomis, J. M., Golledge, R. G., Klatzky, R. L., & Marston, J. R. (2006). Assisting wayfinding in visually impaired travelers. In G. L. Allen (Ed.), *Applied spatial cognition: From research to cognitive technology* (pp. 179–202). Mahwah, NJ: Lawrence Erlbaum Associates.

Loomis, J. M., Klatzki, R. L., & Giudice, N. A. (2012). Sensory substitution of vision: importance of perceptual and cognitive processing. In R. Manduchi & S. Kurniawan (Eds.), *Assistive Technology for Blindness and Low Vision* (pp. 162–191). Boca Raton, FL, USA: CRC Press.

Loomis, J. M. & Klatzky, R. L. (2008). Functional equivalence of spatial representations from vision, touch, and hearing: relevance for sensory substitution. In J. J. Rieser, D. H. Ashmead, F. Ebner, & A. L. Corn (Eds.), *Blindness and Brain Plasticity in Navigation and Object Perception* (pp. 155–185). New York: Lawrence Erlbaum Associates.

Loomis, J. M. & Lederman, S. J. (1986). Tactual perception. In K. Boff, L. Kaufmann, & J. Thomas (Eds.), *Handbook of Perception and Human Performance*, volume 2 (pp. 31–1–31–41). New York: Wiley.

Lötzsch, J. (1994). Computer-aided access to tactile graphics for the blind. In *Proceedings of the 4th international conference on Computers for handicapped persons* (pp. 575–581). Vienna, Austria: Springer-Verlag New York, Inc.

Lynch, K. (1960). *The image of the city*. Cambridge, London: MIT press.

MacEachren, A. M. (1986). A linear view of the world: Strip maps as a unique form of cartographic representation. *Cartography and Geographic Information Science*, 13(1), 7–26.

MacEachren, A. M. (1995). *How maps work*. New York, London: The Guilford Press.

Maglione, F. (1969). *An Experimental Study of the Use of Tactual Maps as Orientation and Mobility Aids for Adult Blind Subjects*. PhD thesis, University of Illinois at Urbana-Champaign, Urbana, IL, USA. PhD Thesis - unpublished.

Marsh, W. E., Hantel, T., Zetzsche, C., & Schill, K. (2012). Cognitive strategies in impossible worlds.

Massie, T. H. & Salisbury, J. K. (1994). The PHANTOM haptic interface: A device for probing virtual objects. In *Proceedings of the ASME Winter Annual Meeting: Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 295–301). Chicago, IL: American Society of Mechanical Engineers (ASME).

McCallum, D., Rowell, J., & Ungar, S. (2003). Producing tactile maps using new inkjet technology: an introduction. *Cartographic Journal, The*, 40, 294–298.

McCallum, D., Ungar, S., & Jehoel, S. (2006). An evaluation of tactile directional symbols. *British Journal of Visual Impairment*, 24(2), 83–92.

McMaster, R. B. & Shea, K. S. (1992). *Generalization in digital cartography*. Washington, DC: Association of American Geographers.

Mellis, D. A. (2011). *Case Studies in the Digital Fabrication of Open-Source Consumer Electronic Products*. Unpublished master thesis, Massachusetts Institute of Technology.

Michel, R. (2000). *Interaktiver Layoutentwurf für individuelle taktile Karten*. Aachen: Shaker.

Michon, P.-E. & Denis, M. (2001). When and why are visual landmarks used in giving directions? In *Spatial Information Theory*, volume 2205 of *Lecture Notes in Computer Science* (pp. 292–305). Berlin / Heidelberg: Springer.

Miele, J. A., Landau, S., & Gilden, D. (2006). Talking TMAP: automated generation of audio-tactile maps using smith-kettlewell's TMAP software. *British Journal of Visual Impairment*, 24(2), 93.

Millar, S. & Al-Attar, Z. (2001). Illusions in reading maps by touch: Reducing distance errors. *British Journal of Psychology*, 92, 643–657.

Millar, S. & Al-Attar, Z. (2002). The Müller-Lyer illusion in touch and vision: implications for multisensory processes. *Perception & Psychophysics*, 64(3), 353–365. PMID: 12049277.

Münzer, S., Zimmer, H. D., Schwalm, M., Baus, J., & Aslan, I. (2006). Computer-assisted navigation and the acquisition of route and survey knowledge. *Journal of Environmental Psychology*, 26(4), 300–308.

Moellering, H. (1980). Strategies of real-time cartography. *Cartographic Journal*, 17(1), 12–15.

Moellering, H. (2007). Expanding the ICA conceptual definition of a map. In *Proceedings: 23th International Cartographic Conference*, volume CDROM Moscow: International Cartographic Association.

Montello, D. (1993). Scale and multiple psychologies of space. In A. Frank & I. Campari (Eds.), *Spatial Information Theory A Theoretical Basis for GIS*, volume 716 of *Lecture Notes in Computer Science* (pp. 312–321). Springer Berlin / Heidelberg.

Montello, D. R. (2005). Navigation. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 257–294). Cambridge, MA: Cambridge University Press.

Moore, D. S. & McCabe, G. P. (1999). *Introduction to the Practice of Statistics*. New York, NY, USA: W. H. Freeman, 3rd edition.

Muehrcke, P. C. (1976). Concepts of scaling from the map reader's point of view. *The American Cartographer*, 3(2).

Niederstadt, J. (October 19, 2009). Der Gutenberg der Blinden. *Frankfurter Allgemeine Zeitung*. Retrieved from `http://www.faz.net/aktuell/wissen/mensch-gene/braille-schrift-der-gutenberg-der-blinden-1868474.html`, May 12, 2013.

Nielsen, J. & Hackos, J. T. (1993). *Usability engineering*. Boston, MA, USA: Academic Press.

Nöllenburg, M. & Wolff, A. (2006). A mixed-integer program for drawing high-quality metro maps. In *Graph Drawing* (pp. 321–333).: Springer.

Noordzij, M. L., Zuidhoek, S., & Postma, A. (2006). The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. *Cognition*, 100(2), 321–342.

Noordzij, M. L., Zuidhoek, S., & Postma, A. (2007). The influence of visual experience on visual and spatial imagery. *Cognition*, 36, 101–112.

Ogrosky, C. E. (1975). Current research in tactual cartography. In J. Kavaliunas (Ed.), *Auto-carto 2: Proceedings of the International Symposium on Computer-Assisted Cartography, September 21-25, 1975* (pp. 204–214). Reston, Virginia, USA: U.S. Bureau of the Census and American Congress on Surveying and Mapping. `http://mapcontext.com/autocarto/proceedings/auto-carto-2/pdf/current-research-in-tactual-cartography.pdf`.

Paivio, A. (1986). *Mental Representations: A Dual Coding Approach*. New York: Oxford University Press.

Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology/Revue canadienne de psychologie*, 45(3), 255.

Paneels, S. & Roberts, J. C. (2010). Review of designs for haptic data visualization. *Haptics, IEEE Transactions on*, 3(2), 119–137.

Parush, A., Ahuvia, S., & Erev, I. (2007). Degradation in spatial knowledge acquisition when using automatic navigation systems. In S. Winter, M. Duckham, L. Kulik, & B. Kuipers (Eds.), *Proceedings of the 8th International Conference on Spatial Information Theory (COSIT 2007)*, volume 4736 of *Lecture Notes in Computer Science* (pp. 238–254). Berlin / Heidelberg: Springer-Verlag.

Perkins, C. (2001). Tactile campus mapping: evaluating designs and production technologies. In *Proceedings, The 20th International Cartographic Conference (ICC2001)*, volume 5 (pp. 2906–2913). Bejing, China.

Peters, D. & Richter, K.-F. (2008). Taking off to the third dimension – schematization of virtual environments. *International Journal of Spatial Data Infrastructures Research*, 3, 20–37.

Peucker, T. K. & Chrisman, N. (1975). Cartographic data structures. *Cartography and Geographic Information Science*, 2(1), 55–69.

Postma, A., Zuidhoek, S., Noordzij, M. L., & Kappers, A. M. (2007). Differences between early blind, late blind and blindfolded sighted people in haptic spatial configuration learning and resulting memory traces. *Perception*, 36(8), 1253–1265.

Pun, T., Roth, P., Bologna, G., Moustakas, K., & Tzovaras, D. (2007). Image and video processing for visually handicapped people. *Journal on Image Video Processing*, 2007(5), 1–12.

Raja, M. K. (2011). *The development and validation of a new smartphone based non-visual spatial interface for learning indoor layouts*. Unpublished master thesis, The University of Maine, School of Computing and Information Science.

Renz, J., Ed. (2002). *Qualitative Spatial Reasoning with Topological Information*, volume 2293 of *Lecture Note in Artificial Intelligence*. Berlin, Heidelberg: Springer.

Révész, G. (1950). *Psychology and art of the blind*. London, UK: Longmans, Green.

Rice, M., Jacobson, R. D., Golledge, R. G., & Jones, D. (2005). Design considerations for haptic and auditory map interfaces. *Cartography and Geographic Information Science*, 32, 381–391.

Robbins, D. C., Cutrell, E., Sarin, R., & Horvitz, E. (2004). Zonezoom: Map navigation for smartphones with recursive view segmentation. In M. F. Costabile (Ed.), *Proceedings of the Working Conference on Advanced Visual Interfaces (AVI)* (pp. 231–234). Gallipoli, Italy: ACM Press.

Rowell, J. & Ungar, S. (2003a). A taxonomy for tactile symbols: Creating a usable database for tactile map designers. *Cartographic Journal, The*, 40(3), 273–276.

Rowell, J. & Ungar, S. (2003b). The world of touch: Results of an international survey of tactile maps and symbols. *Cartographic Journal, The*, 40(3), 259–263.

Salisbury, J. & Srinivasan, M. (1997). Phantom-based haptic interaction with virtual objects. *Computer Graphics and Applications, IEEE*, 17(5), 6–10.

Scaife, M. & Rogers, Y. (1996). External cognition: how do graphical representations work? *Int. J. Human-Computer Studies*, 45, 185–213. doi: 10.1006/ijhc.1996.0048.

Schmid, F. (2008). Knowledge-based wayfinding maps for small display cartography. *Journal of Location Based Services*, 2(1), 57–83.

Schmid, F. (2010). *Personal Wayfinding Assistance*. Unpublished doctoral thesis, Universität Bremen, Bremen. Retrieved from `http://nbn-resolving.de/urn:nbn:de:gbv:46-00101834-15`.

Schmid, F., Kuntzsch, C., Winter, S., Kazerani, A., & Preisig, B. (2010a). Situated local and global orientation in mobile you-are-here maps. In *MoblieHCI'10 Proceedings of the 12th international conference on Human computer interaction with mobile devices and services* (pp. 83–92). New York, NY, USA: ACM.

Schmid, F., Richter, K.-F., & Peters, D. (2010b). Route aware maps: Multigranular wayfinding assistance. *Spatial Cognition and Computation*, 10(2), 184–206.

Schmitz, B. & Ertl, T. (2012). Interactively displaying maps on a tactile graphics display. In C. Graf, N. A. Giudice, & F. Schmid (Eds.), *Workshop Proceedings Spatial Knowledge Acquisition with Limited Information Displays (SKALID 2012)*, volume 888 of *CEUR Workshop Proceedings* (pp. 7–12). Bad Seeon, Germany: CEUR Workshop Proceedings. `http://ceur-ws.org/Vol-888/SKALID2012_Schmitz.pdf`.

Scholtz, D. (1957). Die Grundsätze der Gestaltwahrnehmung in der Haptik. *Acta Psychologica*, 13(1), 299–333.

Seifert, I., Barkowsky, T., & Freksa, C. (2007). Region-based representation for assistance with spatio-temporal planning in unfamiliar environments. In G. Gärtner, W. Cartwright, & M. Peterson (Eds.), *Location Based Services and TeleCartography*, Lecture Notes in Geoinformation and Cartography. Heidelberg: Springer-Verlag.

Sherman, J. C. (1975). The challenge of maps for the visually handicapped. In *Auto-carto 2: Proceedings of the International Symposium on Computer-Assisted Cartography* (pp. 91–98). Reston, Virginia, USA: U.S. Bureau of the Census and American Congress on Surveying and Mapping.

Siegel, A. W. & White, S. H. (1975). The development of spatial representations of large-scale environments. In H. W. Reese (Ed.), *Advances in child development and behavior* (pp. 9–55). New York, NY, USA: Academic Press.

Siekierska, E., Labelle, R., Brunet, L., McCurdy, B., Pulsifer, P., Rieger, M. K., & O'Neil, L. (2003). Enhancing spatial learning and mobility training of visually impaired peoplea technical paper on the internet-based tactile and audio-tactile mapping. *The Canadian Geographer*, 47, 480–493.

Simonnet, M., Vieilledent, S., Guinard, J. Y., & Tisseau, J. (2007). Can haptic maps contribute to spatial knowledge of blind sailors? In A. Luciani & C. Cadoz (Eds.), *Proceedings of ENACTIVE/07* (pp. 259–262). Grenoble, France.

Spencer, C. & Travis, J. (1985). Learning a new area with and without the use of tactile maps: a comparative study. *British Journal of Visual Impairment*, 3(1), 5–7.

Stott, J., Rodgers, P., Martinez-Ovando, J. C., & Walker, S. G. (2011). Automatic metro map layout using multicriteria optimization. *Visualization and Computer Graphics, IEEE Transactions on*, 17(1), 101–114.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive Load Theory*. Springer.

TACMON Consortium (2008). Tacmon newsletter – first issue. Retrieved from `http://tacmon.eu/getel.php?f=/Public/Newsletter/TACMON_Newsletter_issue1.pdf`, August 24, 2012.

TACMON Consortium (2010). Tacmon newsletter – fith issue. Retrieved from `http://tacmon.eu/getel.php?f=/Public/Newsletter/TACMON_Newsletter_issue5.pdf`, August 24, 2012.

Tan, H. Z., Srinivasan, M. A., Eberman, B., & Cheng, B. (1994). Human factors for the design of force-reflecting haptic interfaces. *Dynamic Systems and Control*, 55(1), 353–359.

Taylor, H. A. (2005). Mapping the understanding of understanding maps. In *The Cambridge handbook of visuospatial thinking* (pp. 295–333). Cambridge University Press.

Taylor, H. A. & Tversky, B. (1992a). Descriptions and depictions of environments. *Memory and Cognition*, 20(5), 483–496.

Taylor, H. A. & Tversky, B. (1992b). Spatial mental models derived from survey and route descriptions. *Journal of memory and language(Print)*, 31(2), 261–292.

Taylor, H. A. & Tversky, B. (1996). Perspective in spatial descriptions. *Journal of Memory and Language*, 35(3), 371–391.

Théberge, P. & Taylor, D. F. (2005). Chapter 17 sound maps: Music and sound in cybercartography. In *Cybercartography – Theory and Practice*, volume Volume 4 (pp. 389–410). Academic Press.

Theobald, D. M. (2001). Topology revisited: representing spatial relations. *International Journal of Geographical Information Science*, 15(8), 689–705.

Thinus-Blanc, C. & Gaunet, F. (1997). Representation of space in blind persons: Vision as a spatial sense? *Psychological Bulletin January 1997*, 121(1), 20–42.

Thorndyke, P. W. & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, 14(4), 560–589.

Tinti, C., Adenzato, M., Tamietto, M., & Cornoldi, C. (2006). Visual experience is not necessary for efficient survey spatial cognition: evidence from blindness. *Quarterly journal of experimental psychology (2006)*, 59(7), 1306–1328. PMID: 16769626.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, 55, 189–208.

Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology*, 13(3), 407–433.

Ungar, S. (2000). Cognitive mapping without visual experience. In R. Kitchin & S. Freundschuh (Eds.), *Cognitive mapping: Past, present and future* (pp. 221–248). London: Routledge.

Ungar, S., Blades, M., & Spencer, C. (1993). The role of tactile maps in mobility training. *British Journal of Visual Impairment*, 11(2), 59–61.

Ungar, S., Blades, M., & Spencer, C. (1995). Visually impaired children's strategies for memorising a map. *British Journal of Visual Impairment*, 13(1), 27–32. doi: 10.1177/026461969501300107.

Ungar, S., Blades, M., & Spencer, C. (1996). The construction of cognitive maps by children with visual impairments. In J. Portugali (Ed.), *The Construction of Cognitive Maps*, volume 32 of *The GeoJournal Library* (pp. 247–273). Dordrecht: Kluwer Academic Publishers.

Ungar, S., Blades, M., & Spencer, C. (1997). Strategies for knowledge acquisition from cartographic maps by blind and visually impaired adults. *Cartographic Journal*, 34(2), 93–110.

Ungar, S., Blades, M., & Spencer, C. (2002). Tactile maps and a test of the conjoint retention hypothesis. In *Diagrammatic representation and reasoning* (pp. 141–154). Springer.

Ungar, S., Simpson, A., & Blades, M. (2004). Strategies for organising information while learning a map by blind and sighted people. In M. A. Heller & S. Ballasteros (Eds.), *Touch, blindness and neuroscience* (pp. 271–280). Madrid: Universidad Nacional de Educacion a Distancia.

Vecchi, T. (1998). Visuo-spatial imagery in congenitally totally blind people. *Memory*, 6(1), 91–102. PMID: 9640434.

Verdi, M. & Kulhavy, R. (2002). Learning with maps and texts: An overview. *Educational Psychology Review*, 14(1), 27–46.

ViewPlus Technologies, Inc. (2012). ViewPlus company story. Retrieved from `http://www.viewplus.com/about/story/`, August 24, 2012.

Völkel, T., Weber, G., & Baumann, U. (2008). Tactile graphics revised: The novel BrailleDis 9000 Pin-Matrix device with multitouch input. In *Computers Helping People with Special Needs*, volume 5105 of *Lecture Notes in Computer Science* (pp. 835–842). Berlin / Heidelberg: Springer.

Voženílek, V., Kozáková, M., Šťávová, Z., Ludíková, L., Røužičková, V., & Finková, D. (2009). 3D printing technology in tactile maps compiling. In *Proceedings of the XXIV International Cartographic Conference*.

Walsh, D. E. (1990). *Do It Yourself Vacuum Forming for the Hobbyist*. Lake Orion, MI, USA: Workshop Publishing. `http://www.build-stuff.com/001book_vacuum_forming.htm`.

Wang, J. & Schwering, A. (2009). The accuracy of sketched spatial relations: How cognitive errors influence sketch representation. In *Proceedings of the International Workshop Presenting Spatial Information: Granularity, Relevance, and Integration, held in conjunction with the Conference on Spatial Information Theory, COSIT* (pp. 40–56). Bremen and Melbourne: SFB/TR8 and University of Melbourne.

Ware, J. M., Taylor, G. E., Anand, S., & Thomas, N. (2006). Automated production of schematic maps for mobile applications. *Transactions in GIS (Special issue on Location Based Services and Mobile GIS)*, 10(1), 25–42.

Way, T. & Barner, K. (1996). Towards automatic generation of tactile graphics. In *Proceedings of the Rehabilitation Engineering and Assistive Technology Society of North America RESNA '96 Annual Conference*. Salt Lake City, Utah: RESNA Press.

WHO Media Centre (2012). Fact sheet no. 282 - visual impairment and blindness (june 2012). Retrieved from `http://www.who.int/mediacentre/factsheets/fs282/en/`, June 1, 2013.

Wiedel, J. W., Ed. (1983). *Proceedings of the First International Symposium on Maps and Graphics for the Visually Handicapped*. Washinghton, D.C.: Association of American Geographers.

Wiedel, J. W. & Groves, P. A. (1969). *Tactual Mapping: Design, Reproduction, Reading and Interpretation. Final Report.* Technical Report RD-2557-S 1969, Department of Geography, University of Maryland, Washington, DC. `http://eric.ed.gov/PDFS/ED043986.pdf`.

Wiener, J. M., Büchner, S., & Hölscher, C. (2009). Taxonomy of human wayfinding tasks: A Knowledge-Based approach. *Spatial Cognition & Computation*, 9(2), 152–165. doi: 10.1080/13875860902906496.

Wiener, J. M. & Mallot, H. A. (2003). 'Fine-to-Coarse' route planning and navigation in regionalized environments. *Spatial Cognition & Computation*, 3(4), 331–358.

Winn, W. (1991). Learning from maps and diagrams. *Educational Psychology Review*, 3(3), 211–247.

Wolff, A. (2007). Drawing subway maps: A survey. *Informatik - Forschung und Entwicklung*, 22(1), 23–44.

Wood, D. (1978). Introducing the cartography of reality. In *Humanistic Geography* (pp. 207–219). Chicago, IL, USA: Maaroufa Press.

Xiao, D. & Liu, Y. (2007). Study of cultural impacts on location judgments in eastern china. *Lecture Notes in Computer Science*, 4736, 20.

Zeng, L. & Weber, G. (2010). Audio-haptic browser for a geographical information system. In K. Miesenberger, J. Klaus, W. Zagler, & A. Karshmer (Eds.), *Proc. of International Conference on Computers Helping People with Special Needs (ICCHP)*, volume 6180 (pp. 466–473). Berlin, Heidelberg: Springer Berlin Heidelberg.

Zeng, L. & Weber, G. (2011). Accessible maps for the visually impaired. In G. Weber, H. Petrie, & J. Darzentas (Eds.), *Proceedings of the Workshop on Accessible Design in the Digital World 2011*, volume 792 of *CEUR Workshop Proceedings* (pp. 54–60). Lisbon, Portugal: CEUR Workshop Proceedings.

Zeng, L. & Weber, G. (2012). Building augmented you-are-here maps through collaborative annotations for the visually impaired. In C. Graf, N. A. Giudice, & F. Schmid (Eds.), *Workshop Proceedings Spatial Knowledge Acquisition with Limited Information Displays (SKALID 2012)*, volume 888 of *CEUR Workshop Proceedings* (pp. 7–12). Bad Seeon, Germany: CEUR Workshop Proceedings.

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science: A Multidisciplinary Journal*, 21(2), 179–217.

Zipf, A. & Richter, K.-F. (2002). Using focus maps to ease map reading: developing smart applications for mobile devices. *Künstliche Intelligenz*, 10(4), 35–37.

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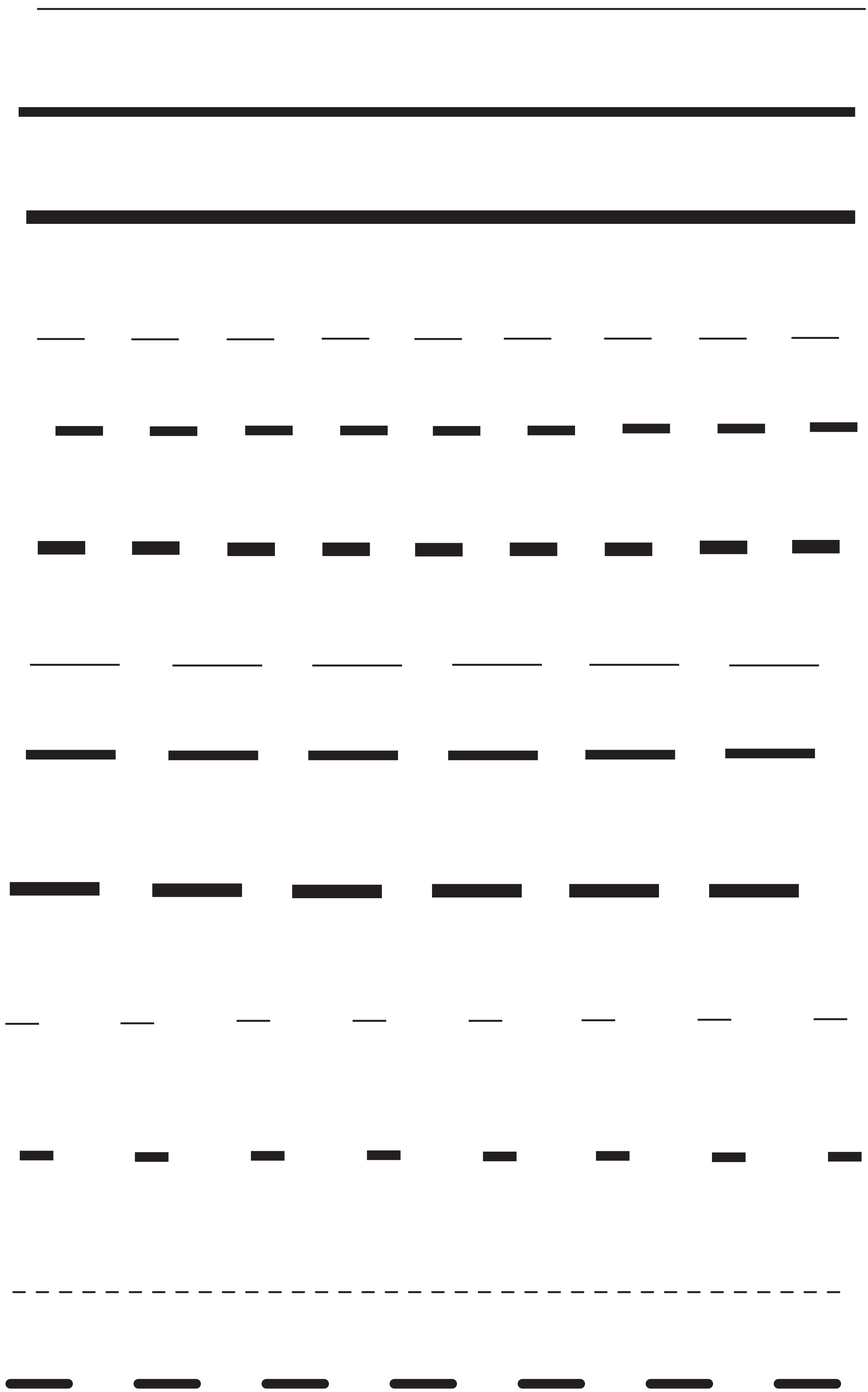
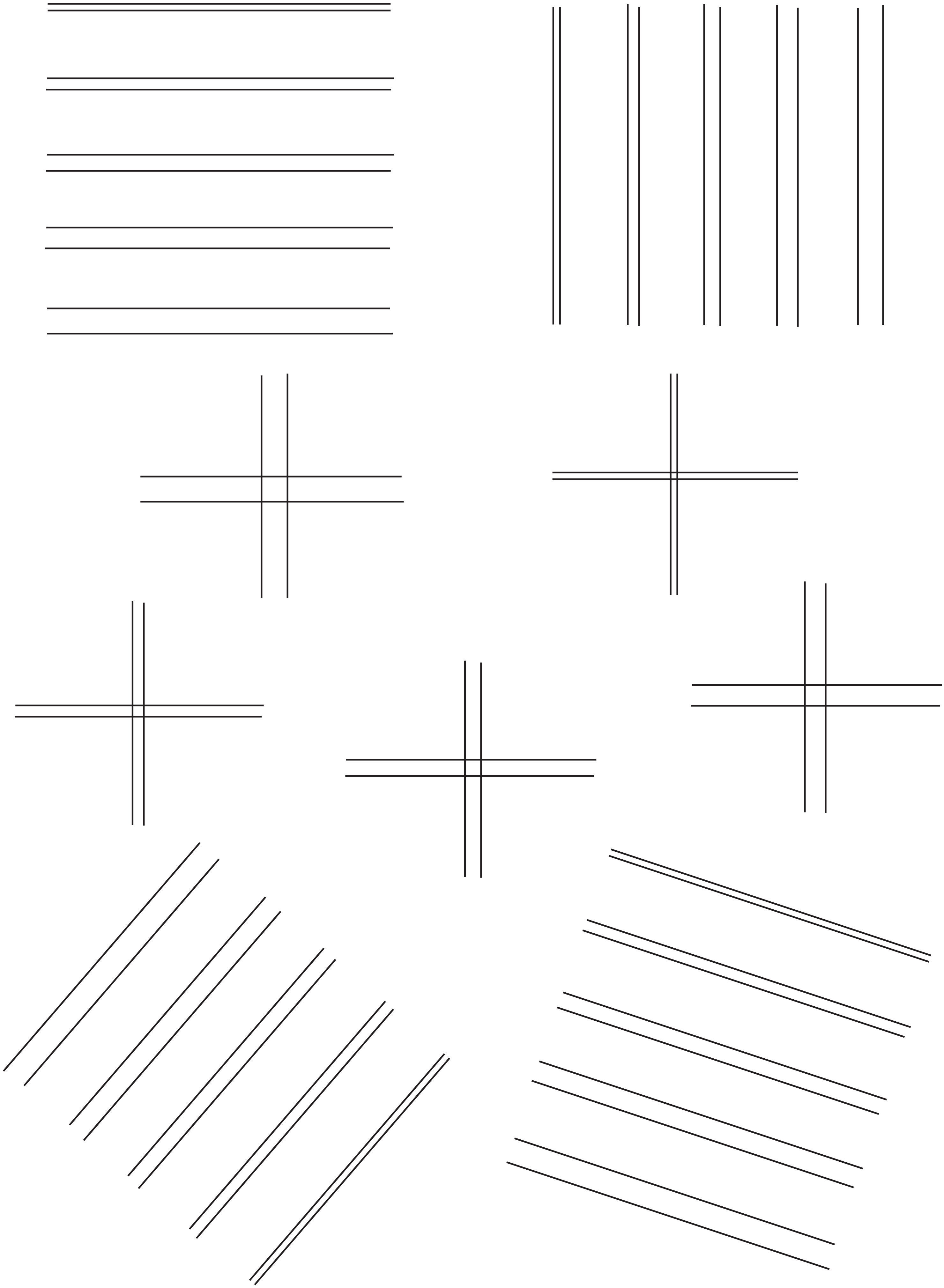
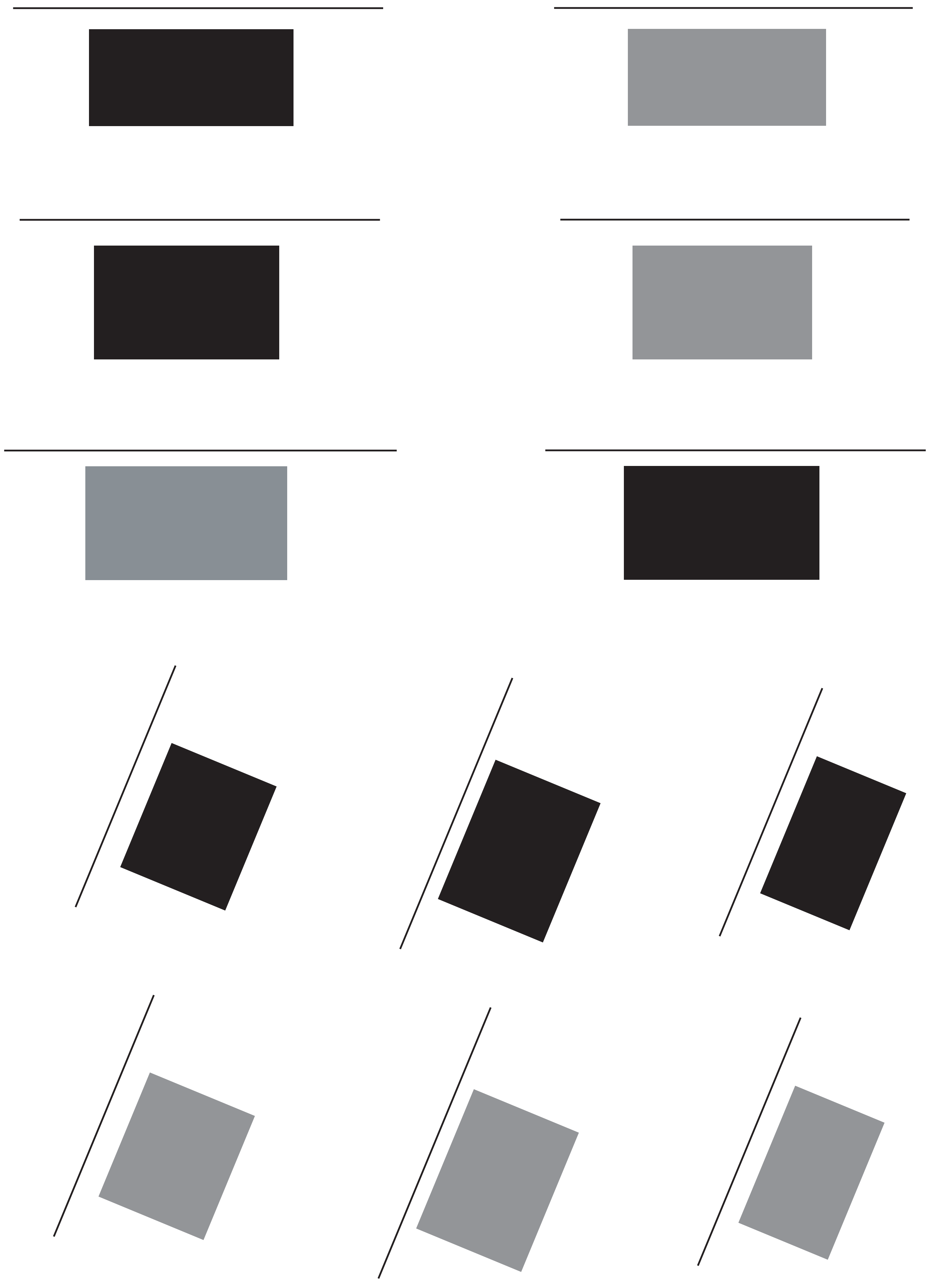
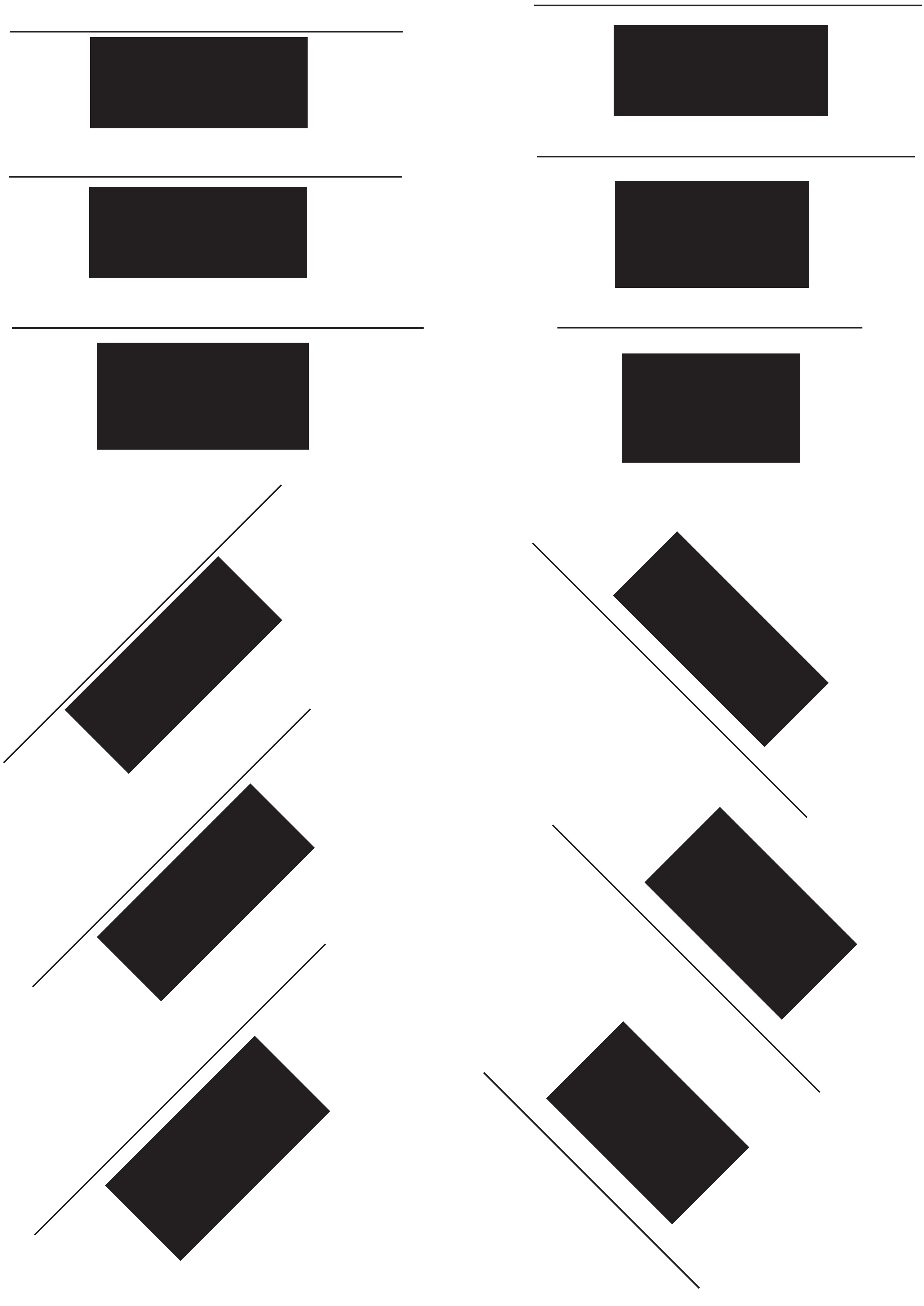
Appendix 1 – Study 1: Instructions, Questionnaires and Results

Note: The materials are mostly in German.









Gruppeninterview Mittwoch, 28.September 2011

Thema 1: Räumliche Orientierung in unbekannter urbaner Umgebung
Beispielszenario: Erster Besuch einer Kleinstadt mit etwas Zeit zur Erkundung derselben

1.1 Wie bereitest du dich vor, wenn du das erste Mal eine unbekannte Umgebung erkunden willst?

1.2 Welche Objekte und Konzepte pägst du dir bei der Vorbereitung besonders ein?

1.3 Welche Strategien verwendest du, um dir eine Vorstellung von der unbekannte Umgebung zu machen?

1.4 Wann sind absolute, globale Himmelsrichtungen, wann relative, egozentrische Richtungskonzepte relevant?

1.5 Wie und woran orientierst du dich bei der Begehung einer unbekannte Umgebung?

1.6 Es gibt unterschiedliche Arten von Landmarken: punktförmige (etwa eine Kreuzung, ein Kiosk), linienförmige (etwa ein Fluss, eine Straßenbahnlinie) und flächige (ein Park, ein Stadion, eine Grünfläche). Welche sind wann wichtig bzw. unter welchen Umständen werden sie relevant? Sind sie alle gleich leicht und sicher zu identifizieren?

1.7 An Kreuzungen kommen z.T. mehr als drei Straßen in unterschiedlichen Winkeln aufeinander. Wie merkst/erklärst du dir das Aussehen einer Kreuzung?

Thema: Anforderung an taktile Überblickskarten

Beispielszenario: Eine taktile Überblickskarte der Kleinstadt soll hergestellt werden

2.1 Welche Hinweise & Informationen sollten in der Übersichtskarte repräsentiert sein?

2.2 Nicht immer werden alle Informationen auf der Karte abbildbar sein. Welche Informationen können zuerst weggelassen werden? Welche dürfen auf keinen Fall weggelassen werden?

2.3 Die metrische Genauigkeit von Überblickskarten: wann ist sie wichtig und wann nicht?

2.4 Abbildung aller abgehenden Straßen von z.B. einer Hauptstraße für die korrekte Orientierung, wenn die Karte nicht metrisch ist: wann ist sie wichtig und wann nicht?

2.5 Abbildung von Kurven und Biegungen zwischen zwei Kreuzungen: wann ist sie wichtig und wann nicht?

2.6 Abbildung von Landmarken an Straßen: wann ist sie wichtig und wann nicht?

2.7 Abbildung von Landmarken an Kreuzungen: wann ist sie wichtig und wann nicht?

Gesprächspartner A

1. Notwendige Informationen in taktiler Orientierungskarte

- Himmelsrichtungen
- markante Orientierungspunkte (zentrale Gebäude, Sehenswürdigkeiten, Haltestellen, ...)
- relevante Kreuzungen und abgehende Straßen bzw. Plätze
- angrenzende Freiflächen (z. B. Parkanlagen, Flüsse u. ä.)
- ca. Entfernungsangaben

2. Ranking der Informationen (aufsteigend)

- Freiflächen (z. B. Parkanlagen, Flüsse u. ä.)
- ca. Entfernungsangaben
- Himmelsrichtungen
- markante Orientierungspunkte (zentrale Gebäude, Sehenswürdigkeiten, Haltestellen, ...)
- relevante Kreuzungen und abgehende Straßen bzw. Plätze

Gesprächspartner B

1. Notwendige Informationen in taktiler Orientierungskarte

- Straßen / Wege
- Gewässer
- wichtige Objekte wie Bahnhof, Kirche, Rathaus und ähnliches,
- Häuser (Art der Bebauung)
- Parks

2. Ranking der Informationen (aufsteigend)

- Häuser
- Rathaus
- Parks
- Kirche
- Bahnhof
- Gewässer
- Straßen

Gesprächspartner C

1. Notwendige Informationen in taktiler Orientierungskarte

- Struktur landschaftlich: ob da berge sind oder flaches Gebiet
- Großstadt oder Kleinstadt
- um von A nach B zu kommen: Straßen, alle (Nebenstraßen untergeordnet zur besseren Unterscheidung), damit gezählt werden kann
- Bäume nicht unbedingt, Wasser für Orientierung im Ort wichtig, weil da nicht rüber kann, Häuser nicht unbedingt, weil schnell veränderbar
- permamente Orientierungspunkte: Brunnen, Denkmäler (nach denen man anderen auch fragen kann), Brücken
- in unbekannte Gegenden werden keine Schritte gezählt, nur in oft gegangen
- Helmut Fuchs aus Harburg, Senior wandert durch Wälder, oft auch alleine und unter anderem unbekannte Wege, auf denen er sich auch mal verläuft
- wichtig ist das Natürliche, nicht flüchtige Orientierungspunkte wie Kioske bestimmte Läden, Häuser, da sich deren Natur häufig ändert und so Wiedererkennungswert verloren geht
- "zu viele Sachen sind schlecht", "je weniger man hat, je besser"

2. Ranking der Informationen (absteigend)

- Straßen/Fußwege
- natürliche Gegebenheiten wie Wasser/Seen/Fluß
- Denkmäler/feste, markante Orientierungspunkte
- (Signal-)Ampeln/Überwege

Group Interview 1 - Summary of Results

Tactile realisation of cartographic survey view representations have been in the focus of the map-making profession for some time. The existing tactile maps produced by professional tactile-map makers are highly sophisticated products. For example, the tactile atlas of Germany produced by the *Deutsche Zentralbibilothek für Blinde* in Leipzig displays Germany as one map plus 16 single maps, one for each state. But they cannot suite the map reader's demand in every situation as the focus group interviews presented here shows. For example, an interviewee commented about those maps as not being clear enough. He wanted to know in what way some states are arranged relatively to each other from a survey perspective. He reported that he could not get to know from the tactile atlas which state has boarders with which other states, even if he had come across tactile maps before and believed to know how to read and interpret tactile maps.

In times of GPS driven, mobile wayfinding systems that are especially customized for blind people there seem to be no need for bulky, tactile maps anymore. In contrast to the expectations of most sighted people, some visually impaired and blind people feel they have advantages from using tactile orientation maps. This is what an interview with a group of three visually impaired but mobile pedestrians brought up. Using maps could make "free and self-dependent", as one interviewee put it. One type of usage is to gain an overview of how large scale environmental configurations are structured, for example how the suburbs of a city are arranged around the city centre and how the street network containing major landmarks is structured.

Concerning spatial navigation the interviewees shared a common understanding that there is a substantial difference between preparing for locomotion in some geographic environment (i.e. “preparation phase”) and actually locomoting that geographic environment (i.e. “execution phase”). They considered that difference as being grounded in two substantially different modes of geographic knowledge acquisition: direct learning in the geographic environment (i.e. “environmental learning”) and indirect learning from models of the geographic environment (“mediated learning”). Environmental learning takes places whenever a navigator roams a geographical environment and tries to track his path mentally. Mediated learning typically happens during preparation for a visit to an environment, for example with textual descriptions or maps. When the environment is visited again or for the first time respectively, the mental model established is matched with the physical reality. The mental model is then revised, updated and refined.

The interviewees characterised their orientation in the preparation phase as being allocentric and focused on distal, abstract information. The information they need is abstract and rather coarse, for example, foregrounding the most important landmarks and their locations. They reported that their mental model of the geographic environment was often structured based on allocentric directions (what landmarks is in the north/south/west/east) in the preparation phase. Contrasting this is the information need in the execution phase. When locomoting the environment, orientation was described as being egocentric and focused on local information. The information they need is detailed and rather fine-grained, for example, foregrounding some local details such as the position of traffic lights at an intersection. The interviewees supported the proposal that their mental model is most often structured based on egocentric directions in the locomotion phase.

When concerning what to display in a tactile map the interviewees pointed out that it is important how well a blind pedestrian already knows the environment in question. If one assumes that someone is completely new to an environment then it might not be a good idea to fill the map with too much detail. Then the existence of tactile walking indicators and the characteristics of the ground should possible not be displayed as they could overwhelm the map reader. It would just be too much. This could be added for later versions of the same map used by blind pedestrians that have already experienced that environment in reality. Such maps could be tools for fostering the learning process by reminding about local details. Such details help to recognise a formerly travelled place during repeated locomotion but the interviewees regarded it less important for first time travels. In the preparation phase information about ground properties such as inclination or material, and information about local support means such as groove plates and attention fields do not provide substantial help to blind pedestrians who want to build up an abstract, rather coarse mental model of the environment.

When discussing the types of spatial concepts that should be represented in a tactile orientation map as support in the preparation phase, several were named (see the following list). Aside from some well excepted ones, some interesting opinions turned up in the interviews, some shared across participants, some only named once.

1) Cardinal directions were named first. Using cardinal directions in learning the position of some spatial entity (for example, a landmark, the start location, the end location) in relation to the displayed area gives the opportunity to roughly know the layout of the environment when being situated in the environment. Knowing the coarse relations of the spatial entities is could be the basis of the spatial representation.
2) The spatial concept of “nearness” is often used to help describing some spatial position of an object related to some other object.
3) There was no common ground to what extend “nearness” can be understood as direction dependent or direction independent, as property of the representation space (i.e. the map) or as property of the represented space (i.e. the geographic environment), for example as a certain distance between map entities respectively geographic entities. Factors such as density of the geographic entities were not mentioned.
4) Common ground was on the ranking of landmark types concerning their importance in a tactile orientation map: point-like landmarks are most important, line-like landmarks second and area-like landmarks least important. The ranking of landmark types seem to reflect the distinctiveness with that each landmark type can support navigation in space. The interviewees regarded point-like landmarks very distinctive concerning its position in space. For example, the Barcaccia fountain is unique among the more than 2500 fountains in Rom and marks a very distinct spot at the lower end of the Spanish Steps. The Berlin Wall in contrast was a line-like landmark that stretched over more than 100km between the former West-Berlin and East Germany. The representation of the city of Berlin on a map could be considered an area-like landmark.
5) Setting a constant scale of a tactile map that allows estimating real-world

distances was considered less important than being exact in topology. The interviewees univocally reported that self-location in the environment by monitoring the passed streets during locomotion is very common and monitoring the distance travelled by counted his steps is rather uncommon. The latter is only used in environments visited regularly to make frequent re-orientation obsolete and thus increase travelling speed.

6) For controlling the locomotion in some environment, the inner and outer acoustic guiding lines of tracks and the unique acoustic characteristics of obstacles were considered important. That is not a surprising finding. Often the outer acoustic guiding line is some car travel because sideways for pedestrian often stretch along streets where cars move along. From mobility training or from their own experience visually-impaired pedestrians know that it is best to orientate towards the inner acoustic guiding line, for example walls of houses, fences etc. First, it is save to walk in some distance to cars. Features such as walls and fences that can be sense with the cane easily is welcomed in such situation. Second, the inner acoustic guiding line is better suited for self-localisation than an unsteady flow of cars that bears no uniqueness. In contrast to an ever changing noise the inner acoustic guiding line has certain sound characteristics at certain locations. These characteristics can be recognised during locomotion and thus can function as landmarks that support self-localisation. The interviewees reported that for their orientation in an unknown environment, it would be helpful for them to know what acoustic characteristics of the inner guiding line to expect along a potential walkway. Especially changes of echo are important as they allow estimating how far someone has already progressed. To benefit in this way the traveller must have learnt the sound characteristics to be expected beforehand. The reason for changes in the echo could be manifold. For example, it could be a drive-way, another street intersecting, or simply an interruption in the formerly close walls of houses because a building has been but further away from the street than all the others. This information is especially important to identify the parts along streets between intersections..

7) The interviewees reported that being at intersections the sound characteristics of acoustic guiding lines are less important because traffic is usually louder. The subtle echoes from static environmental features such as walls vanish in the dynamic noise made by the moving cars and bulks of pedestrians. The attention switches from tracking the echoes to directly accessible guides, for example aids perceivable like attention fields and signalling traffic lights. The interviewees argued that these aids should not be displayed in a map as they can be detected during locomotion when approaching an intersection. Nevertheless knowing about their existence was judged to be an advantage for tour planning. But constrained by limited space in the map they were considered as being of minor importance. Aside from those detectable aids, it is important to know about undetectable aids. For example, at a pedestrian crossing it is usually not clear to the blind pedestrians whether there is an island in the middle of the street where pedestrians could stop to be save from traffic. The existence of such island cannot be detected in other ways. It should be marked be marked in orientation maps because such crossing are more likely to be chosen if a route has to be selected.

8) During the interviews the participants univocally express their opinion that long streets that bend significantly (albeit there was no common ground about what qualifies for a ‘significant bend’) should not be displayed as straight objects, because the map would display an image of the reality that is hard to match with reality when

being in the environment. This would be especially true if the direction in which an intersection is approached differs significantly between the map and the reality.

From a survey among the blind and visually impaired pedestrians the following information resulted as being helpful in tactile orientation maps for giving an overview of some unknown environment:
1. Distinct, persistent locations that could be asked for, for example important or historical buildings, monuments, churches, fountains, bridges, sightseeing spots, stations, stops for public transport
2. Squares, major roads and side streets, pedestrian pathways and intersections
3. Open areas that can be sensed by sound or by olfaction, for example parks or soccer fields, and water bodies such as streams or lakes
4. Labelling approximate distances if the map is not metric or scale changes
5. Cardinal directions to get a feeling of the positions of landmarks
6. Acoustic guiding line characteristics to estimate the sound characteristics during locomotion

Aside from the information in the map information of the general context should be given, for example, whether the map shows a rather flat or rather hilly area, whether the depicted urban environment is a small town or a big city. When asked for a ranking of the named concepts the participants univocally voted for streets and intersections as being the most important information. Valued second most important were natural, static features of the environment such as parks and water bodies. Artificial landmarks such as salient, static buildings and monuments were ranked third. Type of buildings, distance and cardinal points were ranked to be of lower importance. Features that mainly support safe locomotion in the terrain were regarded as to be of minor importance for orientation maps.

Frequency of naming (terms in German):

5 Freiflächen (z. B. Parkanlagen, Flüsse u. ä.)
4 ca. Entfernungsangaben
3 Himmelsrichtungen
2 markante Orientierungspunkte (zentrale Gebäude, Sehenswürdigkeiten, Haltestellen, ...)
1 relevante Kreuzungen und abgehende Straßen bzw. Plätze

7 Häuser
6 Rathaus
5 Parks
4 Kirche
3 Bahnhof
2 Gewässer
1 Straßen

1 Straßen/Fußwege
2 natürliche Gegebenheiten wie Wasser/Seen/Fluß
3 Denkmäler/feste, markante Orientierungspunkte
4 (Signal-)Ampeln/Überwege

Gruppendiskussion 2 - Zusammenfassung
(Zahlen in Klammern sind Zeitstempel in Mitschnitt)

- alle Gesprächspartnerinnen sind mobil, eine ist stark sehbehindert, die anderen blind (4:00); haben noch nie mit taktilen Karten zu tun gehabt (54:00), nur eine kann sicher Braille, eine andere will und wird es nicht mehr lernen
- Strategien bei der Vorbereitung zur Begehung unbekannter Gelände: welche Haltestelle und welche U-Bahn fährt dorthin ? „am besten man schreibt sich das auf" (5:15)
- Strategien bei Begehung unbekannter Gelände: Durchfragen (5:30, 15:30); Problem: manchmal niemand da, Leute kennen sich nicht aus
- Navigationsgeräte für Fußgänger, speziell Blinde: „die funktionieren ja nun nicht überall", „man muss lernen, damit umzugehen", „nicht ganz billig die Dinger", „man muss sich überlegen, ob sich das lohnt" (ab 6:25)
- Interaktion zwischen Blinden und sehenden Mitmenschen auf der Straße: „das Menschliche ist wichtig" nicht nur von Technik abhängig sein ? viele Blinde sind ältere Leute und haben nicht so viel Vertrauen in Technik, sie benutzen eher Langstock und wollen die Interaktion mit Mitmenschen
- Anforderungen an TOMs: Gaststätten mit Bedienung, Museum, Ärztehäuser, Geschäftstypen (was wird dort verkauft?), Cafés mit Bedienung, nicht zu große Karten, Gehwege
- „ich hab' mich mal [im neu gestalteten Einkaufszentrum] verlaufen, seit dem gehe ich da nicht mehr hinein" (32:10)
- Nutzungswillen/-tendenz für TOM (33:30): „wäre 'ne Hilfe" für Wegbestimmung, Straßen(namen) und was rechts und links der Straße ist, Hindernisse, alle Querstraßen damit man sie zählen kann, Kreisel, (Blinden-)Ampel, Insel, Lage des Gehwegs, völlig abgesenkte Bordsteine, Bushaltestellen, Bahnhof, „würde mich informieren, so ist was und das habe ich dann ja im Kopf gespeichert" (39:00), Karte als Gedächtnisstütze
- Symbole sollten Ikonen sein, d.h. Ähnlichkeiten mit dem repräsentierten Objekt aufweisen, etwa Kirche ? spitze Symbol mit Spitze oben „spitzer Punkt" (41:50)
- Problematik: Konventionen der Ausgestaltung müssen als unabhängig von Bedeutung verstanden werden, vor allem wenn parallel ikonographische Symbole verwendet werden und es Verwechslungsgefahr gibt (ab 47:00)
- Maßstab interessant für die Abschätzung von Gehzeiten (50:20)
- Erkennbarkeit von Unterschieden zwischen Karten (54:00): unterschiedliche Linienbreiten fallen auf, Symbole auch; einige sind subjektiv besser zu erkennen als andere, aber VP können nicht sagen, warum ? unterschiedlich gestaltete Linien fallen nicht auf
- Bereitschaft, diese Karten zu nutzen: „halbe Stunde", „kommt drauf an, wie schnell ich das erfasse", „eineinhalb Stunde ist zu lang", „benutze ich solche Karte öfter, dann brauche ich auch weniger Zeit", „wenn ich weiß, es hilft mir, dann würde ich das auch immer wieder nehmen", auch mehrere Karten, um mehr Informationen darzustellen (verschiedene

Aspekte desselben Weltausschnittes)

- Einsatzszenarien für computergenerierte, aktuelle TOM: neue Läden, verlegte Bushaltestellen (z.B. Barmbek) „ist 'ne gute Sache mit den Karten " (1:05:30)
- persönliche Einsatzmöglichkeiten („wo könnten Ihnen diese Karten helfen"): „wenn sich was neues geben würde, dann würde ich mir solche Karten besorgen, um mich dort zu orientieren", „neue Hafencity", „neue U4 – wie die so fährt, wie die Stationen heißen", „Barmbeker Bahnhof, weil sich die Bushaltestellen geändert haben", „große Bahnhöfe, Jungfernstieg, Hauptbahnhof", „wo das Reisezentrum ist"
- wie wichtig ist der Aspekt der schnellen Produktion (1:14:45)? „rechtzeitig besorgen – würde sie mir als Orientierung angucken und dann mitnehmen, das wäre für mich eine Hilfestellung"

Das Wichtigste:

- TOM als nützliche Mittel für die Begehungsvorbereitung, aber auch bei der Begehung selbst, besonders wegen der schnellen Verfügbarkeit und der Repräsentation aktueller räumlicher Gegebenheiten (etwa nach Umbau o.ä.)
- Mehraufwand beim Lernen würde in Kauf genommen werden, denn Lerneffekte werden erwartet, dazu müssten allerdings gleichbleibende Konventionen eingehalten werden
- TOMs werden vor allem als nützlich erachtet für das Informieren über ein bestimmten Weg und das Gebiet in dem er eingebettet ist ? Aufgabenbezogene Verwendung, nicht unbedingt nur so um einen Überblick zu bekommen
- TOM können unabhängig von GPS Ausfällen und nicht vorhandenen Passanten machen, auch könnten sie das unangenehme, wiederkehrende Fragen ersparen, welche Läden denn nun wo seien
- Verschiedene Aspekte eines Weltausschnittes können über verschiedene Karten abgebildet werden und Anwenden wären auch bereit, diese nacheinander zu lesen

Fazit:

- Die potentiellen Anwender schätzen ein, dass TOMs eine Bereicherung für die Mobilität von Blinden darstellen würden, weil mit ihnen die Vorbereitung einer Begehung möglich wird und sie eine Vorstellung eines nicht-bekannten oder nicht ausreichend bekannten Gebietes aufbauen können.
- Als Vorteil gegenüber traditionellen taktilen Karten wird von den potentiellen Anwendern eingeschätzt, dass TOMs vor allem kurzfristig gefertigt werden können. So können sie für eine anstehende Begehung angepasst werden und bilden dafür die aktuellen räumlichen Gegebenheiten ab.
- Anwender schätzen ihre Bereitschaft der Exploration als hoch ein, solange die Karten ihnen einen Nutzen bringen – die Exploration darf allerdings auch nicht zu lange dauern
- begrenzte Menge an Informationen pro Karte notwendig

Vorstudie zu mit dem EMPRINT geprägten taktilen Karten

1. Leitfragen

1. Wie gut sind Linien zu unterscheiden, die paarweise unterschiedlich dick sind (1 Taxel und 2 Taxel)?
2. Wie gut sind Konturen oder Linien diskriminierbar, falls sie unterschiedlich nahe (Zwischenraum 1 Taxel, 2 Taxel, 4 Taxel) beieinander liegen?
3. Wie weit dürfen die Teilstücke einer unterbrochenen Linie auseinanderliegen und wie lang müssen die Linienstücke dann sein, damit noch der Eindruck einer zusammenhängenden Linie entsteht?
4. Wie viel Zeit vergeht, bis VP das Gefühl haben, sie könnten die taktilen Reize ausreichend unterscheiden?
5. Inwiefern stimmt diese subjektive Einschätzung mit objektiven Kriterien überein?
6. Wie explorieren die VP eine Karte, in der keine Hinweise auf den YAH-Punkt gegeben sind?
7. Wie oft ist ein räumliches Suchen (etwa flächig abtasten von oben nach unten und von links nach rechts) zu beobachten, wie oft ein linienorientiertes (entlang spürbarer Linien bzw. Konturen)?
8. Bei welcher Suchstrategie wird eine größere Abdeckung der Karte erreicht
9. Wie sollte das YAH Symbol zum Weg ausgerichtet sein, damit Probanden a) es als Kontext zum Weg finden und b) ihre eigene Ausrichtung zur Karte richtig interpretieren?
10. Welche Komplexität dürfen die Karten durchschnittlich haben, um noch klar diskriminierbar, aber vor allem interpretierbar und memorierbar zu bleiben?
11. Wie gut können die VP einzelne Objekte bei steigender Komplexität eines Plans diskriminieren und benennen?
12. Welche Unterschiede ergeben sich zwischen einem Abruf über free-recall und recognition um Zusammenhänge, speziell Überblickswissen zu testen?
13. Wie detailliert ist das abrufbare Überblickswissen?
14. Verbessert sich die Genauigkeit, wenn beim Lesen der Karte explizit auf die Wichtigkeit der Zusammenhänge hingewiesen werden?
15. Was ist ein akzeptabler objektiver Lernerfolg in der Trainingsphase?
16. Welches Maß an Wahrnehmungsdifferenzierung muss erreicht werden?
17. Wenn der Lernerfolg in der Hauptstudie nicht erreicht wird, wie lange soll nachgelernt werden?
18. Ab welchem Lernniveau (inklusive Nachlernen) schließen wir VP von der Studie aus?
19. Soll der VL Linefollowing als effiziente Strategie (Chan 2007) zur Kartenexloration empfehlen und wenn ja, wann: schon im Training oder erst beim Experiment? Oder gar nicht, weil viele Sehende es anscheinend von sich aus tun (siehe Datenmaterial der Arbeiten aus Heidelberg: Maucher 1999, Maucher et al. 2000, Rieger 2002)?
20. Wie schwierig ist es für die Probanden, von zwei Randmarken am Kartenrand, die die Lage des YAH Symbols angeben, ausgehend das YAH Symbol in der Karte zu finden?
21. Treten bei der kantenparallelen freien Führung der Hände größere koordinative Schwierigkeiten auf, so dass der Bereich mit dem YAH Symbol großräumig verfehlt wird?
22. Wie wird die Exploration von den Randmarken in die Karte vollzogen: seriell einhändig oder parallel beidhändig?

23. Erkennen die VP in den 4 Versuchsbedingungen, dass die Karte immer ein und dieselbe ist, nur unterschiedlich gedreht?
24. Welches Vorgehen zur Außerkraftsetzen der Visus wird von den VP bevorzugt: Augenbinde oder Vorhang?

2. Ergebnisse

Die in der Vorstudie gefundenen Antworten zu den Forschungsfragen sind in Anhang 1 dargestellt. Im folgenden sind die wichtigsten zusammengefasst.

Versuchsdurchführung

Zur Sichteinschränkung wird der Vorhang besser als die Augenbinde empfunden, da Möglichkeit des Kontakts zum Versuchsleiter und die freiere Bewegungsmöglichkeit besteht. Dies erkauft man sich mit irritierenden Berührungen des Vorhangs auf den Oberarmen, da die Karten unmittelbar hinter dem Vorhang liegen und er daher so tief hängen muss, dass er über dem Unterarmen liegt. Die Augenbinde schließt anscheinend nicht genug und verrutscht, so dass die Probanden hätten durchschauen können. Dagegen mussten sie zusätzlich die Augen schließen, diese Maßnahme ist allerdings nicht kontrollierbar und es besteht die Gefahr des Lichteinflusses. Der Vorhang ist demnach besser geeignet, die Probanden vom Blick auf die Karte zu hindern. Um die Irritationen auf den Unterarmen einzuschränken, sollten die Probanden angewiesen werden, langärmelige Oberteile zu tragen und der Stoff des Vorhangs soll möglichst leicht und weich sein (dabei aber immer noch undurchsichtig).
Von einer Versuchsdurchführung in einem kalten Raum ist abzuraten, bei den meisten Personen leiden die Finger dann unter Blutarmut und sind daher nicht so empfindsam. Kalte Tischoberflächen tragen ihren Teil dazu bei, den Probanden das Tasten zu erschweren.

Abstände zwischen Objekten

Zwei Objekte mit einem Abstand von 1mm in der Vorlage können in geprägter Form nicht mehr unterschieden werden. Sie werden als ein Objekt wahrgenommen.

Der Abstand zwischen zwei Linien in der grafischen Vorlage sollte mindestens 3 Millimeter, besser 4 Millimeter betragen. In der geprägten Form entspricht dies ca. 2 Taxel. Dies gilt auch für Abstände zwischen Linie und Konturen, wenn sie horizontal bzw. vertikal liegen.

Der Abstand zwischen zwei Konturen sollte mindestens 4 Millimeter, besser 5 Millimeter, in der grafischen Vorlage betragen. In der geprägten Form entspricht dies ca. 3 Taxel. Dies gilt auch für Abstände zwischen geraden Linien und geraden Konturen, wenn sie schräg liegen oder unterschiedliche Oberflächenprägung aufweisen.

Der Abstand zwischen geraden und runden Konturen sollte mindestens 3 Millimeter, besser 4 Millimeter, in der grafischen Vorlage betragen. In der geprägten Form entspricht dies ca. 2 Taxel. Dies gilt auch für Abstände zwischen geraden Linien und runden Konturen bzw. zwischen runden Linien und geraden Konturen.

Ab einem Abstand von 6 Millimeter (umgesetzt in ca. 4 Taxel Zwischenraum) werden Objekte als nicht mehr zusammengehörig aufgefasst bzw. „übersehen“, weil die Fingerkuppen sie nicht mehr zwangsläufig berühren, z.B. wenn eine Linie nicht mit der Mitte der Fingerkuppe, sondern leicht versetzt mit dem Außenrand abgefahren wird.

Linien

Horizontale und vertikale Linien (d.h. solche die im Raster des Prägedruckers liegen) mit einer Breite von 1 bis 3 Punkt werden in taktile Linien von einem Taxel Breite umgesetzt. Linien von 4 bis 6 Punkt werden zu zwei Taxel breiten taktilen Linien und ab 7 Punkt zu drei

Taxel und breiteren Linien. Problematisch ist, dass in der Vorlage gleich gestaltete Linien (z.B. mit einer durchgängigen Breite) nicht zwingend gleich auf das Papier geprägt werden. So ist es vorgekommen, dass eine 6pt Linie einmal mit 2 Taxel ein anderes Mal (bei der gleichen Ausrichtung der Linie) mit schon 3 Taxel nebeneinander realisiert wird. Da nicht erkennbar ist, wann eine Realisierung mit der einen oder der anderen Breite erfolgt, ist dieses Verhalten als nicht-deterministisch einzustufen.

Schräge Linien/Diagonalen müssen beim Prägen ähnlich dem Dithering in der Grafik aus einer Abfolge von einzelnen neben- und übereinander liegenden Taxel zusammengesetzt werden. Je nach Winkel der Diagonalen zum Horizont werden die Taxel mehr oder minder versetzt zur darüber und darunter liegenden Reihe geprägt. Dabei wird pro Reihe nicht nur ein Taxel gesetzt, sondern meist mehrere. Je kleiner der Winkel zum Horizont („flach“: unter 45°) desto mehr Taxel werden in einer Reihe gesetzt und umgekehrt: je größer der Winkel („steil“: über 45°) zum Horizont, desto weniger Taxel werden pro Reihe gesetzt. Linien von 1 und 2 Punkt Breite werden bei 45° Winkel der Linie zum Horizont mit 1-2 Taxel pro Spalte & Zeile geprägt. Gleiche Linien mit 3 und 4 Punkt Breite werden mit 2-3 Taxel geprägt. Linien mit 5-7 Punkt Breite werden mit 4-5 Taxel geprägt.

Zwei Linien in mittleren Abstand (3mm), die in flachem Winkeln geprägt waren, wurden nicht so gut erkannt wie zwei Linien in mittleren Abstand aber steilen Winkel. Eine gute Separation wurde von den Probanden bei flachen Winkeln erst bei einem Abstand von 4mm erreicht. Die hinreichend gute Wahrnehmung von unterschiedlichen parallelen Linien hängt also auch davon ab, in welchem Winkel zum Horizont diese verlaufen.

Dünne, gerade Linien (ein Taxel Breite) werden genauso gut wahrgenommen wie dicke Linien (drei Taxel Breite). Diese beiden Breiten können klar unterschieden werden. Hingegen gelingt den Probanden dies bei Linien von 2 Taxel Breite im Vergleich zu Linien mit einem oder drei Taxeln Breite nicht zuverlässig. Weiterhin hat sich beim Vergleich unterschiedlicher Linienarten herausgestellt, dass die gleichmäßige unterbrochene Linie (Liniensegment 9mm, Unterbrechung 9mm) die beste von einer durchgezogenen Linie zu unterscheidende Form ist, wenn nur Linien von einem Taxel Breite zu bewerten sind. Ist die Breite freigestellt, werden dicke Linien bevorzugt.

Nur bei breiten Linien haben die Probanden die Oberflächenstruktur wahrgenommen. Dünne Linien werden im Hinblick auf ihre Oberflächenbeschaffenheit her eher undifferenziert wahrgenommen. Eine Unterscheidung der Oberflächen zwischen dünnen und dicken Linien (oder auch flächigen Strukturen) fällt den Probanden daher schwer.

Breite Linien, die scharfe Kurven beschreiben (etwa Ecken in einem Rechteck) werden manchmal nicht vollständig in die Prägeform überführt, d.h. das Taxel in der Spitze der Ecke fehlt. Dieses Fehlen wird von den Probanden klar bemerkt und die Ecke dann als „abgerundet“ beschrieben. Dies ist ein ungewolltes Artefakt, das nicht in die Vorlage vorhanden ist und zu falschen Interpretationen führen könnte. Da nicht erkennbar ist, wann eine Realisierung mit oder ohne Eckpixel erfolgt, ist diese Verhalten als nicht-deterministisch einzustufen.

Linienkreuzungen

Kreuzungen von dicken Linien unterscheiden sich in ihrer Wahrnehmbarkeit grundsätzlich nicht von dünnen Linien. Allerdings fiel es den Probanden leichter, die genaue Beschaffenheit der Kreuzungen von dünnen Linien zu ertasten. Dazu gehört z.B. die genaue Anzahl der sich beteiligten Linien und ob ankommende Linien nicht etwa kurz vorher aufhörten.

Oberflächenbeschaffenheit

Grauwerte von Linien oder Flächen in der Vorlage werden in unterschiedliche Prägehöhen umgesetzt. Ein 100% Schwarz resultiert in 100% Höhe, 0% Schwarz (also Weiß) in 0% Höhe. Es hat sich in der Fallstudie herausgestellt, dass der Unterschied von 100% Höhe und 70% Höhe einer Fläche nicht oder nur unsicher von den Versuchspersonen erkannt wird. Ein Unterschied zwischen maximaler Höhe und halber Höhe wird sicherer erkannt, allerdings auch nicht in allen Fällen. Ein entscheidender Faktor scheint hier die Erwatung zu sein: ist bekannt, dass unterschiedlich starke Prägehöhen genutzt werden, um Objekte zu unterscheiden, achten die Probanden auch darauf. Ohne Hinweis fallen unterschiedliche Prägehöhen meist nicht auf.

Flächen mit taktilen Texturen sind nur dann klar voneinander diskrimierbar, wenn sie sehr grobe Texturen aufweisen. Die bei der Betrachtung von Linien gewonnene Erkenntnis, dass 3mm Abstand ausreichen, um Linien voneinander bzw. Linien von Flächen zu diskrimieren, erweist sich hier als wenig hilfreich. Trotz der Einhaltung dieses Abstands sind Flächen, die mit unterschiedlich schrägen Linienmustern oder einem Gitter gefüllt sind, nicht klar voneinander zu unterscheiden. Einzig ein gleichmäßiges Punktraster mit 3mm Punktabstand ist klar zu diskriminieren, wobei aber die Qualität des Unterschieds nicht klar benannt werden kann. unterschiedliche Schraffuren und Gitter können bei einem Linienabstand von 6mm sicher erkannt und benannt werden.

3. Zusammenfassung & Empfehlungen

Die Wahrnehmbarkeit und Unterscheidungsfähigkeit von Objekten hängt vom Typ der beteiligten Objekte ab, von ihrer Entfernung zueinander, von ihrer absoluten Lage auf dem Papier (es macht einen Unterschied, ob die Abtastung horizontal oder vertikal erfolgt, weil die Haltung der Finger eine Rolle spielt), von ihrer Linienstärke und von ihrer Oberflächenbeschaffenheit.

Zur Fertigung von Versuchsmaterialien mit dem Prägedrucker um die Wahrnehmung und Interpretation taktiler Objekte zu ermöglichen:

- Linien sollen mit einer Stärke von einem Taxel realisiert werden.
- Horizontale und Vertikale Doppellinien sollten einen Abstand von 3 mm haben.
- Schräge Doppellinien sollten einen Abstand von 4 mm haben.
- Unterschiedlich zu interpretierende Strukturen sollten eher in unterschiedlichen Formen gestaltet werden, als in unterschiedlichen Oberflächenstrukturen.
- Zwei gut zu unterscheidende Linienformen sind durchgezogene und unterbrochene Linien, wobei jede Unterbrechung und jedes Liniensegment 1cm lang sein sollte, wenn die Linie 1 Taxel breit ist. Bei breiten Linien von 3 Taxeln sollten die Liniensegmente auf 1,5cm verlängert werden, die Unterbrechungen aber gleich bleiben (also 1cm).
- Linien und Flächen brauchen nicht in unterschiedlichen Höhen realisiert werden, denn dies bringt nur einen kleinen Vorteil bei der Diskrimination. Alle Flächen und Linien können gleichermaßen in maximaler Höhe ausgearbeitet werden.
- Empfehlungen für Linienabstände gelten nur eingeschränkt für taktile Texturen. Diese sind bei einem Linienabstand von 6mm deutlich zu erkennen und zu benennen, nicht schon bei 3 oder 4 mm.
- Wenn es auf scharfe Ecken ankommt, sollte das geprägte Papier genau geprüft werden, denn bei fehlenden Taxel wird eine scharfe Ecke als rund empfunden.

Zur Versuchsdurchführung mit Medien gefertigt mit dem Prägedrucker:

- Der Raum für die Versuchsdurchführung sollte möglichst warm sein, mindestens

20°Celsius.

- Langärmelige Bekleidung ist für das Tasten unter dem Sichtschutz hindurch und als Isolation gegen kalte Tischoberflächen hilfreich. Sie sollte von allen Probanden gefordert werden.
- Eine taktile Legende muss vorhanden sein, damit die Probanden wissen, worin sich die taktilen Objekte unterscheiden und wonach sie suchen müssen.

Literaturnachweise

Chan, C. (2007). Computer-aided design and manufacturing of tactile maps. Mechanical Engineering, Hong Kong University. Abgerufen Juli 15, 2008, von http://sunzi.lib.hku.hk/hkuto/record/B37895722.

Maucher, T. (1998). Aufbau und Test eines taktilen Seh-Ersatzsystems. Diplomarbeit, Heidelberg: Kirchhoff-Institut für Physik, Universität Heidelberg. Abgerufen November 17, 2008, von http://www.ub.uni-heidelberg.de/archiv/22/.

Maucher, T. (2000). The Heidelberg Tactile Vision Substitution System. In *Proceeding of the Sixth International Conference on Tactile Aids, Hearing Aids and Cochlear Implants*. University of Exeter, UK. Zugänglich über http://www.kip.uni-heidelberg.de/Veroeffentlichungen/download.cgi/4285/ps/exkadoc.pdf.

Rieger, K. (2002). Entwicklung eines Sehersatzsystems für Blinde in Form eines microcontroller-gesteuerten taktilen Displays mit hoher Bildauflösung und Durchführung von Praxistests. Diplomarbeit, Heidelberg: Kirchhoff-Institut für Physik, Universität Heidelberg. Abgerufen November 17, 2008, von http://www.kip.uni-heidelberg.de/Veroeffentlichungen/details.php?id=1380.

Anhang: In Vorstudie beantwortete Fragen

A) Zur Wahrnehmung und Interpretation taktiler Objekte

1	Wie gut sind Linien zu unterscheiden, die paarweise unterschiedlich dick sind?	1 und 2 Taxel Linienbreite wird nicht zuverlässig gut unterschieden, 1 und 3 Taxeln wird sicher erkannt. Es kommt auch auf die Richtung der Linien an: schräg laufenden Linien brauchen einen um 1mm größeren Abstand.
2	Wie gut sind Konturen oder Linien diskriminierbar, falls sie unterschiedlich nahe beieinander liegen?	bei horizontaler&vertikaler Laufrichtung und gleicher Erhabenheit: 3-4mm Abstand, bei schrägen Laufrichtung und gleicher Erhabenheit: 4-5mm
3	Wie weit dürfen die Teilstücke einer unterbrochenen Linie auseinanderliegen und wie lang müssen die Linienstücke dann sein, damit noch der Eindruck einer zusammenhängenden Linie entsteht?	Bei einem Abstand von 15mm und einen Segmentlänge von 6mm wird die Linie zwar noch erkannt, die VP äußerten aber Bedenken, dass der Zusammenhang im Kontext einer Karte mit vielen anderen Linien verloren gehen könnte. Ein Abstand von 2mm wird nicht mehr wahrgenommen. Als gut wird ein Abstand von 9mm bei der gleichen Segmentlänge empfunden.
6	Wie explorieren die VP eine Karte, in der keine Hinweise auf den YAH-Punkt gegeben sind?	Anfänglich unterschiedlich: manche die äußere Begrenzung suchend, die anderen gleich an einer Stelle beginnend, meist in einer Ecke; alle Sehende erschließen sich dann den Raum Linien- und Konturenfolgend, die zwei Blinden sind nicht so auf Linien und Konturen fixiert.
7	Wie oft ist ein räumliches Suchen (etwa flächig abtasten von oben nach unten und von links nach rechts) zu beobachten, wie oft ein linienorientiertes (entlang spürbarer Linien bzw. Konturen)?	(Siehe 6)
8	Bei welcher Suchstrategie wird eine größere Abdeckung der Karte erreicht?	Sowohl die räumlich Suchenden, als auch die Linien verfolgenden haben letztendlich den gesamten Raum abgesucht. Es gab in beiden Gruppen VP, die nicht beim ersten Mal alles gefunden hatten. Allerdings war nicht erkennbar, ob es an der Strategie lag, an der geringen taktilen Auffälligkeit der Objekte oder ihrer Lage im Raum bzw. Entfernung zur nächsten Linie.
10	Welche Komplexität dürfen die Karten durchschnittlich haben, um noch klar diskriminierbar, aber vor allem interpretierbar und memorierbar zu bleiben?	Bei einer Wegbreite von einem Taxel können A4 Karten vom verfügbaren Platz her schon sehr komplex werden

11	Wie gut können die VP einzelne Objekte bei steigender Komplexität eines Plans diskriminieren und benennen?	Die drei flächigen Objekte Dreieck, Rechteck und Kreis können klar voneinander unterschieden werden. Linien wurden ohne Einfluss der Komplexität richtig in die Kategorien horizontal, vertikal und diagonal/schräg eingeordnet. Allerdings hatten die Blinden erhebliche Schwierigkeiten, die Kategorien richtig zu verwenden, es kam oft zu Verwechselungen zwischen horizontal und vertikal, dann aber in sich konsistent.
12	Welche Unterschiede ergeben sich zwischen einem Abruf über free-recall und recognition um Zusammenhänge, speziell Überblickswissen zu testen?	Bei drei flächigen Objekten gab es keine Probleme mit dem Recall. Recognition wurde daher nicht getestet. Sehr prägnante Linien wie Begrenzungslinien oder die Karte komplett durchlaufende Linien wurden auch sicher gemerkt. Untergeordnete Linien waren bei Recall nicht mehr präsent, bei Recognition aber doch.
13	Wie detailliert ist das abrufbare Überblickswissen?	Sofern die Karte aus konzeptionell bekannten und benennbaren Formen zusammengesetzt ist, können VP relativ erfolgreich auf dieses Wissen zurückgreifen. Die grobe Form äußere Form des Wegenetzes (z.B. rechteckig) bleibt gut im Gedächtnis und die relative Lage von drei Objekten auf der Karte kann nach erschöpfender Exploration auch benannt werden. Auffällige Wege (volle Diagonalen, Horizontalen oder Vertikalen) werden gut erinnert. Wegbeschreibungen von A nach B erfolgen oft über die am besten erinnerten Wege, d.h. nicht immer über den kürzesten Weg.
15	Was ist ein akzeptabler objektiver Lernerfolg in der Trainingsphase?	(siehe 16)
16	Welches Maß an Wahrnehmungsdifferenzierung muss erreicht werden?	Die VP konnten alle Linienabstände von 3mm zuverlässig erkennen, bei Oberflächenstrukturen führen 6mm Zwischenraum zu gut differenzierbaren Strukturen. Oberflächenrauheiten von Maximallevel (1) zu Mittellevel (0,5) werden auf Nachfrage erkannt.
17	Wenn der Lernerfolg in der Hauptstudie nicht erreicht wird, wie lange soll nachgelernt werden?	Da niemand in den Vorversuchen Probleme mit der Wahrnehmung oder Interpretation hatte, kann diese Frage noch nicht endgültig beantwortet werden. Aus den Beobachtungen lässt sich schließen, dass ein Training von 10-15 Minuten (in denen 2 Karten probeweise exploriert werden können) normalerweise ausreichen sollte. Ein Nachlernen über eine weitere Karte scheint realistisch, wobei diese Karte auf die Bedürfnisse des Probanden angepasst sein müsste, d.h. genau die Konzepte nachlernen, die bisher nicht ausreichend diskriminiert oder interpretiert wurden.
20	Wie schwierig ist es für die Probanden, von zwei Randmarken am Kartenrand, die die Lage des YAH Symbols angeben, ausgehend das YAH Symbol in der Karte zu finden?	Den beobachteten VP fiel es relativ leicht, einen durch zwei Randmarken definierten Punkt in der Karte zu lokalisieren. Allerdings wurde sich verschiedener Methoden bedient, meist die erste: 1) das gleichzeitige Verfolgen der Horizontalen und der Vertikalen bis zum Treffpunkt der Finger, 2) Nacheinander jeweils mit zwei Finger einer Hand die horizontale oder die vertikale

		Komponente verfolgend, um jeweils möglichst parallel zur Kartenkante zu bleiben.
21	Treten bei der kantenparallelen freien Führung der Hände größere koordinative Schwierigkeiten auf, so dass der Bereich mit dem YAH Symbol großräumig verfehlt wird?	Nein (siehe 20)
22	Wie wird die Exploration von den Randmarken in die Karte vollzogen: seriell einhändig oder parallel beidhändig?	Meist beidhändig (siehe 20)
23	Erkennen die VP dass eine Karte schon gezeigt wurde, nur dass sie gedreht wurde?	In den meisten Fällen nicht und wenn eine Vermutung besteht, wird sie schnell wieder fallengelassen also nicht weiter genutzt bzw. überprüft..

B) Zur Versuchsdurchführung

Nr.	**Frage**	**Aus Beobachtung/Befragung gefundene Antwort**
6	Inwiefern stimmt diese subjektive Einschätzung mit objektiven Kriterien überein?	Wenn man als objektive oder zumindest heuristisch belegte Kriterien die Empfehlungen aus Handbüchern zum Bau taktiler Karten zu Grunde legt, dann sind die subjektiven Einschätzungen wenig oder gar nicht geübter VP sehr realistisch. Der Vergleich von geübten (Blinden) und ungeübten (Sehenden) zeigt, dass ihre Einschätzungen sehr nahe beieinander liegen, etwa was die Gestaltung von taktilen Karten angeht (Mindestabstände, Oberflächen usw.).
15	Verbessert sich die Genauigkeit, wenn beim Lesen der Karte explizit auf die Wichtigkeit der Zusammenhänge hingewiesen werden?	Allgemein muss VOR dem Training die nachher gestellte Aufgabe bekannt sein, so dass die VP ihre Aufmerksamkeit selbst leiten können.
19	Ab welchem Lernniveau (inklusive Nachlernen) schließen wir VP von der Studie aus?	Wenn sie nach 15Minuten Training 4mm Abstände nicht erkennen können.
20	Soll der VL Linefollowing als effiziente Strategie (Chan 2007) zur Kartenexloration empfehlen und wenn ja, wann: schon im Training oder erst beim Experiment? Oder gar nicht, weil viele Sehende es anscheinend von sich aus tun (siehe Datenmaterial der Arbeiten aus Heidelberg: Maucher 1999, Maucher et al. 2000, Rieger 2002)?	Linefollowing wurde von sehenden VP bei der ersten Exploration immer angewandt, nur später erfolgte ein räumliches Suchen, um sich auf der schon bekannten Karte schnell zu orientieren. Blinde VP explorierten etwas unstrukturierter. Hier sollte man sich auf ihre Erfahrung verlassen, denn wie die zitierten Arbeiten gezeigt haben, sind sie mit dieser Strategie immer noch schneller als Sehende mit Linefollowing.

24	Welches Vorgehen zur Außerkraftsetzen der Visus wird von den VP bevorzugt: Augenbinde oder Sichtschutz?	Obwohl die Augenbinde von einigen VP für die Tastaufgaben als besser eingestuft wurde, war die Mehrheit der VP der Meinung, der Sichtschutz sei besser, vor allem weil er die visuelle Kommunikation mit dem Versuchsleiter in den Befragungen erlaube und dies als angenehmer empfunden wurde. Außerdem könne man bei nicht richtig sitzender Augenbinde verführt sein, doch zu versuchen, die Karte mit den Augen zu erkennen.

Appendix 2 – Study 2: Types of Intersections

If uniform division is assumed in an 8-direction model like in Klippel (2003) each sector is 45°. The angle between two segments intersecting is some multiple of that angle. For making calculations easier, each angle is represented by its modulus with 45°. In the plane, the full circle has 360°. Hence it is represented by the number 8 ($360 modulus 45 = 8$). The combination of sectors made from the intersection between three streets in the 8-direction model can be read off Table .2.

Combination	Variant of
116	
125	
134	
143	134
152	125
161	116
224	
233	
242	224
251	125
332	233
341	134

Table .2.: All possible types of 3-intersections in the 8-sector model. 1 represents an angle of 45°, multiples of 1 represent multiples of 45°.

There are five prototypical invariants of 3-intersections: 116, 125, 134, 224, and 233. They can be turned into all other variants by rotation and mirroring in the frame of the 8-direction model. The graphical representations of the invariants are depicted in Figure .4. An intersection between four streets divides the full circle into four sections that together must amount to 360°. All combinations of different sectors between four streets can be read off Table .3.

There are eight prototypical invariants of 4-intersections: 1115, 1124, 1133, 1214, 1223, 1232, 1313, and 2222. They can model all other variants by rotation and mirroring in the frame of the 8-direction model. The graphical representations of the invariants are depicted in Figure .5.

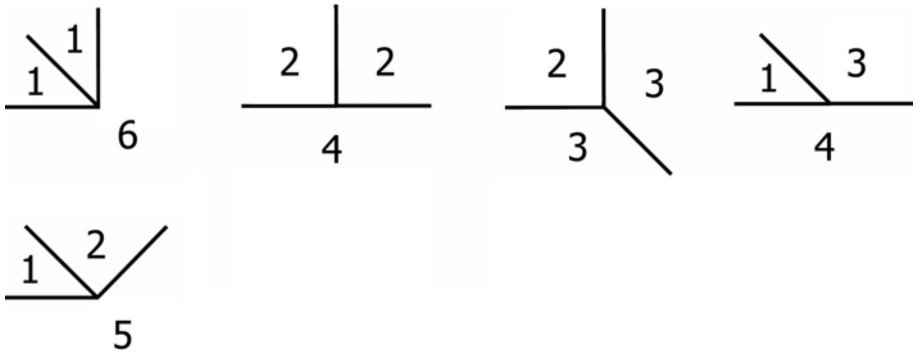


Figure .4.: Prototypical intersections of three streets using the 8-sector model. Variations by rotation and mirroring are not displayed. Numbers represent the size of the angle between adjacent segments. 1 represents an angle of 45°, multiples of 1 represent multiples of 45°.

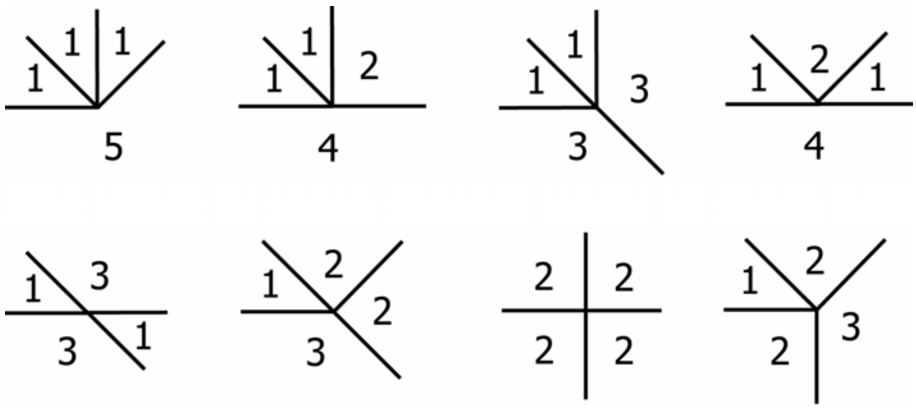


Figure .5.: Prototypical intersections of four streets using the 8-sector model. Variations by rotation and mirroring are not displayed. Numbers represent the relative size of the angle between adjacent streets. 1 represents an angle of 45°, multiples of 1 represent multiples of 45°.

Combination	Variant of
1115	
1124	
1133	
1142	1124
1151	1115
1214	
1223	
1232	
1241	1124
1313	
1322	1223
1331	1133
1412	1214
1421	1124
1511	1115
2222	
2312	1223
2321	1232
2411	1124
3311	1133

Table .3.: All possible types of 4-intersections in the 8-sector model. 1 represents an angle of 45°, multiples of 1 represent multiples of 45°.

Appendix 3 – Study 2: Stimulus and Results

Stimulus Materials for the Tactile Acuity & Tactile Comprehension Test

1. Straight lines that varied in line width (one or three taxels), tactual prominence (maximum elevation or 40% height), and direction of presentation (oblique, vertical or horizontal), four symbols, and two free-form lines of different line width, see Figure .6.

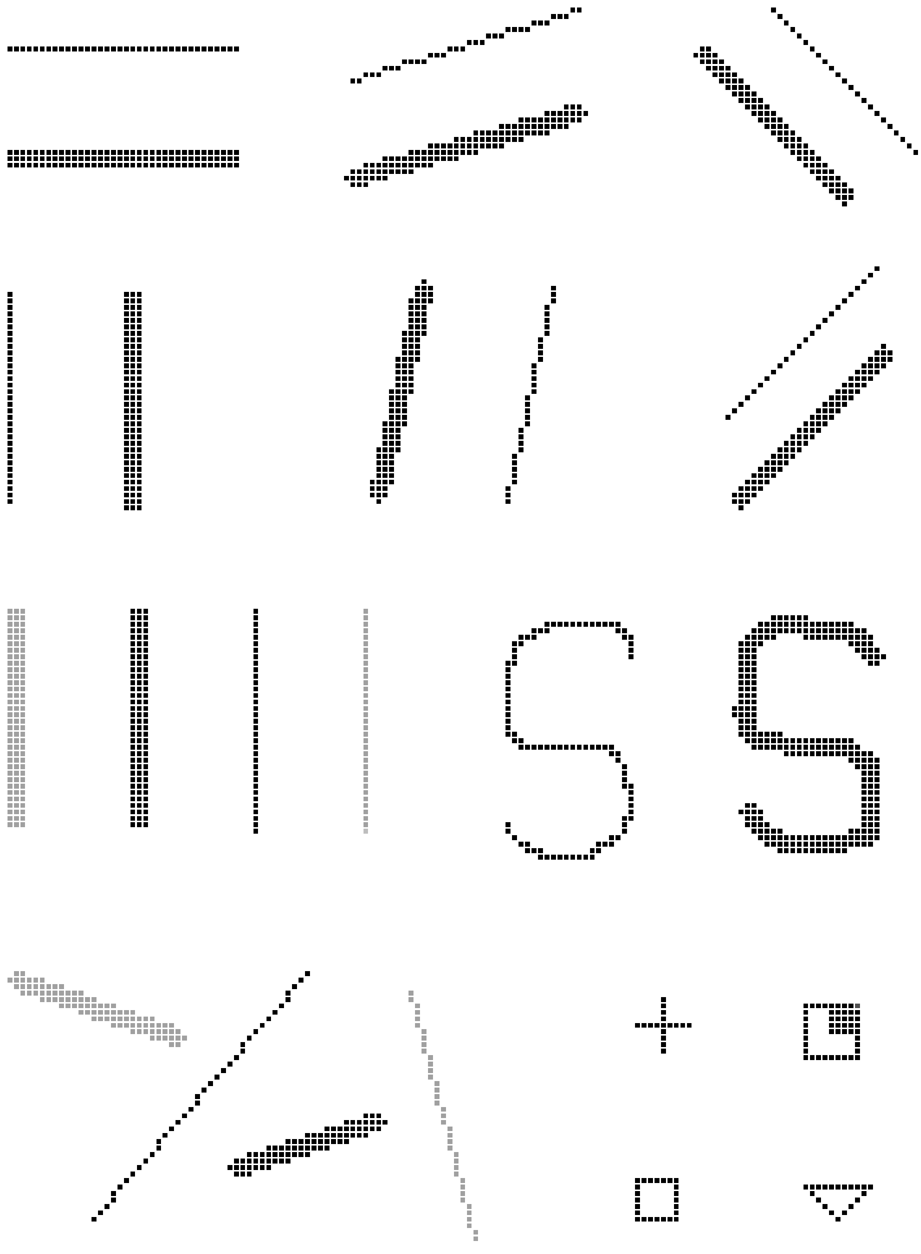


Figure .6.: The first page with stimuli: symbols and line signatures (original in A4).

2. Polygons that varied in number of edges (three or four), width of the outer border (one or three taxels), surface structure (full elevation or 40% height), and orientation of the whole object, see Figure .7.

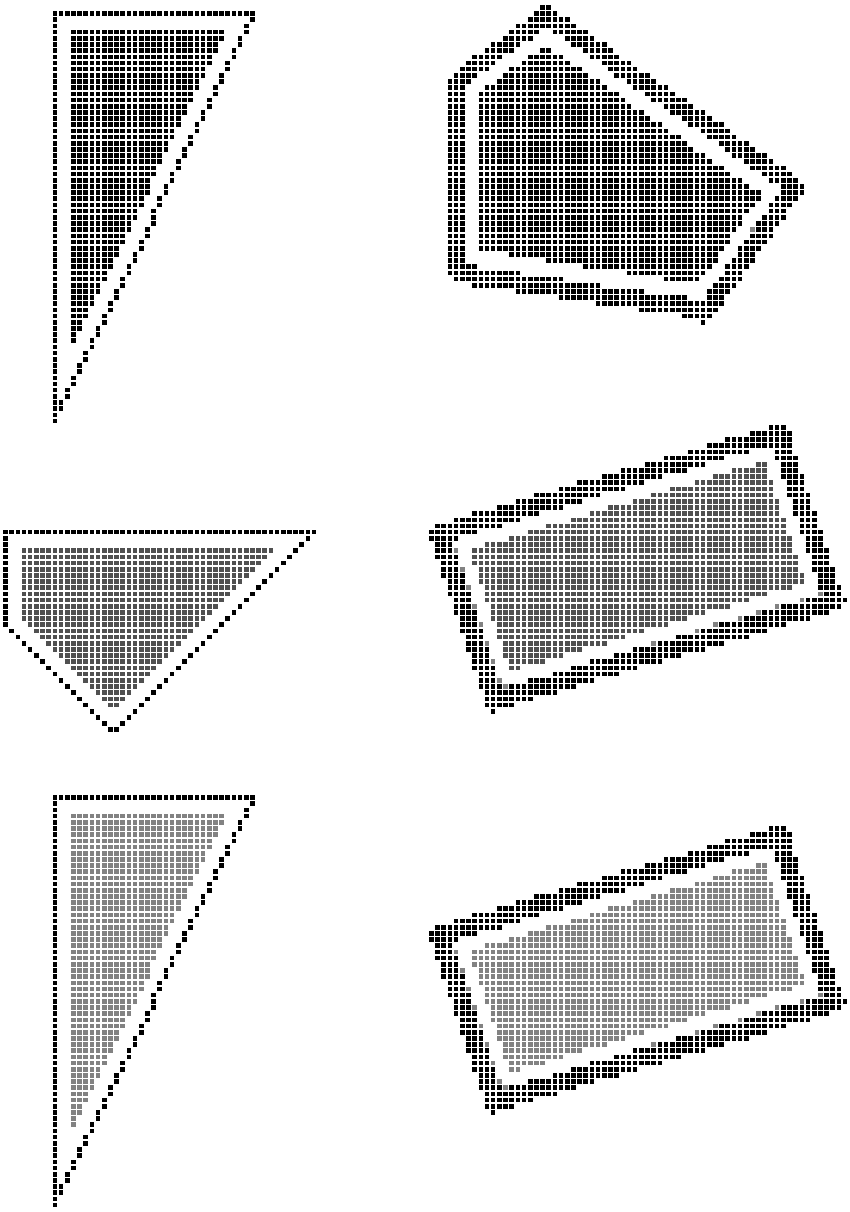


Figure .7.: The second page with stimuli: area signatures (original in A4).

3. T-intersections and X-intersection of lines that varied in line style (straight or free-form), line width (one or three taxels), and orientation of the whole object, see Figure .8.

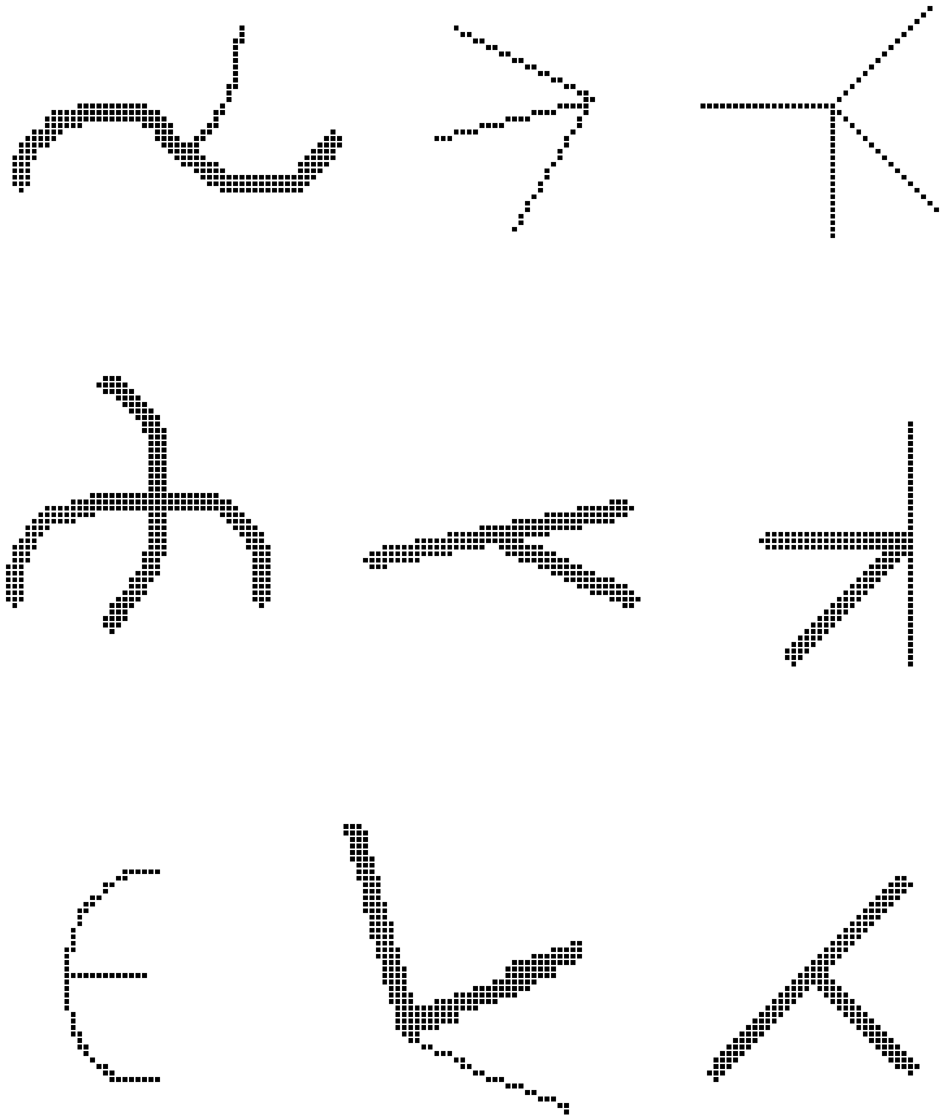


Figure .8.: The third page with stimuli: intersections and orientation (original in A4).

Stimulus Maps Provided to the Participants

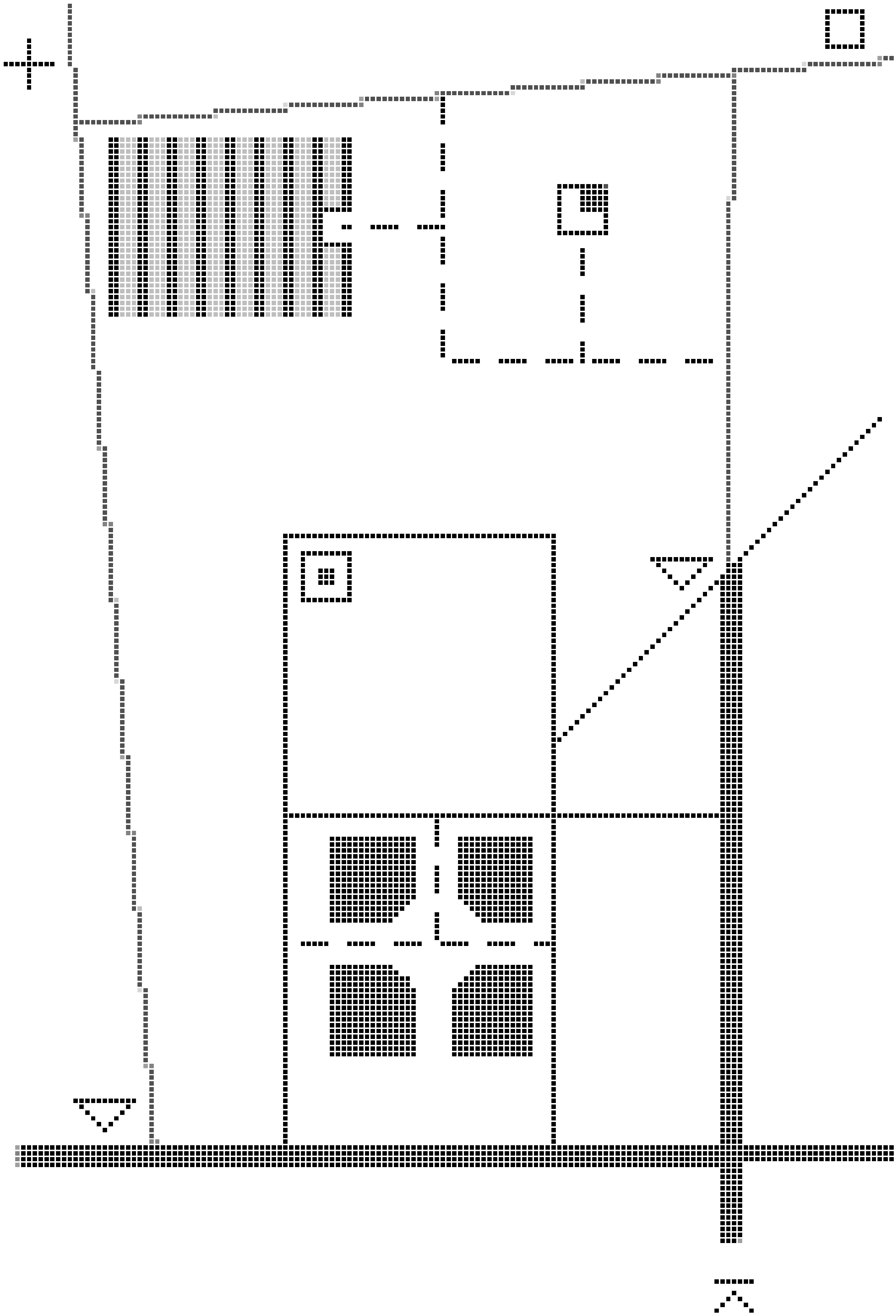


Figure .9.: Tactile Orientation Map used in the training: Southern part of the campus of the

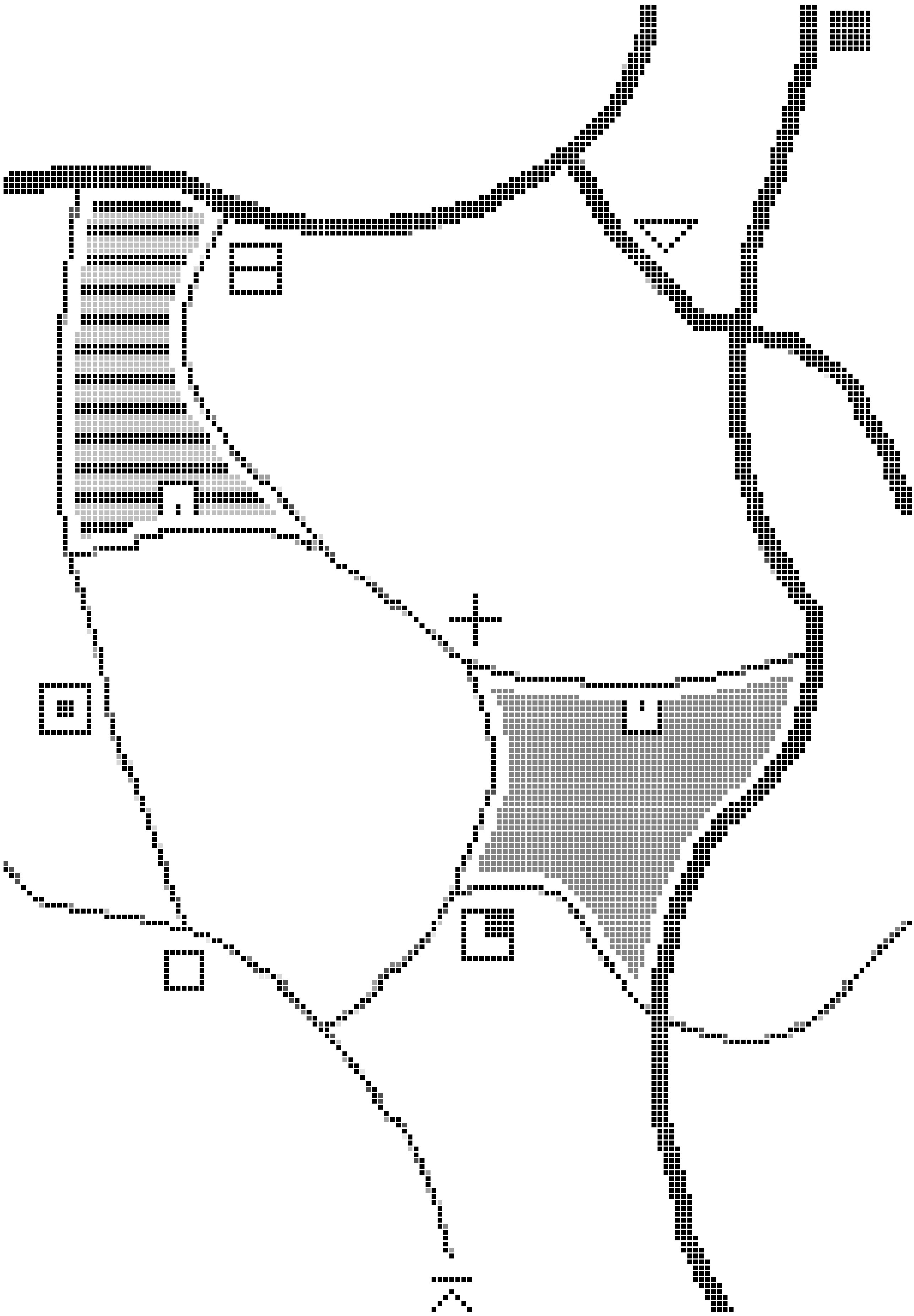


Figure .10.: Artificial tactile orientation map used in the non-abstract trials.

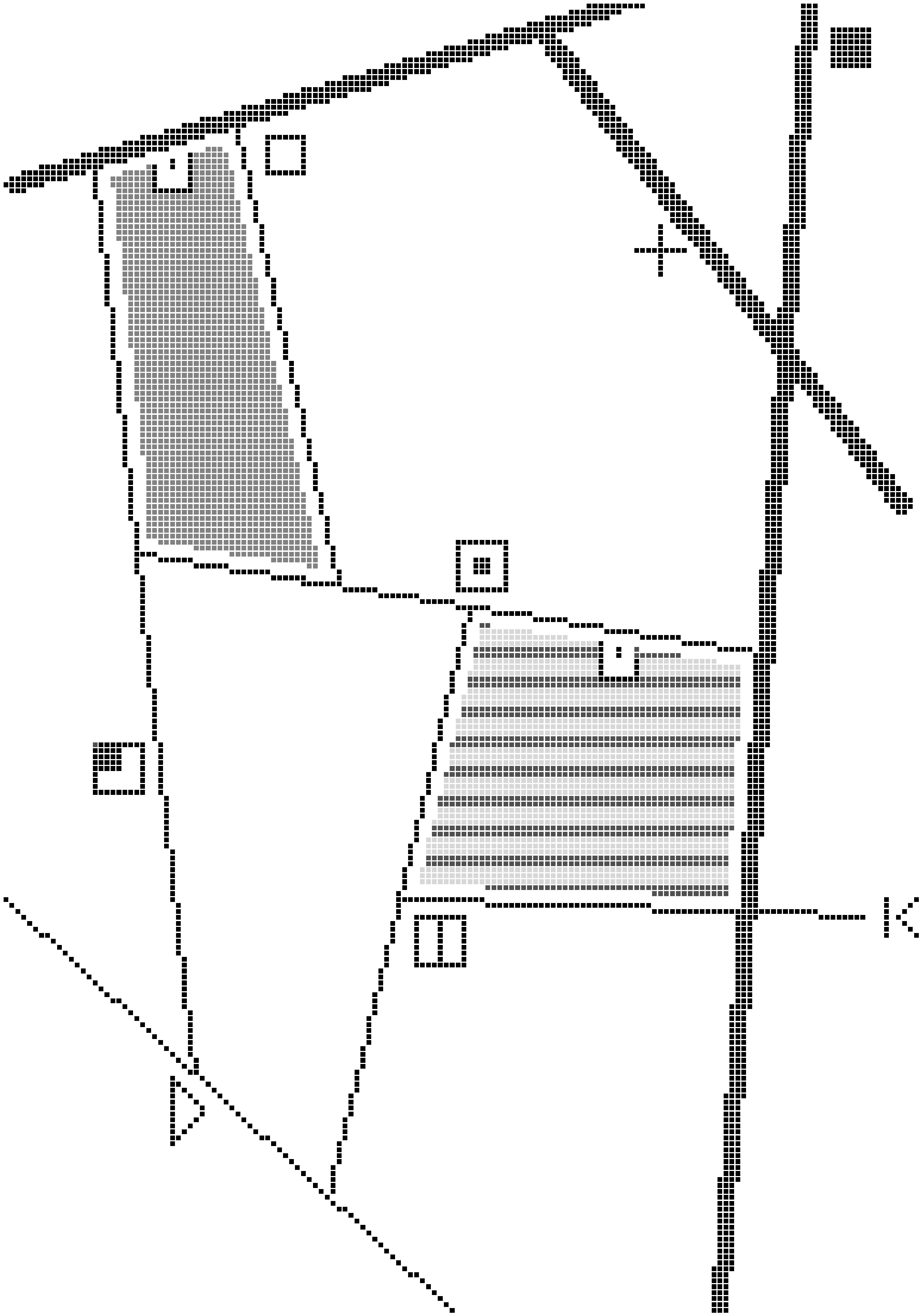


Figure .11.: Artificial tactile orientation map used in the low-abstract trials.

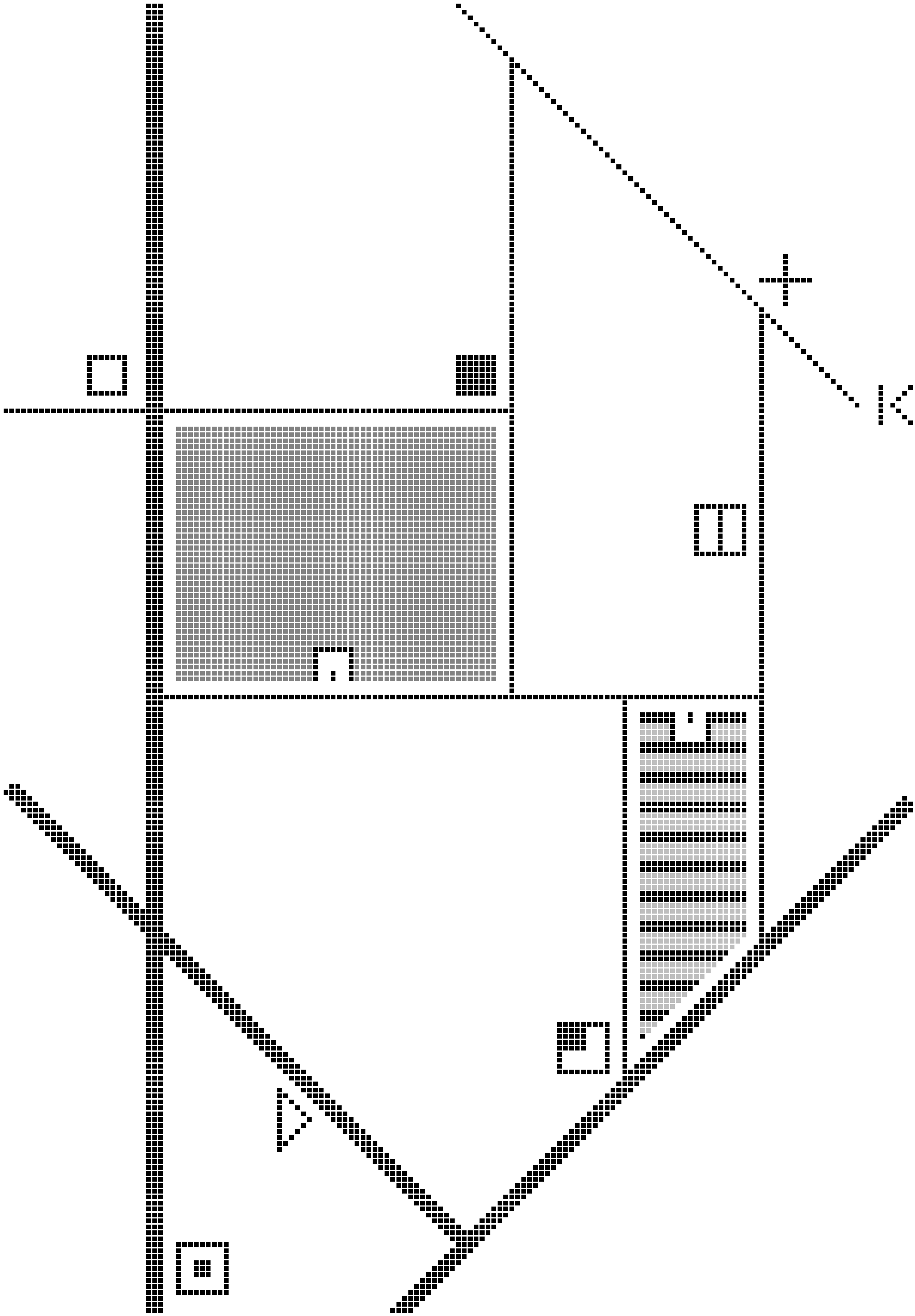


Figure .12.: Artificial tactile orientation map used in the high-abstract trials.

Resulting Sketch Maps Drawn From Memory by the Participants

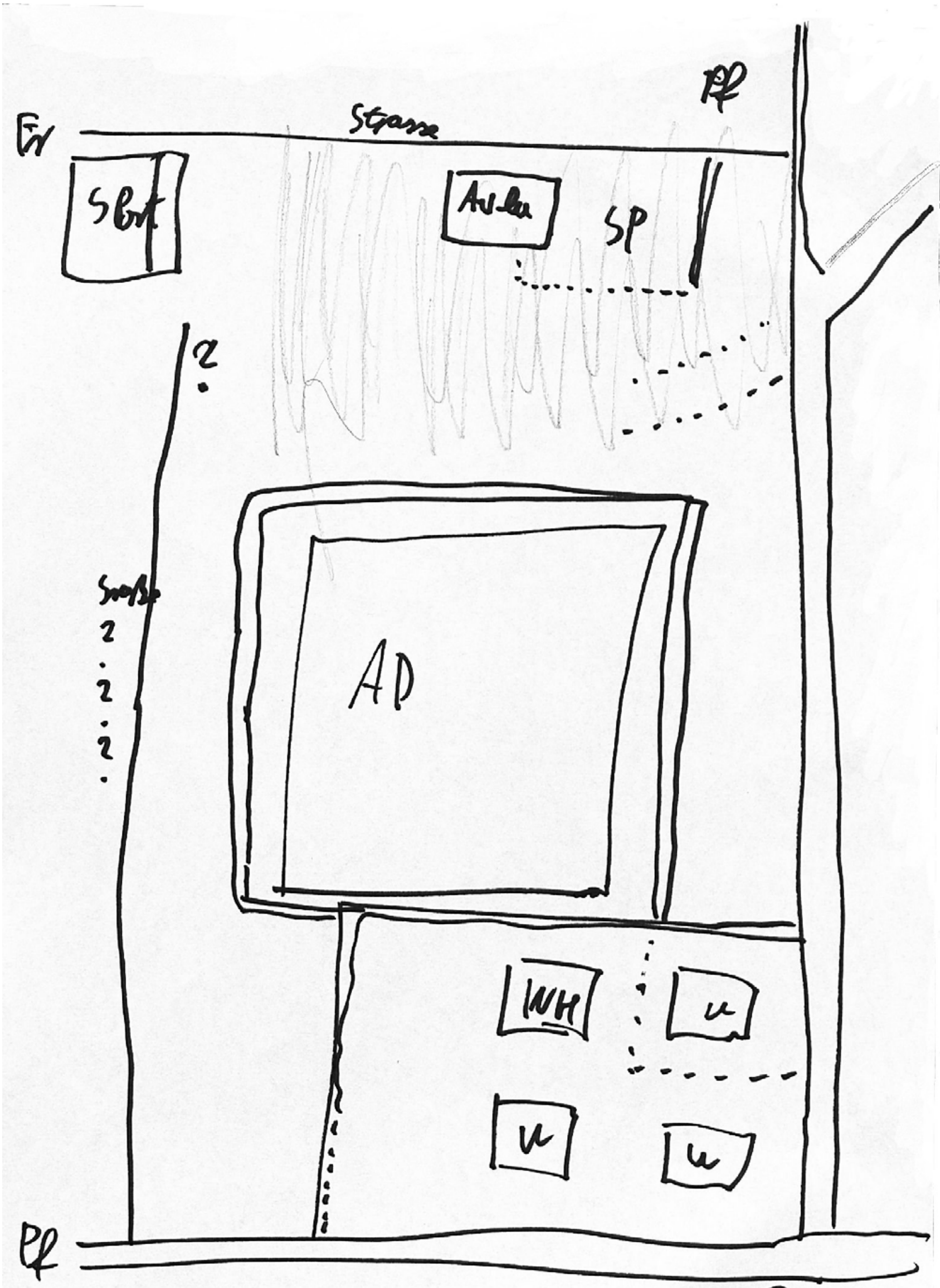


Figure .13.: Sketch of the training map.

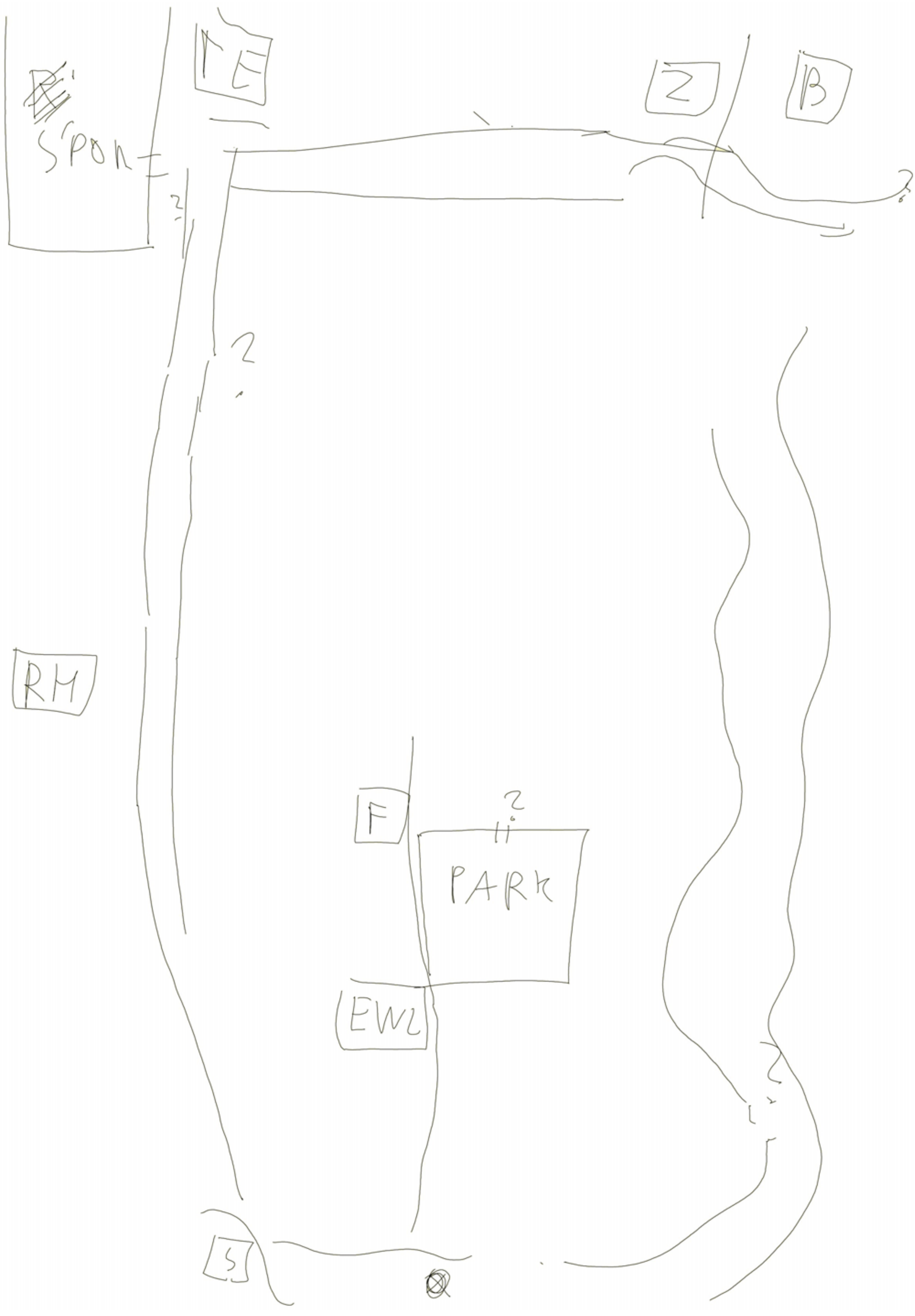


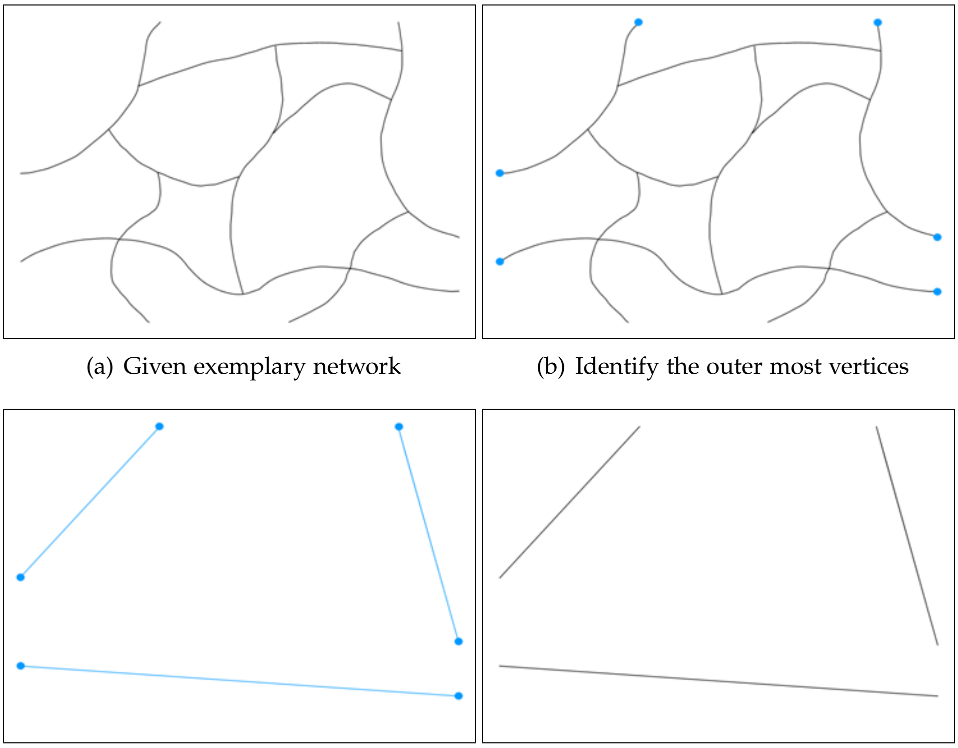
Figure .14.: Sketch of the non-abstract map.

Figure .15.: Sketch of the low-abstract map.

Figure .16.: Sketch of the high-abstract map.

Appendix 4 – Study 2: Procedure to Generate Abstract Maps

Procedure to Generate a Low-abstract Map



(a) Given exemplary network

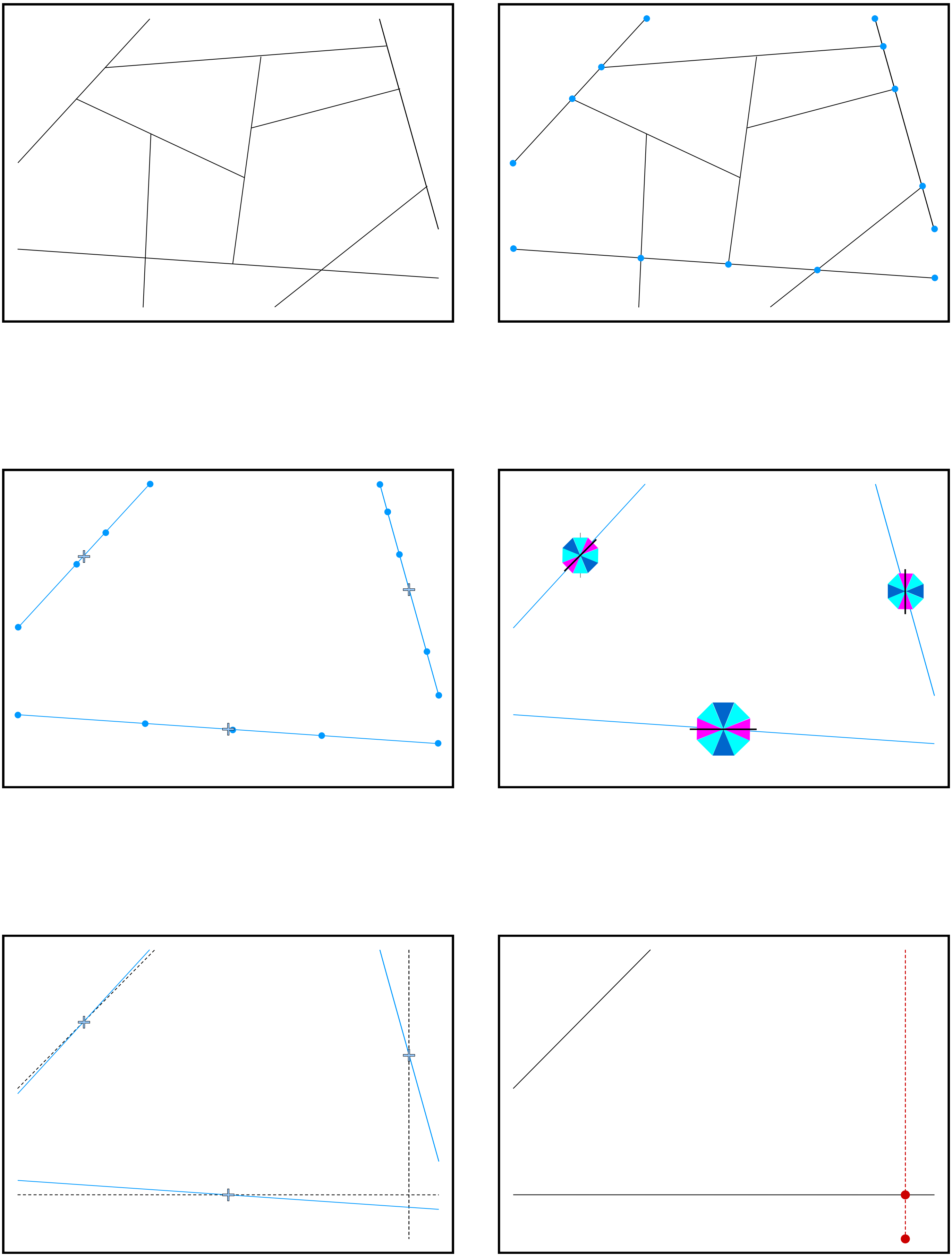
(b) Identify the outer most vertices

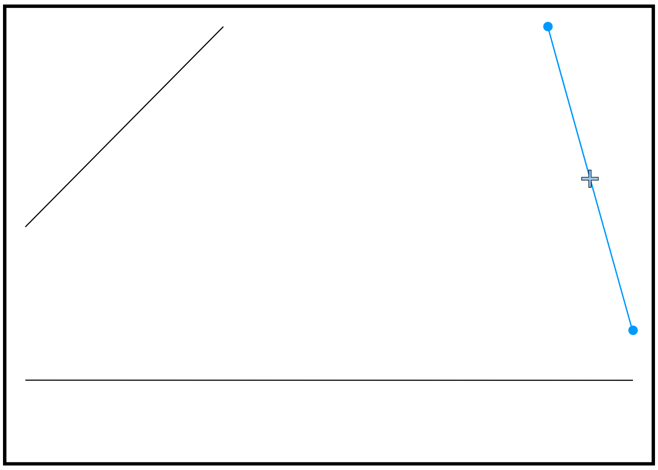
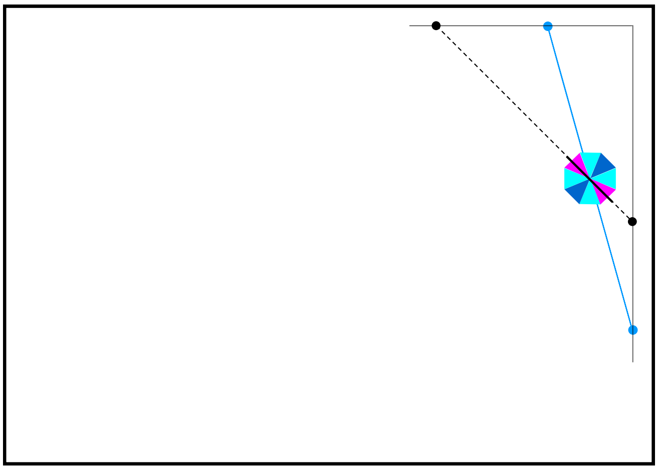
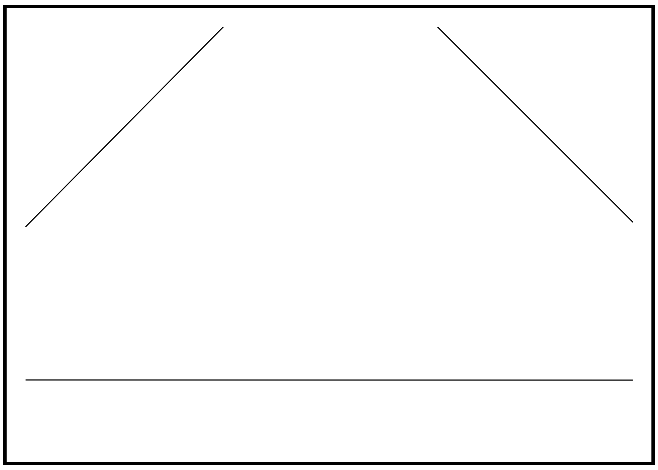
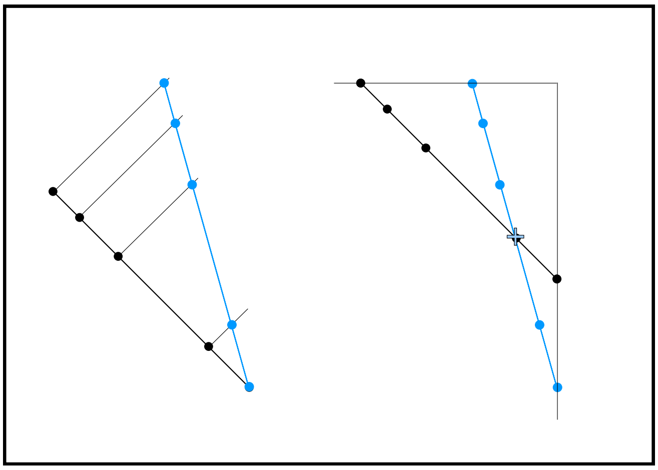
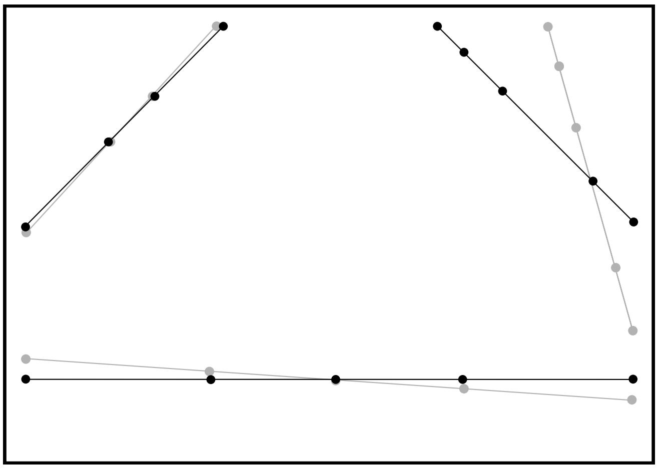
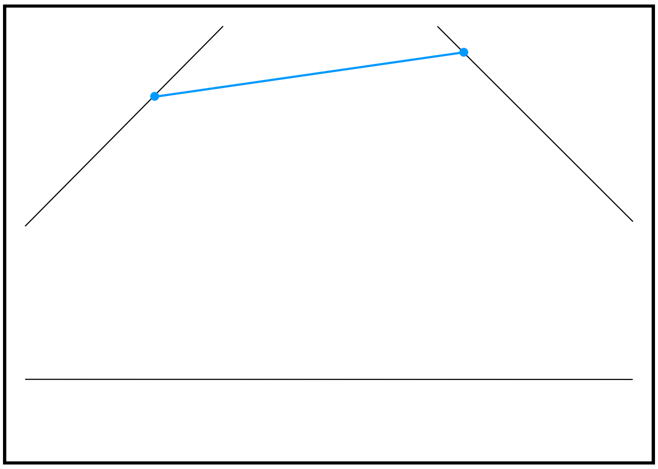
(c) Identified vertices are reconnected with straight lines

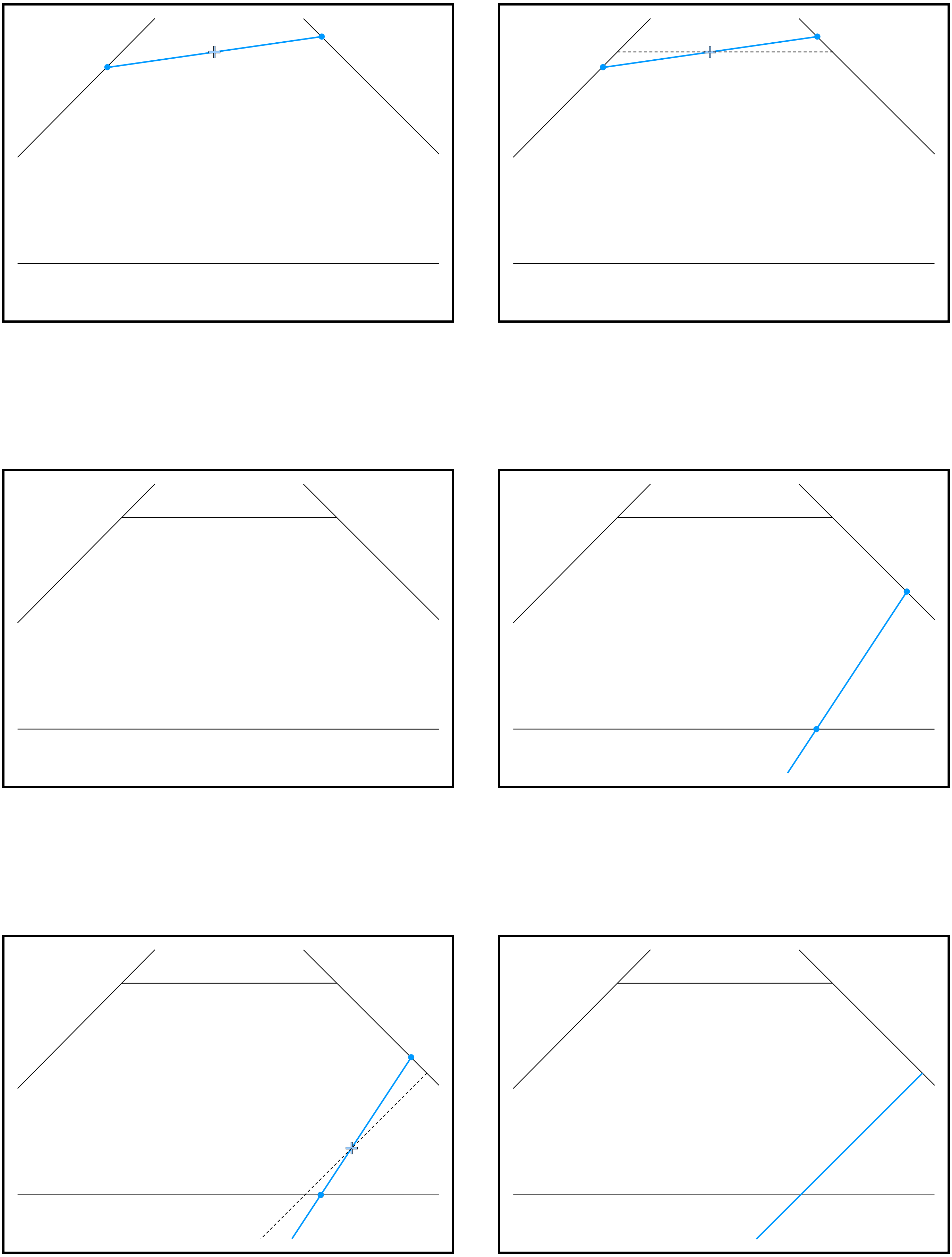
(d) Outer most lines are abstracted

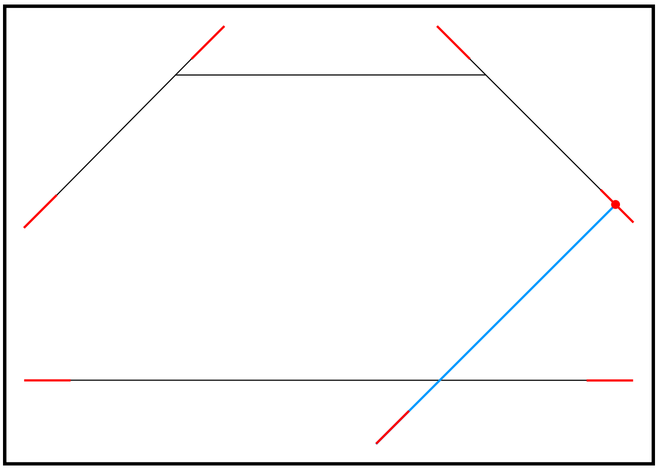
Figure .17.: The first steps of the abstraction procedure to get a high-abstract street network.

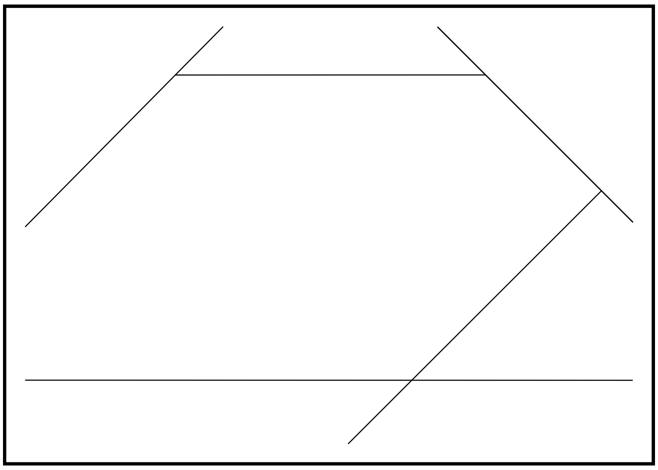
Procedure to Generate a High-abstract Map



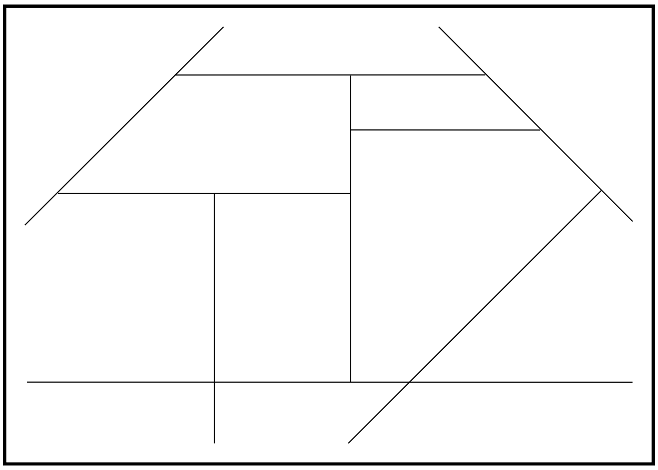




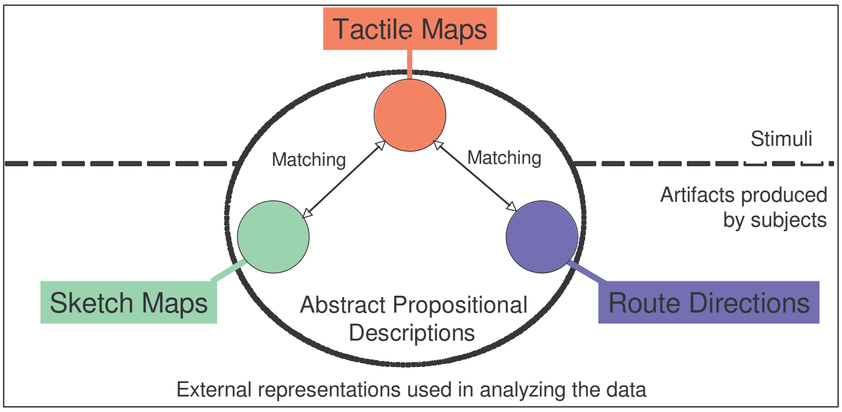


Weiteres Vorgehen

1. Segment s im Urbild wählen (Reihenfolge: Segmente zwischen zwei Randpunkten [Segment 1.Ordnung], Segmente zwischen Segmenten 1.Ordnung [Segment 2.Ordnung], Segmente zwischen 1.Ordung und 2.Ordnung oder zwischen 2.Ordnung und 2. Ordnung [3.Ordnung])
2. Ausrichtung von s und abstrahierte Ausrichtung für Bild in schematisierter Karte über Sektormodell bestimmen
3. Segmentendpunkte p1, p2 auf jeweiligen Stützlinien l1, l2 in schematisierter Karte finden, gedachte Gerade g zwischen ihnen um Mittelpunkt der Strecke p1p2 bis zur Deckung mit Ausrichtung für Bild drehen
4. Schnittpunkte von g mit l1, l2 sind neue Endpunkte p1‘, p2‘ in schematisierter Karte
5. Alle Punkte pi auf Strecke p1p2 im Urbild werden unter Erhalt ihrer *relativen* Abstände auf die Strecke p1‘p2‘ abgebildet.
6. Für alle pj‘ prüfe: wenn die Stützlinie lj am Kartenrand endet und sich pj‘ weniger als 1,5cm vom Kartenrand entfernt befindet, dann verschiebe den Punkt pj‘ auf lj weg vom Kartenrand, bis die Entfernung 1,5cm groß ist



Appendix 5 – Study 3: Methodology to Evaluate the Conceptualisation of Tactile Maps



Schematic visualization of the approach on how to match route directions and sketch maps with corresponding tactile maps.

Evaluation of Verbal Route Directions

It is commonly accepted and was described by e.g Allen (1997), Denis (1997), Klein (1979), and Wunderlich and Reinelt (1982) that two types of information can be found in route directions. First, information about decision points and landmarks, and, second, information about actions the navigator has to perform. The positions at which the navigator can choose between tracks are decision points. They are often characterized in their relation to landmarks. Numerous studies have empirically and theoretically reasoned about the role of landmarks and their function as marking decision/choice points (cf. Allen, 1997; Denis, 1997; Tversky, 1996; Tversky & Lee, 1999) or as means for reassurance to the navigator to be on the right track (cf. Lovelace, Hegarty & Montello, 1999). Decision points and landmarks are organized in an instruction according to a virtual navigator (Klein, 1979), an imaginative person who is thought to walk the route. Providing an own frame of reference, the virtual navigator can be used for grounding projective relations.

Route descriptions can be transcribed without filling sounds and pauses and with corrections overwriting initial statements. All sentences with descriptive character can be trans-coded into the canonical infinitive form to reflect an instructional character (e.g. “I turn right at the intersection.” → “Turn right at the intersection.”). To gain a representation of route instructions for further analysis, each route instruction is segmented into sequences of actions much likely to the approach by e.g. Denis (1997). Primarily these actions are movements and reorientations that can be described by verbs like *go* and *turn*. Positioning can be described by the verb *be*. For an abstract representation of the individual instructions we adopt a representational form as proposed in Tschander et al. (2003). The descriptive actions *go*, *turn* and *be* are represented by the operators GO, CH_ORIENT and BE_AT. The aim is to provide a human-readable abstract representation or each route that is independent from the exact verbal wording. Nevertheless, the abstract representation is not meant to be machine-readable as the syntax of the operators is not formally defined and the semantics of the arguments is not explained in any kind of lexicon.

When using small pieces of propositional expressions, sentences can be seen as being composed from more than one operator. An example of how the canonical infinitive form of individual route directions can be trans-coded to the abstract representation of those route directions with the given inventory is shown in Table 2a.

Canonical Infinitive Form (with *German originals*)	**Abstract Representation**
Walk the path to the left. *Gehe den Weg links runter,*	*GO(left)
straight ahead at the first junction, *an der ersten Kreuzung geradeaus,*	BE_AT(first intersection) *GO(straight)
at the next junction turn to the right, *an der nächsten Kreuzung drehe dich nach rechts,*	BE_AT(next intersection) *CH_ORIENT(right)
then to the left immediately. *dann sofort wieder links.*	*GO(left, immediately)
Then, the building should be at the right side. *Dann müßte das Gebäude auf der rechten Seite liegen.*	BE_AT(building, right)

Table 2a. One route given by a test subject in the canonical form and as formal representation: The asterisk in front of an operator denotes that this proposition has a prescriptive meaning, instead of being a result of executing previous steps (following the notion proposed by Denis, 1997, p. 426).

To evaluate how good the described routes were compared to perfect routes.

These routes where obtained by using the concept of a virtual navigator who has the original map in mind would describe perfect routes between two landmarks. Two requirements were declared: The routes to be described should be the shortest ones between the designated landmarks. It could be expected that people will try to save cognitive resources and thus tend to describe the shortest routes. The concept of shortest route was formulated with two alternatives: “length optimal” is the route (typically denoted with the letter A) that has the smallest distance between the two endpoints; “turn optimal” is any route (typically denoted with the letters B to D, ordered in path length) that includes the smallest number of turns, regardless of the distance or number of segments traveled. With respect to the very simple artificial worlds presented to the virtual navigator, it might happen that the shortest routes are the only ones that describe how to go from one landmark to the other. To prepare for the option that there might be routes that are not shortest but were chosen anyway, longer routes (denoted with E and F) were included that described how to go from one landmark to the other without going circles or using a segment more than one time.

The other requirement was that the virtual navigator should in the beginning and the end always face towards the start landmark respectively the end landmark and that every landmark on the way should be included in the route direction. The last requirement has the consequence that going along several segments that are in one line of sight is not described as one operation but as several consecutive operations. For an example how such an abstract representation of a route from start point A to goal point B might be constructed from a tactile map with the help of a virtual navigator see Table 2b.

Visualization of one Tactile Map (detail)	**Abstract Representation**
	BE_AT(YAH point, front)
	*GO(left)
	BE_AT(first intersection) *GO(straight)
	BE_AT(second intersection) *GO(right)
	BE_AT(next intersection) *GO(left)
	BE_AT(building, right)

Table 2b: A virtual navigator constructs the route from A to B abstract route representation for the same route like in Table 1a obtained with.

For the evaluations, each operation from the abstract route representations gained from the test persons' verbalizations were matched against the corresponding operation from the abstract route representations gained with the virtual navigator. Grounded in the requirements of the virtual navigator the following matching criteria were checked:

1. Orientation towards the start landmark
2. Mandatory actions on route
3. Orientation towards the final landmark
4. Optional succession of straight segments

The more information about the where and when of decision points that mark turn options or the start and end of segments are included in a route instruction, the better the instruction were rated. The sum of wrong instructions (e.g. if someone described a wrong turn operation or a wrong intersection for reorientation) were inverted, i.e. it contributed negatively to the total. Total failure was considered a) if test-persons could not give an initial route description, or b) if the described route could not be matched with any of the routes composed by the virtual navigator in any way. Matching values were normalized to make them comparable (as different routes had different maximal sums resulting from different characteristics of the routes). The range of normalized values between 0 and 1.0 was broken down in equidistant intervals which were then encoded with school grades between 6 (worst) and 1 (best) to make a categorization possible. Under these common rules, three different rating schemes were set up:

1. Equipollent Scheme

Each correct operation is awarded with +1 point, each wrong one with -1 point.

2. Impact Scheme

A weight was assigned to each step of the instruction according to its impact for successful route following. Mandatory actions are the most important factors in route following; they were assigned a weight of 4. For starting a successful route following the orientation towards that start landmark should be clear to build all the following turn operations upon it. As the heading and position was set in the beginning of the experiments it was considered of minor importance to mention it again; orientation was assigned a weight of 1. The same holds for the orientation towards the final landmark. Reorientation on route at decision points (without being turning points) is an operation that is not needed when an exact route description that names unique turn points is given. But redundancy by naming landmarks on the way (such as intersection where the navigator has to proceed) can give feedback to be on the right route; waypoints with reorientation were awarded with 2 points. The rating of descriptions of actions at intersections was bipartite: half of the points were awarded for mentioning the arrival at the intersection, half of the points for naming the correct turn operation (see Table 3, column ‘Weight’).

Individual Abstract Route Instruction	Extracted Abstract Route Instruction	Matching	Weight	Sum
	BE_AT(YAH, front)	☐	1	0
*GO(left)	*GO(left)	☑	4	4
BE_AT(first intersection) *GO(straight)	BE_AT(first intersection) *GO(straight)	☑ ☑	1 1	2
BE_AT(next intersection) *GO(right)	BE_AT(second intersection) *GO(right)	☑ ☑	2 2	4
*GO(left)	BE_AT(next intersection) *GO(left)	☐ ☑	2 2	2
BE_AT(building, right)	BE_AT(building, right)	☑	1	1
		Total	**16**	**13**

Table 3: Example matching of individual route and extracted route: almost all actions can be matched.

3. Cognitive Scheme

The final rating scheme is oriented towards the cognitive value of navigation operations at intersections. The value is differentiated according to how much cognitive effort must be taken to decide for a turn option. In the simplest case, the navigator approaches a corner which only affords one progressive action (the non-progressive was to walk back to same way as one was coming): to proceed around the corner. Another track configuration is if the navigator walks along a track and another track is joining from the side (T-Intersection with going straight) but the navigator ignores the joint and walks straight ahead. This could happen at an X-junction as well, but the navigator has more options there. In all former cases, the navigator has made no decision; he seems to be passive and just walks along. In those cases we cannot tell if the action taken was a deliberate one of if it occurred from not deciding. There are other situations in which the navigator has to make a decision, but they are qualitatively different. If a track ends in another track this is a T-junction and a decision has to be made which way to turn. This decision is forced but it is an active decision. Cases in which the decision is not forced are if the navigator might just have gone straight instead of turning. The two cases are if a) the navigator turns when coming to a T-junction on the leg that is prolonged over the intersection, or if b) the navigator turns when coming to an X-junction. In total there are different considerations how to differentiate the different types of operations at the different types of intersection:

1. If the operation is forced or not (forced at T-junctions if coming from the leg that finishes at the intersection, or corners).
2. If the operation is the supposed default operation (i.e. proceed/going straight) or a deliberate decision to divert from the default operation (i.e. take a turn).
3. How many options are possible when deciding for an operation (one at corners, two at T-junctions, three at X-junctions).

We can assign a weighting to each of the decisions made. For each decision option one point is collected as weighting (flag 'OD' and 'OND', see Table 4). If the decision taken is not the default operation ('DD') the weighting of this option is raised by two. If the decision taken is not forced ('DF') the weighting is again raised by two. An example: If there are three possible directions to go at an intersection (i.e. an X-junction with three options for an operations, the fourth direction is excluded as going back is not considered an option), three points are awarded. At an X-junction, the decision taken is not enforced, thus two extra points are awarded. Let's assume, that the decision taken was not the default operation (i.e. not going straight), this is two extra points. From these considerations one can build a cognitively motivated ranking of all potential turning operations at intersections and corners (excluding the non-progressive ones) and assign a total weighting to them. Table 4 sums up the result of these considerations.

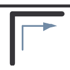
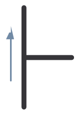
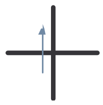
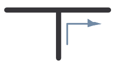
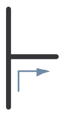
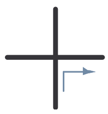
Visual Represen-tation	Propositional Representation	DF: decision is forced	DD: decision is default op.	OD: # possible default ops	OND: # possible no-default ops	Total Weight	Rank
	**Corner & Proceed**	Yes	Yes	1	0	1	1
	**T-Junction & Proceed**	No	Yes	1	1	2	2
	**X-Junction & Proceed**	No	Yes	1	2	3	3
	**T-Junction & Forced Turn**	Yes	No	0	2	4	4
	**T-Junction & Unforced Turn**	No	No	1	1	6	5
	**X-Junction & Unforced Turn**	No	No	1	2	7	6

Table 4: Ranking and weighting of different turn operation in dependency of the intersection characteristics

In the described ways, each verbal route direction given by a test person can be transformed into an abstract propositional representation, and can be given a sum total representing its matching with the propositional representation that stems from a virtual navigator going exactly that route on the original map.

Evaluation of Sketch Maps

For the analytic evaluation of the sketch maps geometric details in each sketch map, which includes imperfect hand-drawn strokes, were abstracted. The resulting abstract sketch map that include only vertical or horizontal single lines, perpendicular line crossings, and well-defined connections between these lines was analysed to gain a grade representing their resemblance with the given map.

Please continue on next page.

Abstraction of Individual Sketch Maps

The tolerance for being a straight line was 6mm discrepancy of y- respectively x-position of the stroke points. Multiple strokes that felt in these tolerances were collapsed to one line. Lines with a slant of up to 6° from horizontal or vertical orientation were corrected to horizontal respectively vertical lines. At potential T-crossings, a tolerance for over-shots of 3mm and for under-shots of 6mm in the hand-drawn sketch maps was accepted and abstracted to a valid T-crossing. Strokes that did not fit in the mentioned margins, e.g. hyperbolic strokes like round corners (i.e. between connected perpendicular lines, see Figure 8a) or diagonals (i.e. between connected co-aligned line, see Figure 8bs), were first abstracted to diagonal lines and then collapsed with the adjacent perpendicular or co-aligned lines (for a detailed visualization of this process, see Appendix C). Other hand-drawn shapes like rectangles and circles were replaced by prototypes. Thus, artifacts that were often encountered in sketches could be simplified to be ready for the analysis (for an example, see Figure 8c).

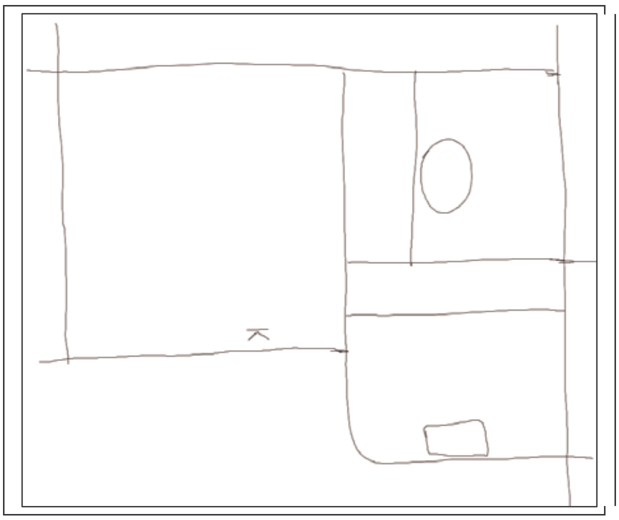


Figure 8a. This sketch map shows a hyperbolic curve in the middle lower part. In the corresponding abstract sketch map it is abstracted to a diagonal line and than collapsed with the adjacent horizontal and vertical lines to form a valid perpendicular intersection between them.

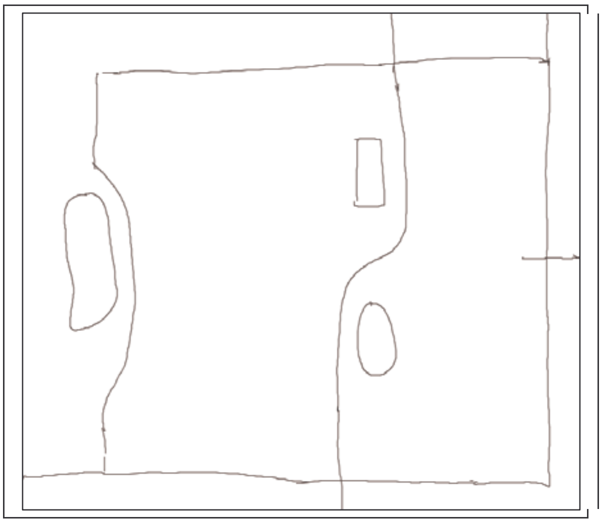


Figure 8b: A sketch map shows a diagonal line (in the center) besides the hyperbolic line at the left. The diagonal line is regarded as diagonal as its slant is not in the tolerance of 6° from horizontal or vertical orientation.

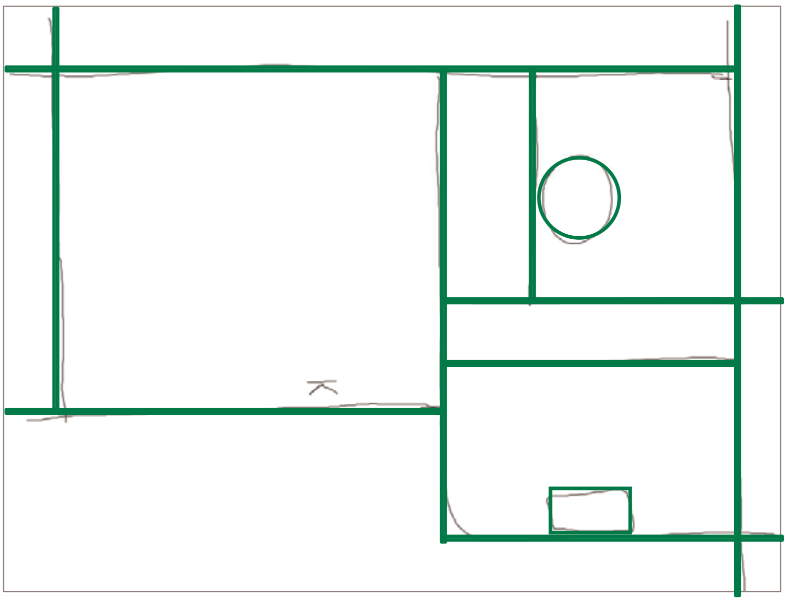


Fig. 8c: The sketch map from Figure 8a abstracted to have straight lines, distinguished intersections and prototypical geometric shapes (lines & shapes in green color).

Analysis of Abstract Sketch Maps

After the abstraction each abstract sketch map was analyzed in two ways to yield a figure for the quality of the map:

A. Two human raters subjectively and independently from each other rated how good the map resembles to the given map.

B. A matching from the abstract sketch map to the given map was applied and different weighting functions on the elements were calculated.

A. Procedure of Subjective Rating

Some common guidelines were given (see Appendix D). The raters assigned ratings according to the correctness of

– the topologic positioning of landmarks,

– the configuration of regions especially how the ones with landmarks relate to each other in the sketch compared to the map, and

– straight tracks that run through more than 2/3 of the extension of the map and that are composed from more than two segments, especially how they relate to each other and to the regions with landmarks.

Grade 1 was awarded for a perfect map that showed the landmarks and streets in correct relation to each other (let alone minor flaws in geometric details), grade 6 was given for a map if there was no resemblance with the structure of the tactile map at all. To consider the nuances between these two poles the sketch maps were compared amongst each other. Thus the grade for each map represents not only an absolute component but also a relative component to some degree.

B. Matching and Weighting Functions

For the matching of the abstract sketch maps with the given map, the characteristics of the sketch map and the given map are encoded propositionally. The directions in the maps are conventionally set according to the Up-North equivalence, i.e. up in the map corresponds to North, right corresponds to East, left corresponds to West and down corresponds to South. The problem of linearization of the spatial map into a serial description (Daniel, Carité, & Denis, 1996) is solved by imposing a horizontal and vertical order onto the (vertical respectively horizontal) lines and to make them identifiable by a unique naming convention as prerequisite for a propositional encoding. Vertical lines are denoted with a “V”, and horizontal lines with an “H”. Spatial origin for both orders is the left corner at the bottom of each map. This is somewhat unusual for maps, which mostly employ the convention of the origin being in the upper left corner, but is in line with the convention in mathematical diagrams. The result of such labeling is displayed in Figure 9.

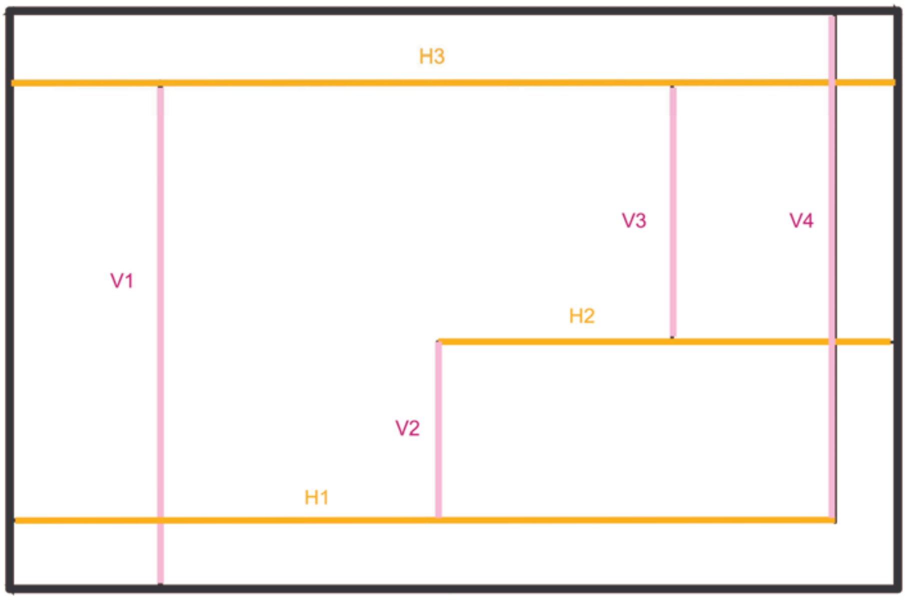


Fig. 9: Example ordering of vertical and horizontal lines and regions that are built from the assembly of lines.

Another, second ordering scheme is used to label each segment of a line. This makes it possible to propositionally not only encode whole lines but each segment of it and relations of segment amongst each other. Segments are labeled according to a scheme that is based on an ordering additional to the proposed one for whole lines (see above). To each horizontal line, a horizontal order is added and to each vertical line a vertical order is added to number the segments. The naming convention is adopted: in horizontal lines, the horizontal position of the segment is identified by a second index, separated by a dot from the first index. In vertical lines the vertical position is labeled alike. As segments are defined from the intersection with other lines, this ordering scheme applies to intersections points (labeled with “P”) as well. Regions are labeled with “R” plus two indices: the first represents the index of the horizontal line with the smallest index the region is adjacent to; the second represents the index of the vertical line with the smallest index the region is adjacent to. The result in labeling all segments, points and regions is exemplified in Figure 10.

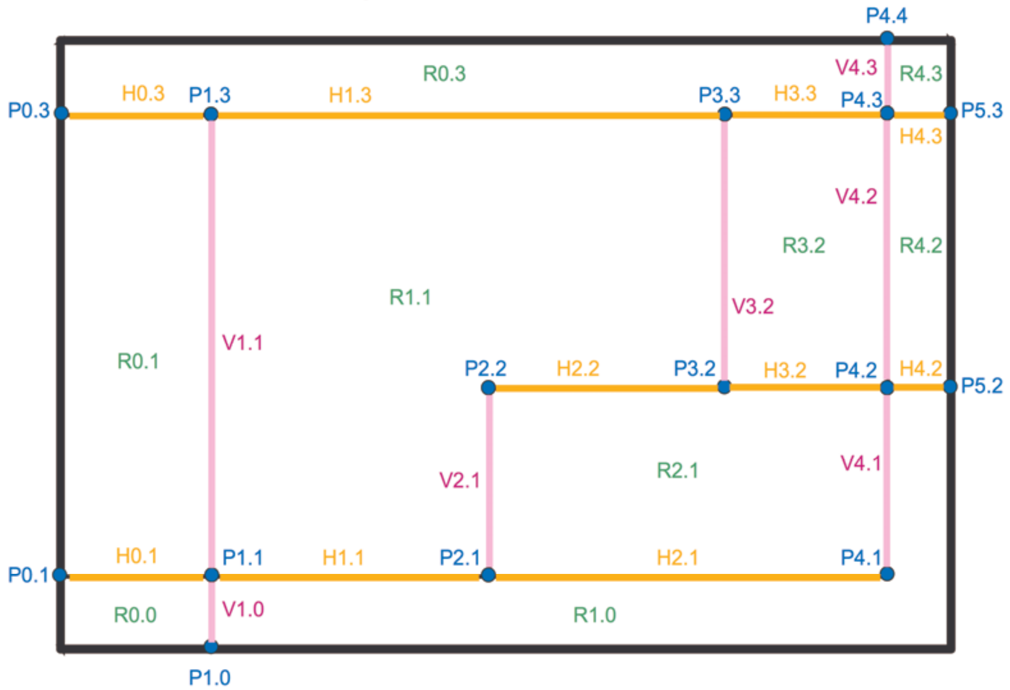


Fig. 10: Each segment of a line is labeled with a distinctive name, as well as each intersection point and the regions

In the propositional encoding of a map, topology, geometric positions of landmarks, and special characteristics of the map are taken into account. For topology, the neighborhood relation of regions was encoded, but only for those regions that have a landmark. This is due to the consideration that landmarks as premier entity for orientation and navigation will possibly play a major role in identifying and remembering certain regions and the relationship of regions. The position of a landmark is specific with respect to in which region it is contained (a topological property) and with which segment it maintains the Nearest Relation, i.e. which segment is closest (a geometric property) – see Figure 11. As special characteristic the concept of "dominant" lines was introduced, i.e. long lines that run through more than the half of the vertical or horizontal extension of the map and that have more than 2 segments. In the example map displayed in Figure 9 (and Figure 10) this would be H1 (H0.1 – H2.1), H3 (H0.3 – H4.3), and V4 (V4.1 – V4.3. This purely geometric definition of "dominant" lines could be substituted with a more cognitively orientated definition, e.g. through assessing how often a segment would be traveled if all possible routes between any two landmarks were assessed. If there would be any difference to the present work will be an open question for future work.

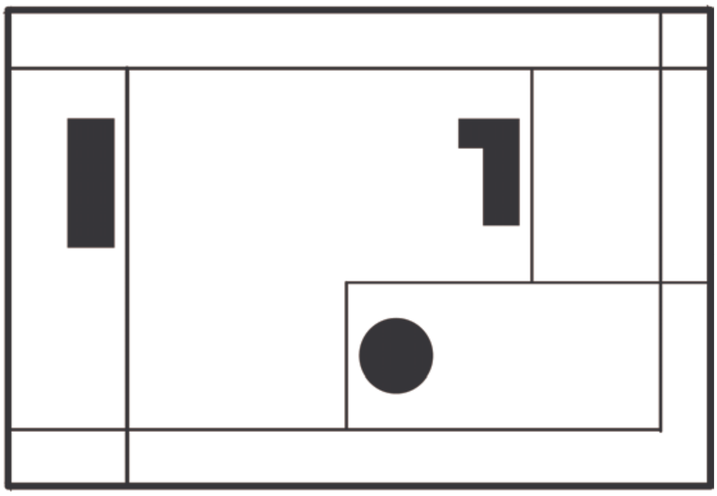


Fig. 11: An example map with landmarks, each topologically contained in one region and non-arbitrarily placed, i.e. nearer to one segment than any other segment.

The naming conventions and the ordering of elements are the prerequisite to test different ways of encoding the map propositionally. Encoding both, the template map and the sketch maps drawn by test-subjects, into a common format allows for a matching of the two, given that the encoding captures the relevant features.

Some encodings that base on the enumeration of all lines or segments and their interconnections are proposed in Appendix B. They were tested with the displayed map (see Figure 11, above) but were not found suitable for the task of separating sufficient sketch maps from insufficient ones (see the Discussion section in Appendix B). Focusing on the relation of single segments or lines to other segments or lines seems not to be suitable to capture aspects of an adequate analysis that is supposed to capture the concepts important for human cognitive processing. On the background of the investigations detailed in Appendix B and aiming for a cognitive approach to the serialization of maps I propose some concept to be included and to be structured in a certain way.

As the encoding should contain aspects of the map that are relevant to acquire survey knowledge from, which can than be used to construct routes between arbitrary locations, the concepts usually found in navigational instructions (see Denis, 1997 & 1999) are included: landmarks (in this context: the buildings & the YAH point), decision points (in this context: the intersections). I propose to build an inventory for the propositionalisation of spatial configurations in its essential characteristics as representation of survey knowledge of the displayed geographic area. The requirements for the resulting representation is that it should afford the assessment of the quality of the original material in an intermediate format (see the beginning of this Appendix).

Aside from the mentioned concepts that are essential for later route construction I propose to include some more concepts that on the one hand are targeted on the providing a survey perspective and on the other hand might make arbitrary route construction easier. The proposed candidates are:

1. the concept of Landmark Regions,
2. the concept of Neighborhood,
3. the concept of Dominant Lines,
4. the Connect-Trough Relation,
5. the Contact-Relation,
6. the Near-to Relation, and
7. the concept of Cardinal Directions.

In the following I will introduce the proposed concepts.

1. Same regions are differentiated from other in that they include a landmark. These regions will be called landmark region. From the importance of landmarks for navigation and orientation, it is assumed that humans handle these regions with a higher weight than regions without a landmark.

2. The concept of neighborhood means that regions are adjacent. That is, two regions are incident to/share the same line segment. With neighborhood one can define the structure of the region.

3. Dominant lines are those lines in an abstract sketch map or the map templates that represent long tracks in the geographic area and that are supposed to be more used in navigation than short tracks, especially for moving through large parts of the area (see page 43).

4. The Connected-Trough Relation (CTR) captures topological characteristics that focus on the structure of space between regions with landmarks. This might be of interest when constructing the route from one

landmark to the other. A first-order CTR is characterized through two regions that each shares one edge with the same third region or that have one vertex in common. In this work, only first order relations were taken into account, i.e. CRT is not transitive. Thus, the number of CTRs between two regions depends on the number of regions they both regions share at least one segment with. See Figure 12 for some examples.

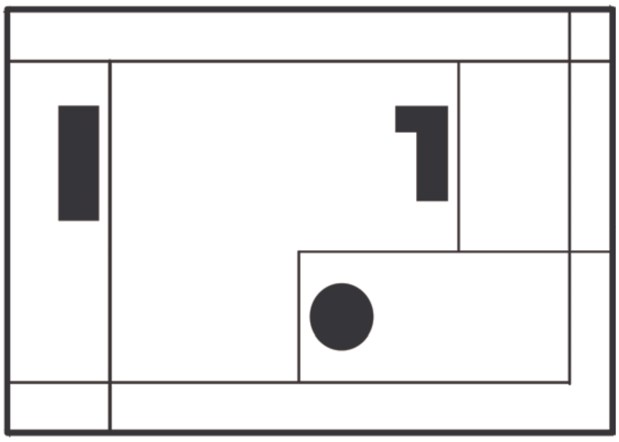
Fig. 12: Two qualitative different examples of a CTR score of 2. The regions A and B in the top example have one vertex in common but no segment. In the lower example the regions A and B have no vertex and no segment in common.

5. In this work, it was considered a special case if two regions do not share one segment but one point. This spatial configuration cannot be adequately described by the concepts so far introduced. Consider the spatial configuration in Figure 12. In both examples, the regions A and B are not neighbor (they do not have a segment in common) and they both have a CTR of 2. To distinguish such differences I introduce the ‘contact relation’ concept, i.e. when two regions share exactly one point.

6. The Near-To Relation is useful to correctly assigning landmarks to segments so that they can serve as re-orientation and decision points in navigation.

7. Cardinal directions afford the specification of the local position of a landmark near some segment without naming the segment. It also affords the specification of the global position of large-scale objects like regions or long tracks in the reference frame of the map.

Serializing one map into its propositional form is done in a top-to-bottom fashion, i.e. from survey information to more detail. Some of the content can be handled on different levels of granularity, e.g. lines with more than one segment and particularly long lines can be encoded on the global level (as one line) but also on the local level (as set of segments). This is taken into account by alternatively representing these concepts on both levels. A similar case is the representation of the amount of (represented by “#”) segments, intersections and regions. As Euler showed (an English and German translation of Euler’s original work can be found through Krömer, 2008) there is a dependency between these figures, from each two of them the third can be computed. To limit the likelihood that one fact about a map is encoded twice (and therefore will be regarded twice in the following matching, hence have unequal, double weight compared to the other) such information is marked as alternative (in light grey color). Please note that certain properties of a map are represented in different parts simultaneously. The propositional encoding of the example map (see Figure 11 above, or the following replica) can be found in Listing 1.



Listing 1: Propositional encoding of the example map, displayed above. Grey text means that the proposition is only used in the fine grained analytic schemes 2 and 4 (see the next paragraph).

Überblickswissen
Übersicht – Grobstruktur
Es gibt 3 horizontale Linien.
Es gibt 4 vertikale Linien.
Übersicht - Feinstruktur (äquivalent zu Grobstruktur)
Es gibt 2 horizontale, lange Linien.
Es gibt 1 vertikale, lange Linie.
Es gibt 1 horizontale, kurze Linien.
Es gibt 3 vertikale, kurze Linien.
Übersicht – Landmarken
Es gibt 3 Landmarken.
Die Landmarken sind in verschiedenen Regionen.

(Erweiterte) Topologie

 # Nachbarschaften der Regionen mit Landmarken
Die Region mit dem rechteckigen Gebäude ist mit 3 Regionen benachbart.

Die Region mit dem runden Gebäude ist mit 3 Regionen benachbart.
Die Region mit dem L-förmigen Gebäude ist mit 5 Regionen benachbart.

Paarweise Nachbarschaften von Regionen mit Landmarken
Die Region mit dem rechteckigen Gebäude ist mit der Region benachbart, die das runde Gebäude enthält.
Die Region mit dem rechteckigen Gebäude ist nicht mit der Region benachbart, die das runde Gebäude enthält.
Die Region mit dem L-förmigen Gebäude ist mit der Region benachbart, die das runde Gebäude enthält.

Verbunden-Über-Relation zwischen Regionen mit Landmarken
Die Region mit dem rechteckigen Gebäude und die mit dem runden Gebäude sind verbunden durch eine Region.
Die Region mit dem rechteckigen Gebäude und die mit dem L-förmigen Gebäude sind verbunden durch eine Region.
Die Region mit dem L-förmigen Gebäude und die mit dem runden Gebäude sind verbunden durch eine Region.

Berührung von Regionen als Spezialfall der Verbunden-Über-Relation

Die Region mit dem rechteckigen Gebäude berührt die Region mit dem runden Gebäude nicht.
Die Region mit dem L-förmigen Gebäude berührt die Region mit dem runden Gebäude nicht.
Die Region mit dem rechteckigen Gebäude berührt die Region mit dem YAH-Punkt nicht.

Geometrie
Lage der Landmarken
Die Region mit dem rechteckigen Gebäude befindet sich im westlichen Teil der Karte.
Das rechteckige Gebäude liegt nah am östlichen Rand der Region.
Die Region mit dem runden Gebäude befindet sich im südöstlichen Teil der Karte.
Das runde Gebäude liegt nah am westlichen Rand der Region.
Die Region mit dem L-förmigen Gebäude befindet sich im nordöstlichen Teil des Geländes.
Das L-förmige Gebäude liegt nah am östlichen Rand der Region.

Vorlagengetriebener Vergleich : Übereinstimmungen
Segmente: 40
Regionen: 13

Skizzengetriebener Vergleich : Überschuss
Segmente
Regionen

Given the propositional representation of each stimulus map and each map produced by the some test person, they can be matched. During matching, the different parts of the propositionalisation could be assigned different weights. In this way certain aspects can be accentuated or even be given a dominant role. I developed and employed four analytic schemes (plus one test scheme) that define what weight is assigned to a fit between propositions.

1 “Standard Logical Scheme”: either the proposition is correct in its whole extent (i.e. true in its logical meaning) or not. In a set of proposition that constitute the abstract propositional form of a map, each proposition is worth 1 point. Example: “There are 4 horizontal lines” is only true (i.e. worth 1 point) if there are exactly 4 lines, not more not less. If there were too few lines, the full reward would not be given but points would be deducted (one per missing line). If there were too many lines no points would be deducted as the consequences of that topologic error would have been accounted for in a different proposition. Double minus scoring should be omitted in this way.

2 “Fine Grained Logical Scheme”: This scheme is almost identical to

the first one but it is finer grained. For example, instead of just encoding how many horizontal and vertical lines there are, it might be important to distinguish if these lines are prominent one (and might be better to remember because of there potential importance) or not. Prominent lines are believed to be long ones that govern the spatial configuration.

3 “Standard Complex Scheme“: In contrast to the logical interpretation in scheme 1 and 2, propositions that capture multiple characteristics are worth more points (the scoring is intra-propositional). Example: “There are 4 horizontal lines” is worth up to 4 points. If there were too few lines, the full reward would not be given but points would be deducted (one per missing line). If there were too many lines no points would be deducted as the consequences of that topologic error would have been accounted for in a different proposition. Double minus scoring should be omitted in this way.

4 “Fine Grained Complex Scheme”: This scheme combines characteristics of scheme 2 and 3. The level of detail captured in the propositions is high (as in scheme 2) and scoring happens on the intra-propositional level, not on the logical level (like in scheme 1 and 2).

5 TEST “Only Survey Details”: As the other schemes appeared too bulky this scheme was introduced as test in condition FL. In contrast to the fine grained schemes 2 and 4 which contain other characteristics as well, this scheme only captures the very details that were introduced to check for the characteristics that are believed to capture survey knowledge, i.e. long lines and the relation of regions with landmarks.

The different characteristics of the analytic schemes (except from the test scheme) can be compared in Table 5.

		Level of Detail	
		Standard	High
roach	Whole propositional level	Standard Logical Scheme	Fine Grained Logical Scheme

	Intra- proposition level	Standard Complex Scheme	Fine Grained Complex Scheme

Table 5. Four different analytic schemes that can be displayed in a 2x2 matrix spanned by the factors Scoring Approach and Level-of-detail were used for the evaluation of each abstract sketch map.

The sum of all weights of the matching process accounts for the total matching. A figure from the total matching represents how complete a map was reproduced by the test-person: the better the reproduction, the better the figure. Through the analytic schemes it is determined which aspects are taken into account during the matching. Comparing absolute figures from different schemes is not useful, but relative comparisons or intra-scheme comparisons have meaning, as the total amount of weights between two analytic schemes can be quite different. This depends on which aspects were in focus during matching, e.g. the pure existence of all elements (Scheme 1) in contrast to the existence and embedding of single, important elements (Scheme 3) in the spatial configuration. The collection of schemes is motivated by the question what effect different aspects have on the result of the analysis, if this effect is statistically significant and if it makes sense compared to a subjective assessment that is done focused on how much of the survey information is encoded.

Appendix 6 – Study 3: Evaluations of Route Descriptions

Propositionalisierung der Wege anhand der Kartenvorlagen

Christian Graf:
Alle Aktionen sind gleichgewichtet.

Christian Graf:
- Bewertung der Kreuzungsart nach Rangfolge der kognitiven Bewertung

Christian Graf:
- Bewertung der Kreuzungsart nach Anzahl der Inzidenzen und Qualität der Weiterbewegung (keine Turnentscheidung o.Turnentscheidung, erzwungen o. Nicht erzwungene Turnentscheidung)
- implizit ist das Ankommen an einer Kreuzung, daher keine Bewertung dieses Teils)

Christian Graf:
Da die Nennung der Orientierung zum Startpunkt in einer Situation passiert, in der angenommen wurde, dass diese Orientierung gegeben sei, wird die explizite Nennung nur mit einem Punkt belohnt. Die erste Aktion ist dagegen umso wichtiger und wird wie eine essentielle Abbiegeaktion mit einem Gewicht von 4 belegt. Bei Abiegeaktionen gibt es 2 Punkte für die Selbstlokalisierung, und zwei für die Aktion. Das Nennen einer Kreuzung zur Reorientierung wird mit 2 Punkten bewertet, (sie ist nicht so wichtig wie die Turns), jeweils wieder geteilt in Lokalisierung und Aktion. Die Endlokalisierung wird mit einem Punkt bewertet, weil der virtuelle Wanderer entweder

Karte FL

Bedingung	Weg	Formalisierung	Kreuzungsart	Gewichtungsschema 1	Gewichtungsschema 2	Gewichtungsschema 3a	Gewichtungsschema 3b
YAH-R	A	BE_AT(YAH, front)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(second intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	5	1	2	5	5
		BE_AT(building, right)	4	1	1	4	4
				9	**16**	**21**	**22**
	B	BE_AT(YAH, front)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(second intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(third intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(building, left)	4	1	1	4	4
				11	**18**	**23**	**25**
	C	BE_AT(YAH, front)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(second intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(building, right)	4	1	1	4	4
				13	**24**	**32**	**35**
K-R	A	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	5	1	2	5	5
		BE_AT(goal building, right)	4	1	1	4	4
				9	**18**	**24**	**25**
	B	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(next intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(goal building, left)	4	1	1	4	4
				11	**20**	**26**	**28**
R-K	A	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(goal building, left)	4	1	1	4	4
				9	**18**	**22**	**23**
	B	BE_AT(start building, behind)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	5	1	2	5	5
		BE_AT(intersection)		1	1	0	0
		*GO(straight)	2	1	1	2	3
		BE_AT(second intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(goal building, right)	4	1	1	4	4
				11	**20**	**25**	**27**
	C	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(straight)	3	1	2	3	4
		BE_AT(building, right)	4	1	1	4	4
				11	**22**	**26**	**28**

Karte RM

Bedingung	Weg	Formalisierung	Art der Kreuzun	Gewichtungss	Gewichtungss	Gewichtungss	Gewichtungsschema 3
YAH-K	A	BE_AT(YAH, front)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	3	1	2	3	4
		BE_AT(building, right)	4	1	1	4	4
				9	**18**	**22**	**24**
	B	BE_AT(YAH, front)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	2	1	1	2	3
		BE_AT(second intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(building, left)	4	1	1	4	4
				11	**20**	**26**	**28**
YAH-R	A	BE_AT(YAH, front)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	1	1	2	1	2
		BE_AT(building, left)	4	1	1	4	4
				7	**14**	**15**	**17**
K-R	A	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	4	1	2	4	4
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(second intersection)		1	2	0	0
		*GO(left)	1	1	2	1	2
		BE_AT(goal building, left)	4	1	1	4	4
				11	**20**	**20**	**22**
	B	BE_AT(start building, behind)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	4	1	2	4	4
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(second intersection)		1	2	0	0
		*GO(straight)	2	1	2	2	3
		BE_AT(third intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(goal building, right)	4	1	1	4	4
				13	**24**	**27**	**30**
	C	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	4	1	2	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	2	1	1	2	3
		BE_AT(second intersection)		1	2	0	0
		*GO(right)	6	1	2	6	7
		BE_AT(goal building, right)	4	1	1	4	4
				11	**20**	**26**	**29**
R-K	A	BE_AT(start building, behind)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	1	1	2	1	2
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	3	1	1	3	4
		BE_AT(second intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	5	1	2	5	5
		BE_AT(goal building, right)	4	1	1	4	4
				11	**20**	**22**	**24**
	C	BE_AT(start building, behind)		1	1	0	0
		*GO(left)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(first intersection)		1	1	0	0
		*GO(straight)	2	1	1	2	3
		BE_AT(second intersection)		1	2	0	0
		*GO(left)	6	1	2	6	7
		BE_AT(next intersection)		1	2	0	0
		*GO(right)	5	1	2	5	5
		BE_AT(goal building, right)	4	1	1	4	4
				11	**20**	**27**	**30**

Karte GI

Bedingung	Weg	Formalisierung	Art der Kreuzun	Gewichtungss	Gewichtungss	Gewichtungss	Gewichtungsschema 3
YAH-R	A	BE_AT(YAH, front)		1	1	0	0
		*GO(right)	4	1	4	4	4
		BE_AT(next intersection)		1	2	0	0

		*GO(left)		4	1	2	4	4
		BE_AT(next intersection)			1	2	0	0
		*GO(right)		6	1	2	6	7
		BE_AT(building, left)		4	1	1	4	4
					7	**14**	**18**	**19**
YAH-K	A	BE_AT(YAH, front)			1	1	0	0
		*GO(left)		4	1	4	4	4
		BE_AT(next intersection)			1	2	5	5
		*GO(left)		5	1	2	0	0
		BE_AT(building, left)		4	1	1	4	4
					5	**10**	**13**	**13**
K-R	A	BE_AT(start building, behind)			1	1	0	0
		*GO(right)		4	1	4	4	4
		BE_AT(next intersection)			1	2	0	0
		*GO(right)		4	1	2	4	4
		BE_AT(next intersection)			1	2	0	0
		*GO(left)		4	1	2	4	4
		BE_AT(next intersection)			1	2	0	0
		*GO(right)		6	1	2	6	7
		BE_AT(goal building, left)		4	1	1	4	4
					9	**18**	**22**	**23**
R-K	A	BE_AT(start building, behind)			1	1	0	0
		*GO(right)		4	1	4	4	4
		BE_AT(next intersection)			1	2	0	0
		*GO(left)		6	1	2	6	7
		BE_AT(next intersection)			1	2	0	0
		*GO(right)		5	1	2	5	5
		BE_AT(next intersection)			1	2	0	0
		*GO(left)		5	1	2	5	5
		BE_AT(goal building, left)		4	1	1	4	4
					9	**18**	**24**	**25**

Appendix 7 – Study 3: Materials Used in the Schematisation Studies

Universität Bremen
cognitivesystems
I2-[MapSpace]
Universität Bremen
Fachbereich 3 Informatik, Cognitive Systems
SFB/TR 8 Spatial Cognition
Project I2 – [MapSpace]

Deckblatt zum Experiment No. ____

Datum: ___.___.___

Beginn des Experiments: ___:___

Angaben zum Probanden

1. Ruf- & Familienname: _______________
2. Geschlecht: m / w
3. Alter: _______________
4. Probanden-Code: _____________ (1.Buchstabe des Rufnamens + 1. Buchstabe des Familiennamens + zweistellige Summe der letzten zwei Ziffern des Geburtsjahres)

Notizen:

____

____

____

____

____

____

____

____

☐ Vorzeitiger Abbruch wegen ____

Ende des Experiments: ___:___

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Version 2.0 – 10.12.2011

MAPS4VIPS

Herzlich willkommen!

Schön, dass Sie interessiert sind, an meiner Studie teilzunehmen. Hier erfahren Sie, um was es geht und was Sie erwarten können.

Ihr Christian Graf

Allgemeine Informationen zur Studie

Ziele der Studie

Das übergeordnete Ziel unserer Studie besteht in in der Entwicklung von Verfahren zur systematischen, durch Computer unterstützte Konzeption von taktilen Überblickskarten. Über das Ertasten dieser Karten sollen sich Kartenleser z.B. den Überblick über eine unbekannte Stadt verschaffen können.

Allgemeine Informationen zur Teilnahme

Der Kern der Studie ist die Erforschung der Interpretation von Tastwahrnehmung. Ihre Teilnahme ist freiwillig und kann von Ihnen jederzeit auch ohne Angabe von Gründen widerrufen werden, ohne dass Ihnen irgendwelche Nachteile entstehen.

Alle eingesetzten Verfahren sind ungefährlich und werden regelmäßig in der Forschung eingesetzt. Es entstehen Ihnen durch die Studienteilnahme keinerlei Kosten. Im Gegenteil, für Ihre Teilnahme erhalten Sie eine Aufwandsentschädigung in Höhe von 7€ pro Stunde.

Zu einem späteren Zeitpunkt wird es gegebenenfalls eine Folgestudie geben. Sollten Sie an einer nochmaligen Ansprache interessiert sein, können Sie das auf der Einverständniserklärung vermerken. Wir werden uns dann gegebenenfalls bei Ihnen melden.

Bitte umblättern und auf Seite 2 weiterlesen!

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zur Person: http://cosy.informatik.uni-bremen.de/staff/christian-graf

Inhalt und Ablauf des Studie

Sofern Sie mit der Teilnahme einverstanden sind und die Einverständniserklärung unterschrieben haben, werden einige Angaben zu Ihrer Person per Fragebogen erhoben. Zunächst werden Sie Gelegenheit haben, in einem kurzen Training die Art des Materials kennen zu lernen, das mit einem Sensibilitätstest endet. Im Anschluss daran beginnt der eigentliche Studiendurchlauf, wobei jeder Teilschritt erklärt und durch mich begleitet wird. Es geht bei dieser Studie nicht um Ihre individuelle Leistung, sondern darum, wie gut das Ihnen vorgelegte Material ist. Daher hat es keinen Sinn, „besser" als irgendjemand sein zu wollen.

Sollten die Ihnen vorgelegten Informationen oder Instruktionen nicht verständlich sein, oder wenn Sie weitergehende Erläuterungen brauchen, wenden Sie sich bitte vertrauensvoll an die Versuchsleitung.

Die Studie findet normalerweise im Blinden- und Sehbehindertenverein Hamburg (BSVH) statt. Bei Bedarf und nach Absprache sind auch andere Orte möglich. Ein Durchlauf dauert bis zu 90 Minuten.

Datenverarbeitung und Datenschutz

Die Vorschriften über die Schweigepflicht der Versuchsleitung und des Projektpersonals sowie über den Datenschutz werden im Rahmen dieser Studie eingehalten. Dritte erhalten keinen Einblick in Originalunterlagen. Es werden zum Zwecke der statistischen Datenanalyse nur anonymisierte Daten auf Fragebögen und auf elektronischen Datenträgern ohne Namensnennung erhoben.

Ihre anonymisierten Daten und Angaben werden zum Zweck der wissenschaftlichen Auswertung ausschließlich innerhalb des Sonderforschungsbereichs 8 weitergegeben oder an zu Rate gezogene Wissenschaftler weitergegeben. Im Falle von Veröffentlichungen der Studienergebnisse bleibt die Vertraulichkeit Ihrer persönlichen Daten ebenfalls gewährleistet.

Die Beachtung des Bundesdatenschutzgesetzes ist in vollem Umfange sichergestellt.

Aufwandsentschädigung

Für die Teilnahme an einer Studiensitzung können Sie bei Bedarf 7€/Stunde erhalten.

Vielen Dank für Ihr Interesse

Christian Graf

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Einverständniserklärung

Voller Name des Teilnehmenden: ________________________________ (bitte in Druckbuchstaben)

Die unten genannte Studienleitung hat mich über Art, Umfang und Bedeutung dieser Studie aufgeklärt. In diesem Zusammenhang bestehende Fragen wurden besprochen und beantwortet.

Die schriftliche Probandeninformation (Dokument “Allgemeine Informationen zur Studie”) mit den Erklärung zu Datenverarbeitung und Datenschutz habe ich erhalten, gelesen und verstanden. Mit dem in der Probandeninformation beschriebenem Vorgehen bin ich einverstanden.

Ich bin bereit, freiwillig unter den genannten Bedingungen an der Studie teilzunehmen. Ich hatte ausreichend Zeit, mich für oder gegen eine Teilnahme zu entscheiden. Meine Einwilligung zur Teilnahme an dieser Studie kann ich jederzeit ohne Angabe von Gründen und ohne persönlichen Nachteil widerrufen. Auch die Studienleitung kann meine Teilnahme jederzeit beenden.

Mir ist bekannt, dass diese Studie in erster Linie der Wissenserweiterung dient und gegebenenfalls keinen persönlichen Vorteil für mich bringen kann.

Ich möchte über Folgeexperimente informiert werden, falls ich nachfolgend meine E-Mailadresse angegeben habe:

____

________________________ ________________________

Ort, Datum — Unterschrift Teilnehmer/-in

Von Studienleitung auszufüllen:

Persönlicher Promanden-Code: __________ ________________________

Unterschrift Studienleiter/-in

Eigenauskunft Proband ____

1. Bitte geben Sie Ihr Sehvermögen an! Etwaige Fehlsichtigkeit, die mit Brille oder Linsen korrigiert wurden, müssen nicht angegeben werden.
   - ○ keine Einschränkung des Sehens (100% Sehrest)
   - ○ keine visuelle Empfindung (0% Sehrest)
   - ○ Sehrest (bitte in Prozent angeben, wenn bekannt, UND die Art des Sehrests, etwa "nur Hell-Dunkel Unterschiede" oder "Konturen großer Gegenstände auf 3m" oder "zentrales Scharfsehen auf 10cm"): ____
2. Verlauf der Sehfähigkeit, wenn heute Einschränkungen vorliegen
   - ○ geburtsblind
   - ○ erblindet mit Jahren: ______
3. Ist die Beweglichkeit oder Kontrolle Ihrer Arme, Hände oder Finger durch aktuelle oder vergangene Vorkommnisse eingeschränkt (z.B. durch Medikamenteneinnahme, Verletzungen, Nervenbahnschädigungen, Viruserkrankungen, zentrale Schädigungen etc.)?
   - ○ nein / ja : ___________________________________
4. Ist Ihr heutiges Tastvermögen durch aktuelle oder vergangene Vorkommnisse eingeschränkt?
   - ○ nein / ja : ___________________________________
5. Haben Sie jetzt gerade kalte, taube oder überempfindliche Fingern?
   - ○ nein / ja : ___________________________________
6. Können Sie Brailleschrift lesen? ○ ja ○ nein
   1. Wenn Ja: Als wie erfahren würden Sie sich beim Lesen von Braille einschätzen?

      Sehr ---------- Mittel ------------ Gar nicht

      Jahre des Gebrauchs von Braille: ___________

2. Wenn Nein: Haben Sie schon jemals vorher Ihren Tastsinn aktiv oder über längere Zeit genutzt, um damit spezifische Aufgaben zu lösen?

   ○ nein / ja : ________________________________

7. Bitte schätzen Sie sich selbst bzgl. Ihrer Nutzung von (Stadt-)Karten oder Übersichtsplänen ein:

   a) Benutzen Sie aktuell irgendwelche Karten und wenn ja, wofür und wie oft?

   b) Wieviel Erfahrung mit Karten konnten Sie in der Vergangenheit sammeln?

   c) Wie erfolgreich schätzen Sie sich in der Orientierung mittels Karten ein, um unbekanntes Terrain kennenzulernen?

Universität Bremen
Fachbereich 3 Informatik, Cognitive Systems

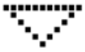
SFB/TR 8 Spatial Cognition
Project I2 – [MapSpace]

Legende zur Karte

Straße

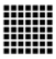

Hauptstraße


Eigener Standort


Zeitungskiosk

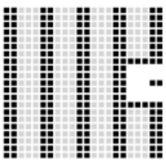

Frisör


Supermarkt

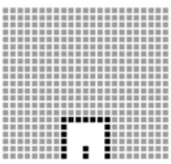


Kaufmannsladen

Park



Sportplatz



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Version 2.0 – 10.12.2011

Endbefragung Proband ____

1. Sie haben drei taktile Orientierungskarten abgetastet, die mit der gleichen Anzahl und Art von Objekten (je eine Standortmarke, Haupt- und Nebenstraßen und 6 Gebäude) gefüllt waren.

   Bitte schätzen Sie ein, wie sehr sich die Karten in ihrer Struktur, d.h. der Anordnung von Wegen und Landmarken, ähnelten. Geben Sie bitte danach an, wie sicher Sie sich in Ihrer Einschätzung sind.

   0 (Keine Ähnlichkeit)
   1 (sehr wenig Ähnlichkeit)
   2 (wenig Ähnlichkeit)
   3 (einige Ähnlichkeit)
   4 (viel Ähnlichkeit)
   5 (sehr viel Ähnlichkeit)
   6 (Identisch)

   Auf einer Prozentskala (0% „gar nicht“ bis 100% „absolut“) ausgedrückt, bin ich mir in meiner Einschätzung sicher zu: %

2. Die drei Karten unterschieden sich unter anderem auch in der Ausgestaltung der Wege. In der einen waren die Wege geschwungen, in der zweiten begradigt und in der dritten auf die Himmelsrichtungen abstrahiert.

   a. Welche der Macharten fanden Sie am besten? :
   b. Welche am schlechtesten? :

3. Jede der Karten sollte dazu dienen, Ihnen einen Überblick über ein Ihnen unbekanntes Gelände zu verschaffen, mit dem Ziel Ihnen die spätere Orientierung und Navigation im Gelände selbst zu erleichtern.

   a. Würden Sie Karten dieser Art benutzen, um die Orientierung in einem Gelände zu erleichtern?

   b. Würden Sie Karten dieser Art weiterempfehlen und aus welchem Grund? c. Und wenn ja, wem insbesondere?

4. Was könnte verbessert werden?

5. *Sonstige Bemerkungen:*

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Protokoll Proband ____

A. Sensibilitätstraining & -test

Startzeit ______

1. Einfache Linien: Unterscheidung 1Taxel vs. 3Taxel Linien — OK?
   a. gerade & achsenparallel ☐
   b. gerade & nicht achsenparallel ☐
   c. geschwungen ☐
2. Linienkreuzungen: Erkennung von je zwei Kreuzungsformen
   a. gerade & achsenparallel: 1 Taxel Linien ☐☐
   b. gerade & achsenparallel: 3 Taxel Linien ☐☐
   c. gerade & achsenparallel: 1+3 Taxel Linien ☐☐
   d. gerade & nicht achsenparallel: 1 Taxel Linien ☐☐
   e. gerade & nicht achsenparallel: 3 Taxel Linien ☐☐
   f. gerade & nicht achsenparallel: 1+3 Taxel Linien ☐☐
   g. geschwungen: 1 Taxel Linien ☐☐
   h. geschwungen: 3 Taxel Linien ☐☐
   i. geschwungen: 1+3 Taxel Linien ☐☐
3. Vielecke: Erkennung der Form, Kontur und Füllung
   a. Dreieck: Kontur 1 Taxel, Fläche 30% schwarz ☐☐☐
   b. Rechteck: Kontur 3 Taxel, Fläche 70% schwarz ☐☐☐
   c. Viereck: Kontur 3 Taxel, Fläche 30% schwarz ☐☐☐
   d. Vieleck: Kontur 1 Taxel, Fläche 70% schwarz ☐☐☐
4. Symbole: Erkennung von 4 Symbolen ☐☐☐☐

Endzeit ______

Punktzahl: _______

TESTERGEBNIS: ☹ 😐 ☺

(☹ Ungenügend: < 25 Punkte, 😐 Nachtraining: 25-32 Punkte, ☺ Genügend: > 32 Punkte)

B. Kartenexploration & Befragung

0. Kartenlegende ______________________ Start ______ Ende ______

1a. Exploration 1. Karte _________________ Start ______ Ende ______

1b. Skizze o. Fragebogen ________________ Start ______ Ende ______

2a. Exploration 2. Karte __________________ Start ______ Ende ______

2b. Skizze o. Fragebogen ________________ Start ______ Ende ______

3a. Exploration 3. Karte _________________ Start ______ Ende ______

3b. Skizze o. Fragebogen _______________ Start ______ Ende ______

C. Endbefragung Start ______ Ende ______

Notizen:

____

____

____

____

Ende ______

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Appendix 8 – Digital Production Methods for Physical Tactile Media

Laser & Water Cutting : As laser cutters are extremely bulky hardware and need high voltage, home use is not intended.

Computerized Numerical Control (CNC) Milling : CNC milling is a subtractive method. In contrast to laser or water cutting, mechanical tools are used to excavate portions of material from a solid block. In such way the surface can be shaped. CNC milling is widely used in the mechanical industry to make first physical prototypes of newly developed parts (*rapid prototyping*). CNC machines are expensive, heavy and intended for industrial use (see Figure .18). They can be operated only by trained personal that usually has obtained a certification of aptitude for a particular machine model.

Figure .18.: A CNC milling machine © Gildemeister Aktiengesellschaft, Wikimedia Commons, licensed under Creative Commons License BY-SA 3.0, URL: http://commons.wikimedia.org/wiki/File:Dmu80p_Formfr%C3%A4sen.jpg

Stereolithography : Stereolithography is an additive methods. A bath of liquid polymers is penetrated by a precisely controlled UV light beam that turns the liquid into solid material. Portion by portion one layer is build up by targeting all positions that need to have solid material. After a layer is finished the just build model is lowered a bit and a new layer can be build on top of the existing one. Iteratively the desired 3d form comes into existence (see Figure .19). Machines for stereolithography are expensive, heavy and intended for industrial use.

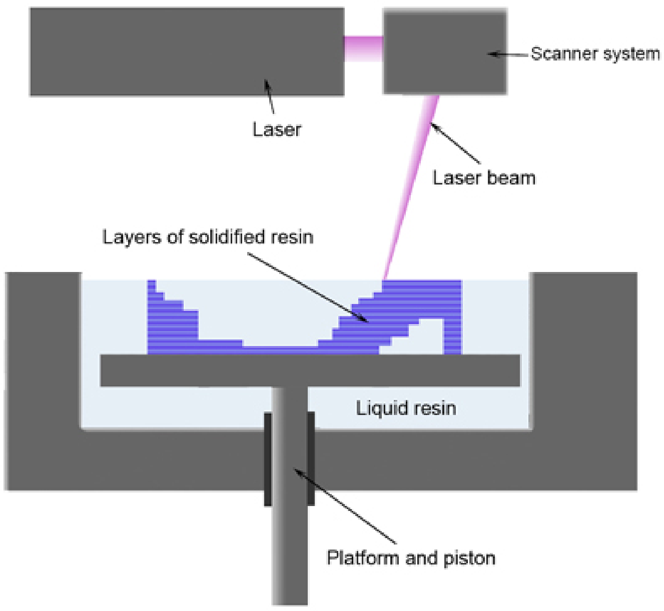

Figure .19.: Schematic illustration of a stereolithography apparatus © Materialgeeza, Wikimedia Commons, licensed under Creative Commons License BY-SA 3.0, URL: `http://commons.wikimedia.org/wiki/File:Stereolithography_apparatus.jpg`

Selective Laser Sintering (SLS) : Selective laser sintering is an additive method. Similar to stereolithography, a laser iteratively builds up the piece by sintering thin layers of material on top of each other. First, a powder of the material (often metal) is spread. Then a laser targets the position where the solid should be which causes the powder to fuse with the other material at that position. This is done for all positions that should become solid in that layer. Then the model is lowered a bit, new powder spread and the laser sinters the next layer, fusing it with the previous one (see Figure .20). Today, laser sinters are extremely expensive, heavy and not suitable for home use, quite similar to CNC machines. But developments for machines for home-use are underway[3] and it might not be long to have this high-quality process be running at private homes.

[3]see article (in German) "Pulver-3D-Drucker für daheim" (Available online at `http://www.heise.de/`

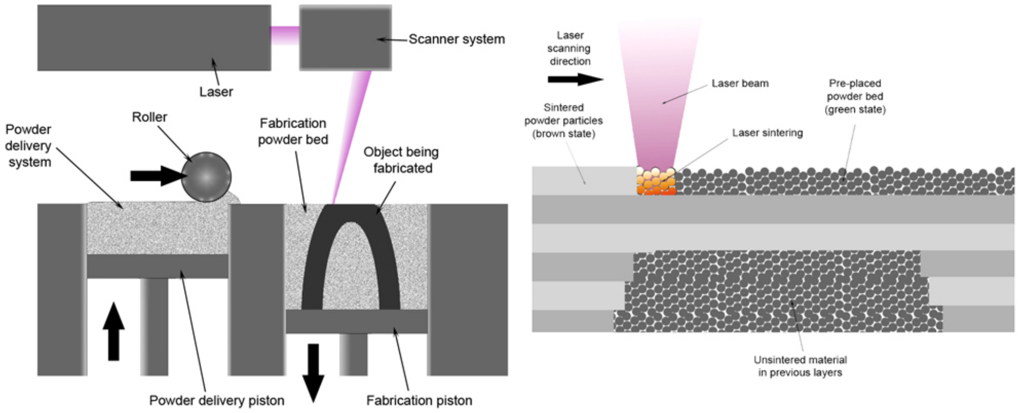

Figure .20.: Schematic illustration of a SLS system © Materialgeeza, Wikimedia Commons, licensed under Creative Commons License BY-SA 3.0, URL: http://commons.wikimedia.org/wiki/File:Selective_laser_melting_system_schematic.jpg

Extrusion : Extrusion is an additive approach and means that some 2d form is repeatedly sdrawn in one direction such that it becomes 3d. With some printers, the 2d form can be changed during the extrusion process which causes the printout having different levels. Printouts usually have a base plate and are made from plastic. One printer is the 'GraphTact'[4]. With this machine, three levels of two-dimensional shapes can be created. Home use is not possible as production is only through contract with the company Braille Jymico.

Fused Deposition Modelling (FDM) : FDM is an additive approach. The technological production process behind FDM is similar to that of an ink-jet printer. Instead of ink a polymer substance is deposited and instead of applying the ink at one level to the base material the polymer is applied in multiple levels - one level on top of the other. The polymer is a thermoplast, often an ABS (Acrylonitrile Butadiene Styrene) plastic: soft when heated and hard when cooled off (see Figure .21).

newsticker/meldung/Pulver-3D-Drucker-fuer-daheim-1660668.html, last accessed August 08, 2012)

[4]Graphtact is a trademark of Braille Jymico.

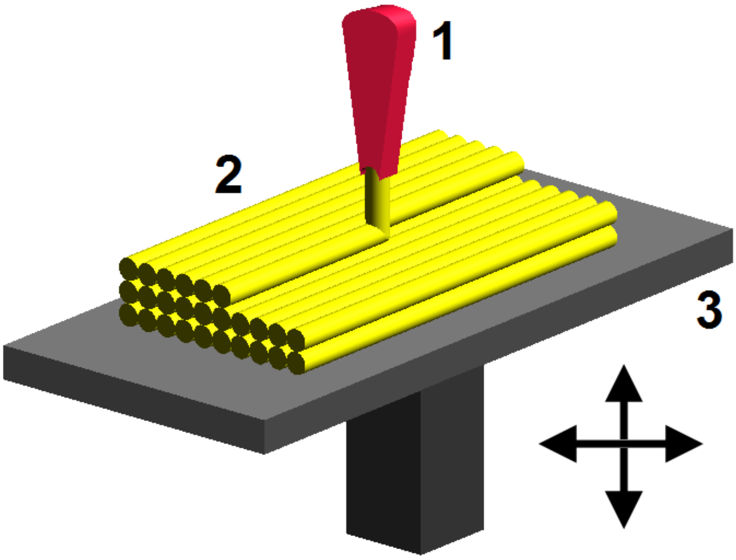

Figure .21.: Fused deposition modelling (FDM), a method of rapid prototyping: 1 - nozzle ejecting molten material (plastic), 2 - deposited material (modelled part), 3 - controlled movable table. © Zureks, Wikimedia Commons, licensed under Creative Commons License BY-SA 3.0, URL: `http://commons.wikimedia.org/wiki/File:FDM_by_Zureks.png`