COGNITIVE PRINCIPLES OF SCHEMATISATION FOR WAYFINDING ASSISTANCE

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Dissertation

zur Erlangung des Grades
eines Doktors der Ingenieurwissenschaften
— Dr. Ing. —

Fachbereich 3 (Mathematik und Informatik)
Universität Bremen

Februar 2012

ZUSAMMENFASSUNG

Damit Menschen ihren Weg auch in unbekannten Umgebungen erfolgreich finden, existiert heute eine Vielzahl unterschiedlicher Wegfindungsassistenzsysteme, die darauf abzielen, die benötigten Informationen zur Wegfindung adäquat darzustellen. Einige dieser Assistenzsysteme bedienen sich hierbei wissenschaftlichen Erkenntnisse der Kognitionswissenschaft, um kognitiv-ergonomische Ansätze zu entwickeln und zu designen. Diese Ansätze versuchen, Assistenzsysteme zu entwickeln, mit denen der Benutzer mühelos interagieren und auf eine natürliche Art und Weise diese Informationen aufnehmen kann.

Hierzu ist es notwendig zu wissen, welche Informationen genau der Benutzer benötigt, um eine bestimmte Wegfindungsaufgabe zu lösen und zudem zu untersuchen wie diese Information vom Wegsuchenden verarbeitet und konzeptualisiert wird, um sie in der Assistenzsituation adäquat zu präsentieren.

Kognitiv-motivierte schematische Karten sind ein Beispiel für diese Herangehensweise, welche die relevante Wegfindungsinformation hervorheben und diese auf eine leichtverständliche Art repräsentieren.

In meiner Doktorarbeit stelle ich einen Transferansatz vor, um dieses fundierte Wissen über Schematisierungstechniken von einer Externalisierung, wie eine Karte, zu einer anderen Externalisierung, wie eine virtuelle Umgebung, nutzen zu können.

Zu diesem Zwecke wird eine Analyse des Informationsbedarfs der Wegfindungsaufgabe *Routen folgen* anhand von einer funktionalen Dekomposition durchgeführt sowie eine Inspektion unter repräsentationstheoretischen Gesichtspunkten für Karten und virtuelle Umgebungen vorgenommen.

Aufgrund der Resultate dieser Analysen werden Richtlinien zum generellen Transfer von Schematisierungsprinzipien zwischen unterschiedlichen Repräsentationstypen aufgestellt.

Anhand von einem exemplarischer Transfer der Schematisierungstechnik *Wegfindungschoreme*, entwickelt für eine Kartenexternalisierung, integriert in ein virtuelles Stadtmodell, werden die theoretischen Voraussetzung genau ausgeführt und gezeigt, dass ein erfolgreicher Transfer möglich ist. *Wegfindungschoreme* sind abstrakte mentale Konzepte von Abbiegesituationen, welche man auch graphisch externalisieren und zur Kartenschematisierung einsetzen kann. Sie betonen die korrekte Abbiegeaktion an Kreuzungen entlang einer Route, indem sie die genaue Winkeldarstellung an einer Kreuzung durch einen Prototypen von einem Winkel von 45° oder

90° ersetzen. Durch die Unterstützung des Abgleichs zwischen der externen und der mentalen Repräsentation wird die Wegfindungsleistung durch den Gebrauch dieser Schematisierungstechnik erhöht.

In dieser Arbeit integriere ich das Konzept der *Wegfindungschoreme* in eine Repräsentation einer virtuellen Stadt und teste, ob diese transferierte Schematisierungstechnik auch eine positive Auswirkung auf die Leistung des Wegfindenden hat.

Die im Rahmen dieser Arbeit durchgeführten empirischen Studien zeigen deutlich, dass der Transfer der Schematisierungstechnik erfolgreich ist. Abhängig von der Komplexität der gegebenen Route zeigen die eingebetteten *Wegfindungschoreme* eine Verbesserung der Wegfindungsleistung von Versuchsteilnehmern, die einer Route aus der Erinnerung heraus folgen sollten. Diejenigen Versuchspersonen, die in einer schematisierten virtuellen Stadt trainiert und getestet wurden, waren signifikant besser als die anderen Teilnehmer in einer nicht modifizierten Welt.

Diese Doktorarbeit ist ein Beispiel des engen Entwicklungskreises zwischen kognitiver Verhaltensforschung und repräsentationstheoretischen Analysen hin zur Entwicklung von Assistenzsystem und der Evaluation und möglichen Rückschlüsse wieder für die kognitive Verhaltensforschung

Damit leistet diese Arbeit einen Beitrag in der interdisziplinären Betrachtung des Zusammenspiels von Umgebungsfaktoren und mentalen Prozessen anhand des Beispiels von Winkelinformationen und deren mentalen Weiterverarbeitung und Deformierung dieser Information.

ABSTRACT

People often need assistance to successfully perform wayfinding tasks in unfamiliar environments. Nowadays, a huge variety of wayfinding assistance systems exist. All these systems intend to present the needed information for a certain wayfinding situation in an adequate presentation.

Some wayfinding assistance systems utilise findings for the field of cognitive sciences to develop and design cognitive ergonomic approaches. These approaches aim to be systems with which the users can effortless interact with and which present needed information in a way the user can acquire the information naturally.

Therefore it is necessary to determinate the information needs of the user in a certain wayfinding task and to investigate how this information is processed and conceptualised by the wayfinder to be able to present it adequately.

Cognitive motivated schematic maps are an example which employ this knowledge and emphasise relevant information and present it in an easily readable way.

In my thesis I present a transfer approach to reuse the knowledge of well-grounded knowledge of schematisation techniques from one externalisation such as map to another externalisation such as virtual environment.

A analysis of the informational need of the specific wayfinding task *route following* is done one the hand of a functional decomposition as well as a deep analysis of representation-theoretic consideration of the external representations maps and virtual environments.

Concluding from these results, guidelines for transferring schematisation principles between different representation types are proposed.

Specifically, this thesis chose the exemplary transfer of the schematisation technique *wayfinding choremes* from a map presentation into a virtual environment to present the theoretic requirements for a successful transfer. *Wayfinding choremes* are abstract mental concepts of turning action which are accessible as graphical externalisation integrated into route maps. These *wayfinding choremes* maps emphasis the turning action along the route by displaying the angular information as prototypes of 45° or 90°. This schematisation technique enhances wayfinding performance by supporting the matching processes between the map representation and the internal mental representation of the user.

I embed the concept of *wayfinding choremes* into a virtual environment and present a study to test if the transferred schematisation technique also enhances the wayfinding performance.

The empirical investigations present a successful transfer of the concept of the *wayfinding choremes*. Depending on the complexity of the route the embedded schematisation enhance the wayfinding performance of participants who try to follow a route from memory. Participants who are trained and recall the route in a schematised virtual environment make fewer errors than the participants of the unmodified virtual world.

This thesis sets an example of the close research circle of cognitive behavioural studies to representation-theoretical considerations to applications of wayfinding assistance and their evaluations back to new conclusions in cognitive science.

It contributes an interdisciplinary comprehensive inspection of the interplay of environmental factors and mental processes on the example of angular information and mental distortion of this information.

"Twenty years from now you will be more disappointed by the things you didn't do than by the ones you did do. So throw off the bowlines, sail away from the safe harbor. Catch the trade winds in your sails. Explore. Dream. Discover."

—Mark Twain—

ACKNOWLEDGMENTS

Writing a thesis is like a journey. You cannot plan everything and everything will come a little bit different than you expected. This journey brings with it excitement, pleasure and happiness but also times of disorientation and struggles. Nothing is than as great as to have friends and family supporting you.

At this point I like to express my gratitude to several people who help and support me during my thesis journey.

First of all, I like to thank Christian Freksa, my supervisor, for his advice, encouragement, and support. He creates an open-minded and interdisciplinary research environment with an inspiring and productive atmosphere, which I enjoyed so much. Thanks for the advantageous discussions, which make me look at me work from a different perspective and open up my mind.

Furthermore, I thank Stephen C. Hirtle for being my second supervisor of my thesis.

I extend my special gratitude to Kai-Florian Richter for all our beneficial and inspiring discussions and collaborations. With all his help, fruitful critic and inspiring ideas he keep my on the track and constantly pushing me forward so that I success this task. Thank you so much.

Working interdisciplinary is a demanding task and only possible being surrounding by collaborative researchers like Christoph Hölscher, Simon Büchner, Martin Brösamle, Jana Holsanova, Thora Tenbrink, Holger Schultheis and Thorsten Kluß. Thanks for all support in all my psychological questions. Their discussions and feedback help me a lot in designing the study and evaluate it.

Particularly I thank my colleagues Tassilo Glander, Matthias Trapp and Jürgen Döllner from Computer Graphics Systems Group of the Hasso-Plattner Institute of Potsdam. Without our cooperation work, many of my ideas could not get realised and they tremendously helpful in setting up the virtual environment.

I notable enjoyed working with my colleagues of Cognitive Systems group who bear with me talking about the same things over and over again and who gave me valuable feedback especially Diedrich Wolter, Lutz Frommberger and Julia Gantenberg as well in technical matters as in all research questions. Also I like to thank Thomas Barkowsky who coaching me in the writing phase of my thesis. Stephanie Kuhn took care that my English is readable in many chapters of my thesis.

For the financial support of the I2-[MapSpace] project of the Transregional Collaborative Research Centre SBF/TR 8 Spatial Cognition within which this work was carried out, I thank the German Research Foundation (DFG).

My heartfelt gratitude to my family for endured all my curiosity and trying hardly answering all my questions when I was little and loving support throughout all the past years.

Most importantly, I thank Tino who I owe so much for all his support and belief in me during the last years. I am deeply grateful for all his patience discussing my work, spending time and effort helping my success in this thesis. I dedicate my thesis to him.

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1 INTRODUCTION

> ”Few things are as fundamental to human experience as the interaction between humans and their environments—be it physical or virtual.”
> [Darken et al., 1999, p. iii]

In unfamiliar environments like a new city, wayfinding is a demanding task. A classical example for a wayfinding task is finding a route from a starting point to a goal. Depending on the city, this task can be either simple or challenging.

Some cities, as people report, are easier to navigate than other cities. Sometimes persons enter a new city and they find their way easily. Without any difficulties, they recognise places or intersections they have seen only once before and know immediately how to follow a route. In other cities, wayfinding can be time-consuming and effortful. All streets seem to look alike—or the streets lead into unexpected directions. People frequently get lost and even when assisted it is hard for them to succeed in a wayfinding task.

These observations raise the question, which factors influence the difficulty of navigation in an unfamiliar city?

Researchers of different disciplines have been searching for answers. They have found that certain elements and structures in an urban environment influence the complexity of solving a wayfinding task.

One hypothesis is that certain structures and features are easier to work with because they fit our internal way of decoding, processing and encoding information. Following this argumentation, our internal representation can process these structures effortlessly. These environmental structures somehow reflect the structures of mental spatial processes and internal spatial representations.

Some fields of research in spatial cognition utilise this knowledge of mental processing for designing cognitively ergonomic navigation assistance. Cognitively ergonomic approaches search for effortless interaction between a technical system and its human users by presenting an interface or information in the way a person would usually expect it or as it naturally occurs.

One starting point for developing wayfinding assistance is to inspect how the human mind internally processes and reasons about spatial information. This knowledge facilitates to support these cognitive processes and mental representations of spatial information by presenting spatial information in an adequate externalisation.

For designing a suitable navigation assistance system it is essential first to know the relevant information for solving a specific wayfinding task. Secondly it has to be investigated how the user processes and conceptualises the given information. Finally, the kind of presentation of spatial information has to be chosen which suits with the internal spatial representation of the relevant information.

Cognitively motivated schematic maps are examples for applications which integrate and employ this knowledge. These maps are designed for assisting a person with a specific wayfinding task in that they emphasise relevant information and present them in a cognitively easily readable format. They aim to support underlying cognitive processes and internal mental representations. Consequently, for developing these maps the designer must know which information is relevant for the task and how it should best be presented.

An example of these kinds of maps is the LineDrive map developed by Agrawala and Stolte [2001]. This approach to automatically creating route maps for drivers mimics manually generated route sketches. Here, route segments where no turning actions take place are displayed much smaller, whereas certain areas where many turning actions must be performed are displayed as an enlarged view. Figure 1 presents an example of a LineDrive map. This innovative approach successfully shows how wayfinding performance can be enhanced by cognitively ergonomic application.

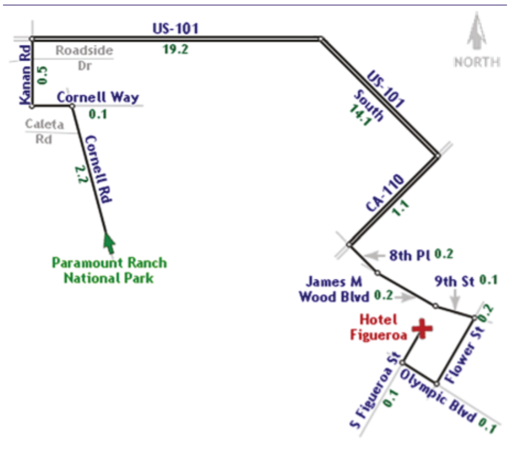


Figure 1: Example of a LineDrive map (modified from [Agrawala and Stolte, 2001])

To this day, most published research studies on cognitively ergonomic navigation assistance systems have been focusing on maps and route descriptions, while other types of presentations have often been neglected.

However, navigation assistance services nowadays are being presented to the user in a huge range of different presentation types—for example, as interactive maps with three-dimensional objects, panoramic picture views or virtual environments. Depending on the respective task, it can be helpful to display the spatial information in different presentation types.

In this thesis, I will explore the question whether this knowledge that has been gained by developing cognitively motivated maps can also be used for other spatial information presentation.

1.1 wayfinding, conceptualisation and schematisation

For an adequate assistance of a person during a wayfinding task it is necessary to know the way this person is likely to solve this task and which information is needed in which situation. Therefore the developer of such assistance systems needs knowledge of wayfinding in general and about the way people conceptualise spatial information in particular. The terms *wayfinding, conceptualisation* and *schematisation* are key concepts and terms in my thesis. For this reason I will give a brief definition of and an introduction to these terms.

1.1.1 *Navigation and Wayfinding*

Navigation and *wayfinding* are two central terms that appear in the entire thesis. Montello defines *navigation* as a ″coordinated and goal-directed movement of one's self (one's body) through the environment.″ [Montello, 2005, p. 261] and he splits up navigation into two components: locomotion and wayfinding. The first component, locomotion, refers to the movement part of the task, which includes everything concerning the movement through the environment, beginning from movement patterns like walking or running to processes like obstacle avoidance.

Wayfinding is the second component of navigation which Golledge defines as ″...the process of determining and following a path or route between an origin and a destination″ [Golledge, 1999, p. 6]. This part of the task concentrates on the cognitive elements of getting from the origin to the destination. During wayfinding a person must solve tasks like searching, exploring, route following, or indoor and outdoor route planning in urban or natural settings or even in virtual environments. The cognitive resources for solving these tasks can differ with respect to a person's knowledge of the environment, problem solving strategies, choice of perceptual inputs from the environment and choice of adequate movement patterns.

1.1.2 *Representation*

In this thesis I am dealing with two types of representations of spatial information: internal representations of spatial information in our mind and external representations of wayfinding information in terms of maps or virtual environments.

Classical examples for external representations of wayfinding information are public transport maps like tram network maps. These maps usually inform travellers about names of stops of a tram along routes, connections and their basic spatial embedding in the city. Certain information is selected to be presented on these maps in an abstract manner—as icons and lines are reduced to the essential, that is, convey the necessary information. Additionally, some aspects—such as distance information—are represented in a distorted way. Distance information is often manipulated on tram network maps to present a large area in a legible way. Figure 2 illustrates an example of a tram and bus network map of the German city of Bremen.

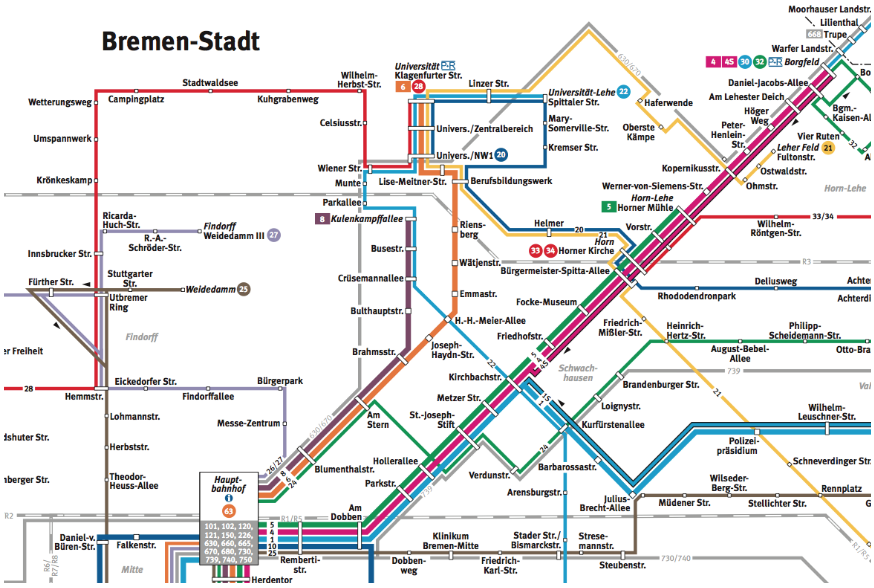


Figure 2: Map of the tram and bus network of Bremen (taken from http://bsag.de/_Linienuebersichtsplan_2011_.pdf)

In this thesis I define the term representation according to Palmer [1978]. From Palmer's point of view representations are a central topic in cognitive science. The substantial factor is that representations are usually not a perfect copy but they present certain selected aspects of the represented world. When inspecting this representational system, five questions are to be answered: "1. what the represented world is; 2. what the representing world is? 3. what aspects of the represented world are modelled; 4. what aspects of the representing world are doing the modelling; 5. what are the correspondences between the two worlds. A representation is really a *representational system* that includes all five aspects." [Palmer, 1978, p. 262].

1.1.3 *Conceptualisation*

In my thesis I focus on the conceptualisation of spatial information and employ this knowledge for wayfinding assistance systems. Therefore the notion of conceptualisation needs to be specified: I refer to conceptualisation as the mental processing of information from our represented outside world to our internal representation: such as the filtering, handling, reasoning and saving of information.

In the context of solving wayfinding tasks, conceptualisation differs from task to task. To solve a route following task, for example, persons need different information and conceptualise spatial information differently than if they are trained to learn a certain route.

However, leaving the macroscopic view of a task and proceeding to a more detailed microscopic view, similarities in the conceptualisation of these two tasks become apparent. Certain aspects of the real world are processed in similar ways due to their conceptualisation, and certain information is stored into the internal representation with similar biases and distortions. Evidence for these assumptions comes from errors people make during their wayfinding processes. Errors provide an insight view into conceptualisation and its influence on mental processes and mental representations. Some error occur due to the usage of certain external representations, such as maps that present spatial information in a predefined way, while other errors take place unrelated to aspects of external representations.

1.1.4 *Schematisation*

Almost all external representations of spatial information present information about the real world in an incomplete and distorted way. Certain aspects are simplified, some are exaggerated and others are omitted.

The adequate reduction of the amount of incoming information is an important feature of human cognition. Palmer claims that reasoning and interacting with representations of the world is often easier than the interaction with the represented world itself [cf. Palmer, 1978].

In the field of cognitive science, this information reduction is often termed *schematisation*. In the context of my thesis I will elaborate this general definition according to Klippel et al. [2005b] who define schematisation as the process of intentionally simplifying a representation beyond technical needs to achieve cognitive adequacy. *Cognitive adequacy* can be interpreted in two ways. On the one hand, a representation is cognitively adequate if it characterises mental knowledge representation in a formal model or implementation and claims to be an adequate model for these cognitive processes. On the other hand, a representation is cognitively adequate if it enhances or supports cognitive processes when dealing with a cognitively adequate representation to achieve a cognitively ergonomic and user-friendly interaction and reasoning with the external representation [Strube, 1992].

Schematisation plays an essential role in my work because schematisation is an effective tool to develop and design an external representation in order to assist a person in their wayfinding task in a cognitively ergonomic way.

1.2 THESIS, AIMS AND APPROACH

My research focuses on developing suitable external representation for a given wayfinding task sufficient to achieve cognitively ergonomic wayfinding assistance.

I postulate that schematisation techniques that fulfil specific criteria can be transferred from one external representation type to a new one provided that both schematised representations have positive influences on cognitive processes.

My aim is to demonstrate that schematisation knowledge obtained by the long tradition of map development and design can also be transferred to and reused for other representation types.

For transferring knowledge of cognitively motivated schematisation techniques, it is essential first to analyse wayfinding tasks referring to informational needs and then to decompose a given task referring to mental processes, internal representation, and conceptualisation. The analysis of the informational need of a wayfinding task is done by functional decomposition. This decomposition analysis allows for establishing a theoretical model of information needs matching the requirements of the external representations.

A successful transfer results in an external representation that contains all necessary information for a person to effectively perform a wayfinding task. Therefore it should be determined whether the original and new representation presents comparable information content in an adequate way. This information analysis will be done under representation-theoretical considerations as well as cognitive inspections.

These results of both analyses deliver the necessary information to postulate the theoretical requirements for transferring a schematisation technique.

For investigating the theoretical requirements I will take advantage of a spatial context model and inspect the correspondences between the environment, the external representation and the human user according to a specific wayfinding task.

Finally, an exemplary transfer approach of a schematisation technique for a map representation to a virtual environment will be presented. Conducing a case study in a schematised virtual environment, the hypothesis is tested that the transferred schematisation technique enhances the wayfinding performance of the user, too.

1.3 contribution

This thesis provides several contributions to the field of spatial cognition in general and to research in the context of cognitively motivated wayfinding assistance in particular. The key contributions are:

- A thorough analysis of information needs of wayfinding tasks. This analysis comprises on the one hand the functional decomposition of wayfinding tasks according to their information needs. On the other hand, this analysis will link the representation-theoretic considerations of external representations to the wayfinding task and match them with the requirements for the external representation by considering the consequences of cognitive principles and processes of a task at hand.

- A guideline for schematisation principles to transfer knowledge of schematisation techniques between different representation types. This thesis can be seen as a starting point for research into transferring and generalising the representational-theoretic considerations from maps to other representation types.

- A comprehensive inspection of environmental factors and mental processes using the example of angular information and mental distortion of this information. By schematising the angular information we get feedback of the mental representation. This method highlights the closing of a research circle from behavioural study to representational consideration to cognitive processes.

1.4 structure of the thesis

The next chapter introduces the state of the art my approach is based on. The basis of these findings is derived from the field of cognitive science, particularly from spatial cognition. Therefore I will mainly focus on topics like wayfinding and wayfinding assistance, such as internal and external representations of spatial information in the context of solving a wayfinding task.

Chapter 3 introduces a functional decomposition analysis of wayfinding tasks. In particular, I inspect the wayfinding tasks with regards to route following tasks—route following with maps and route following from memory. Therefore each task will be decomposed in its subtasks to analyse the mental processes according to their information needs. The knowledge achieved from this will be used to analyse the similarities according to information needs.

Chapter 4 presents an analysis of contained and presented information of two types of external representations: maps and virtual environments. According to the results of this, I will be able to identify the extent to which the representations are suitable for the introduced tasks.

Chapter 5 combines the results of chapters 3 and 4 with the approach of schematisation. I will introduce a spatial context model and the requirements needed for the transfer of schematisation techniques. Furthermore I present the transfer of the schematisation technique *wayfinding choreme*. I will introduce the integration of a schematisation technique that is developed for maps and transfer it to virtual environments. I will present the design and development of a schematised virtual environment.

In Chapter 6 I will test the schematised virtual environments in the context of a user study. This study focuses on the question if the schematised virtual environment enhances the wayfinding performance.

Finally in Chapter 7 I will summarise the achievements of my thesis and present an outlook of the enhancements and applications.

2 WAYFINDING AND WAYFINDING ASSISTANCE

In this chapter, I provide an overview of research on wayfinding and wayfinding assistance. For either topic, a large amount of research is carried out in different research disciplines. In this chapter I will concentrate on the information requirements for solving wayfinding tasks and on the way human beings conceptualise spatial information. I will discuss the implications of cognitive research on wayfinding assistance and present computational approaches that take them into account and integrate or employ cognitively motivated conceptualisation into their assistance systems.

2.1 SPATIAL KNOWLEDGE

Spatial cognition is a field of research that concentrates on the acquisition, organisation, utilisation and revision of knowledge about spatial environments [1]. These capabilities enable human beings, animals and animates to cope with many basic and high-level cognitive tasks in everyday life. Research disciplines like geography, psychology or artificial intelligence seek for an understanding of spatial cognition in human beings and in technical systems.

As pioneers in this field of research can be recalled Tolman [1948] and Lynch [1960] who inspired the ideas of the term *cognitive map* on the one hand and the way spatial behaviour is influenced by architecture on the other.

Over the past 30 years, a vast number of research publications have begun to concentrate on the mental representation of spatial knowledge [e.g. Stevens and Coupe, 1978; Tversky, 1981; Thorndyke and Hayes-Roth, 1982; Hirtle, 2011].

Research on spatial cognition indicates that human spatial knowledge does not veridical reflect physical space but is distorted by perceptual and cognitive filtering and processing and is biased, for example, the presented geographic knowledge [Golledge, 2002].

1 http://www.spatial-cognition.de/, retrieved January 05, 2012

2.1.1 *Acquisition of Spatial Knowledge*

Human beings can acquire spatial knowledge directly by interacting with their environment or indirectly by using external representations of the environment that can be presented in several different types, such as maps or verbal descriptions.

This knowledge includes information about locations, distances and directions and any other information that is useful for accomplishing the spatial task.

Several mechanisms enable human beings to successfully accomplish this performance. These mechanisms deal with the sensory input and the internal knowledge of the environment. Depending on the circumstances, the navigator must acquire the necessary information for wayfinding from memory or perform the task by using an external representation.

Many researchers have investigated the acquisition of spatial knowledge and its development [e.g. Piaget and Inhelder, 1967; Hart and Moore, 1973; Siegel and White, 1975; Montello, 1998; Herrmann et al., 1998]. They mainly distinguish between three different types of spatial knowledge: *landmark knowledge, route knowledge* and *survey knowledge*.

LANDMARK KNOWLEDGE Landmark knowledge describes the knowledge to recognise individual landmarks without knowing about spatial relations between them.

A landmark can be defined as a salient geographic entity that provides certain location with recognisable features so that it can be used for orientation and navigation [cf. Elias, 2003; Lynch, 1960].

Thus, an object or entity can be salient or memorable due to its visual distinctness and singularity, its prominence and its contrast to the surroundings in certain environments, in its semantics, i.e., in its content, its usage and cultural significance. Classifying landmarks by their quality, landmarks can be divided into three main groups: *visual landmarks, structural landmarks* and *semantic or cognitive landmarks* [e.g. Sorrows and Hirtle, 1999; Tomko and Winter, 2006].

This spatial knowledge on its own is not sufficient for performing wayfinding tasks like route following. However this knowledge provide essential information to orientate in an environment by anchoring action at a landmark for example without knowing the spatial relations to other landmarks.

ROUTE KNOWLEDGE Route knowledge is defined as a certain order of landmarks: "If one knows at the beginning of a journey that one is going to see a particular landmark (or an ordered sequence of landmarks), one has a route" [Siegel and White, 1975, p. 28].

This knowledge refers to the knowledge that is needed to build up 'string-like' or sequential knowledge to navigate along a route from one point to another to a certain goal. This knowledge usually defines an action-location sequence which maps an action that has to be performed at a certain point.

In this context a route represents a behavioural pattern, contrary to a path that represents the physical entities like *path-segments* connected with *branching points* [Klippel, 2004].

A route is directed, going from the starting point to a certain destination, and it consists of *route-segments* and certain points along the route, each of which requiring that decisions be made. Thus these points are termed *decision points*.

Route knowledge delivers the information that is necessary to successfully travel a route by navigating along its *route-segments* and by identifying every following route segment at a *decision point*.

There are contradictory research results about the structure of route knowledge. It is assumed that route knowledge is "a kind of serial learning" [Siegel and White, 1975, p. 24] where the wayfinder learns a sequence of decisions containing associations between landmarks and bearing changes. When memorising a route, people subdivide or chunk the route down to segments [Richter, 2008]. The decomposition of routes is an important chunking process and it simplifies the recall process. In the centre of a chunk there is a decision point marked by certain attributes, like "at the second intersection with the church left". Gale et al. stated that "...one must acquire a declarative database, a set of rules for locomotion, and the appropriate associations between place identification and motor response" [Gale et al., 1990, p. 18]. Accordingly, successful navigation implies knowledge of a sequence of association pairs of places and movements which lead to the destination [Gale et al., 1990].

SURVEY KNOWLEDGE Survey knowledge is the knowledge of the layout of locations and their spatial interrelationships. This knowledge delivers the necessary information on the direction and the distance to a certain point—regardless of whether or not a specific path to this point is known. (Take, for example, me sitting in my office, knowing that the central station is 6 kilometres to the north.) Contrary to route knowledge, survey knowledge is 'map-like' and enables people to perform shortcuts, pointing to locations that are not visible to the eye, or to draw sketch maps.

DEVELOPMENT OF SPATIAL KNOWLEDGE Initially, researchers suggested that spatial knowledge is developed sequentially, starting with landmark knowledge, followed by route knowledge and finally developing into survey knowledge [e.g. Piaget and Inhelder, 1967; Siegel and White, 1975]. However, there is evidence that the development of spatial knowledge is not completely sequentially. Montello claims that survey knowledge can be acquired rather quickly from the first moment of the inspection of a new environment [Montello, 1998]. People acquire survey knowledge after walking a route twice [Montello and Pick, 1993]. Beyond that, other studies present that resident of district do not express much survey knowledge and externalise more route knowledge [Appleyard, 1970].

2.1.2 *Cognitive Map*

The term *cognitive map*, introduced by Tolman [1948], is used by many researchers to refer to an internal representation of spatial entities and spatial relationships.

A cognitive map is seen as a mental representation of spatial knowledge [O'Keefe and Nadel, 1978]. This metaphor was traditionally used to reflect that space is represented in a continuous, metric and two-dimensional way. Nowadays, most researchers doubt that a cognitive map is a continuous, metric and two-dimensional representation of spatial information [e.g. Montello, 1998; Hirtle, 2011].

Many studies have given evidence instead that the spatial components of this mental representation are not veridical in the sense of a physical map but that they are represented in a deformed and distorted manner [cf. Tversky, 1981; Thorndyke and Hayes-Roth, 1982; Golledge, 2002; Montello et al., 2004; Hirtle, 2011]. Lynch inspired the idea of a rubber sheet model [Lynch, 1960], as if the mental map was distorted like rubber.

COGNITIVE COLLAGE In contrast to the 'map-like' idea of a mental representation of spatial information, Tversky [1993] introduced the idea of a more disparate and complex representation termed *cognitive collage*. This metaphor describes the variability of the mental representation which not only stores one piece of information in a specific format like a location by its position and spatial relations, but also represents a fragmented collection of partially overlapping pieces of knowledge like spatial, semantic, visual or textual information.

This means that a cognitive collage can include images, sounds, smells or other abstract facts like numerical information. For example, a cognitive collage of the German city of Bremen might contain a picture of the four 'Town Musicians' from the fairy tale, or information on the soccer team 'Werder Bremen', and the smell of the river Weser.

This idea has inspired other researchers to rethink the concepts of a *cognitive map* [e.g. Portugali, 1996; Hirtle, 1998] on the one hand, and to represent spatial information for assistance in a partly redundant way with different types of external representations on the other hand [e.g. Hirtle, 2000].

2.1.3 *Scale of Space*

An important factor which strongly influences perception, thinking, memory and behaviour is the scale of space [Montello, 1993]. The scale of space has a strong impact upon the way human beings deal with spatial information.

Traditionally, in spatial cognition a distinction is made between small-scale space and large-scale space. In small-scale spaces, a person can see all places within the respective space from a single vantage point. By contrast, in large-scale spaces a person cannot experience this space from a single view.

Many researchers classify space or spatial representation into large-scale space and small-scale space, or they even introduce more separate classes of space [for an overview see Hirtle, 2011].

The scale of space has an important influence on the way human beings deal with spatial information, and several qualitatively distinct scale classes of space exist. To define the scales of space I am following Montello [1993]'s definition, since he states that scale of space is the "ratio between the dimension of a representation and those of the thing that it represents" [Montello, 1993, p. 316].

Montello shifts the classification to a more psychologically orientated position. He states that "Space is not space is not space" [Montello, 1993, p. 313]. He distinguishes the different spaces by considering the projective size of each space, taking the human body as a reference. In his classification, Montello also respects the way the spaces are perceived. He distinguishes four major classes: figural, vista, environmental, and geographical space.

Figural space is smaller than the human body. No locomotion is needed to enter this kind of space. One can further distinguish this space into pictorial space and object space. Examples for pictorial space are maps. Objects that can be experienced by haptic signals are examples for object space.

The space around the person's body which opens up to them visually without their moving from one point to another, is called vista space. It is as large or even larger than the human body. This space includes the rooms or streets somebody can look into without moving.

Environmental space is much larger than the human body and surrounding it. This space is directly experienced by locomotion, and the information thus derived has to be integrated over time. Environmental space is the space of urban spatial situations, such as buildings and cities, or natural places like forest or fields.

Finally, the largest space is the geographical space. This space is much larger than the human body and cannot be experienced by direct locomotion;

it is learned via symbolic representations like maps or models instead. Maps and models have the advantage that they can reduce geographical space to figural space.

2.1.4 *Frame of Reference*

Another factor, especially for presenting and communicating spatial information, is the *frame of reference*. This concept describes the coordinate system that underlies an external representation.

"Put simply, a reference frame is a means of representing the location of entities in space" [Klatzky, 1998, p. 1]. It is a conceptual base of representing and determining spatial relations of different entities in a spatial configuration.

In order to describe a spatial configuration, for example someone's office, one has to decide from what perspective it shall be displayed. One can use a floor plan of the respective room to describe every object in this room according to this plan, or utilise oneself as a reference, sitting on a chair in the middle of the room, and determine every spatial relation according to this reference point. Depending on the reference frame and the selected underlying coordinate system, two different descriptions of this office would be produced. Typically, two types of reference frames are distinguished: the allocentric and the egocentric one.

ALLOCENTRIC REFERENCE FRAME In an allocentric reference system all spatial relations are defined with respect to features of the environment, such as the perceived direction of gravity, the sun's azimuth, cardinal directions or landmarks. The axes of the allocentric reference frame are predefined by environmental or global features but also by the layout of the space itself, be it, for example, a sheet of paper or the long axis of a rectangular room [Mou et al., 2004]. In an allocentric reference frame, all the positions of points are conveyed in either a Cartesian or polar coordinate system. The terms 'exocentric' and 'geocentric' are used synonymously with the term allocentric.

EGOCENTRIC REFERENCE FRAME Spatial information which is presented by a representation with an egocentric frame of reference is given in relation to an oriented user. Egocentric reference frames specify locations and orientations with respect to the organism. In an egocentric representation, all the positions of points are expressed in a special polar coordinate system whose origin is located at the ego, and its reference axes are aligned with the ego's orientation [Klatzky, 1998]. In this reference frame a location is defined by its distance and direction to the ego.

2.1.5 *Spatial Primitives*

Spatial primitives are the basic elements of spatial concepts that unintentionally influence and bias via cognitive processing and filtering of spatial information.

There is an ongoing debate among researchers from different research fields on the question which spatial primitives exist and how these primitives may influence our spatial representation.

I will exemplarily introduce two different concepts of spatial primitives: one of them concentrating on the influence of physical elements of the environment and the other focussing on cognitive components of spatial knowledge.

KEVIN LYNCH Lynch [1960]'s pioneering work introduced a new perspective of the influences of architectural and geographic characteristics on the spatial behaviour of individuals. In his work, Lynch focuses on how people perceive and structure their habitat cities. He proposes that the inherent structures of a city influence the way people build up their mental picture of the city. By studying three sample cities, Lynch developed his key idea that there is a limited number of recurring structures or elements in a city which form a mental picture of this city. These elements or structures can be regarded as *conceptual spatial primitives*. He defines five basic elements (see Figure 3): *paths, edges, districts, nodes* and *landmarks*.

- *Paths:* Lynch defines paths as the predominant elements that organise and structure a city. Paths create connections between places or environmental elements of the city, such as streets, sidewalks, transit lines, canals or railroads. People experience a city by moving in it along paths.
- *Edges:* Edges are linear elements which serve as boundaries between certain areas. People observe edges as elements that divide areas by their characteristics or as physical elements, such as walls or water. Perceiving an edge (and what is perceived as an edge) is dependent on the observer's way of motion: if the observer is a pedestrian, a highway may become an edge, whereas to a car driver it is a path.
- *Districts:* To Lynch, districts are two-dimensional extents that help the observer to regionalise areas by certain characteristics. Most people structure the image of their city in this way and know when they are inside of a district or outside of it, for example in or out of a living district, the town centre or a park district.

- *Nodes:* Lynch describes city nodes as critical points. This is due to the fact that people turn their attention to these points and view them intensively because nodes are either intersections, places where the route is intermitted, or crossings of convergent paths.

- *Landmarks:* Lynch introduces the concept of landmarks and specifies examples of landmarks, such as buildings, signs, stores or mountains. Landmarks are generally outstanding in their surroundings because of their visibility, their location and their meaning. Some of them which are distant and can be viewed from many angles and distances are used as global reference points. Others are rather local and visible only in a restricted area, such as store fronts, trees or other urban details. Such global and local cues of identity, or structures, facilitate our orientation in an urban environment. Certain moving objects like the sun, for example, can be used as landmarks too.

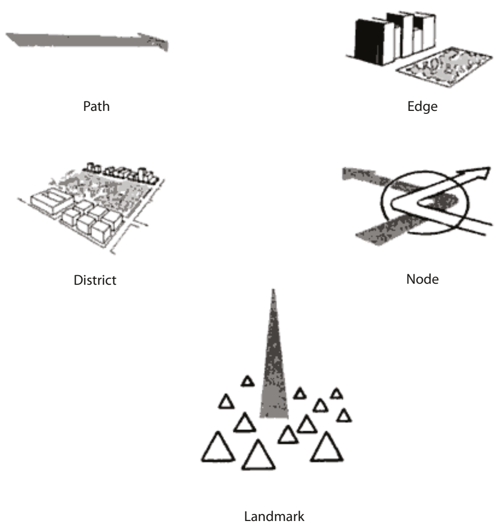


Figure 3: Basic elements of a city, introduced by Kevin Lynch (modified from [Lynch, 1960])

REGINALD G. GOLLEDGE Reginald G. Golledge defines another cognitively inspired approach that has strongly influenced the view on spatial primitives. He identifies basic components of spatial knowledge and terms them spatial primitives [Golledge, 1991, 1992, 1993, 1995b, 2002]. Contrary to Lynch, Golledge does not focus on the physical structure and components of the environment but on specific spatial relations. These spatial primitives are classified into two groups: *first-order spatial primitives* and *derivable concepts*.

He distinguishes between four *first-order primitives*: *identity, location, magnitude*, and *time*.

Deriving from these *first-order primitives* Golledge infers the following *derived concepts*: *distance, angle and direction, sequence and order*, and *connection and linkage*.

Golledge advances the view that introducing these spatial primitives into geographic information services will positively influence interaction with them. He states that knowledge about these spatial primitives helps to understand how these spatial concepts and relations influence the acquiring of geographic knowledge and their accommodations.

He summarises that, as a result of cognitive filtering and processing, biases occur in geographic knowledge. In his paper he lists several examples for such biases, like the cognitive misalignment of positions to a certain reference frame, or summarising geographic information by simplifying them into regional forms [for a complete listing see Golledge, 2002].

2.2 WAYFINDING

Wayfinding is the central topic of the present thesis. It is an everyday process in everybody's life. People go to work, travel around the world or find their way in complex buildings.

2.2.1 *Wayfinding Problem*

Wayfinding is "...perhaps the most prominent real-world application of spatial cognition" [Wiener et al., 2009, p. 152] and it yields very robust behaviour. People are able to cope with incomplete uncertain information and are capable of dealing with unexpected wayfinding situations.

A person who must find their way in any environment has to solve several cognitive and physical tasks to successfully perform navigation. They reason and plan their route from the starting point to their destination, determined by certain personal circumstances or motives like leisure during holidays, economic considerations during shopping tours or time pressure in cases of emergency, etc.

Often a destination is remote from the starting point so that it cannot be viewed from the beginning of the journey. In case it cannot be viewed by the wayfinder, a route to the destination must either be recalled or planned, facilitated by cognitive mapping or externally, with the help of external spatial representation.

Distinguishing between these two options, in the first case the wayfinder knows the goal and the route beforehand, whereas if the people do not know their environment, they cannot rely on their internal representation of spatial knowledge. In this case people usually utilise external representations of this environment, such as maps, verbal directions or even another person for their guidance. If no external representation is available or/and the person gets lost during the wayfinding task, they will search for the destination.

Everything that is required for successful wayfinding is part of the wayfinding tasks—as, for example, the identification of places in order to plan a route and overcome one's incomplete spatial knowledge or other constraints.

2.2.2 *Components of Wayfinding Tasks*

During a wayfinding process a person has to solve different wayfinding tasks like searching, exploring, route following or route planning. The variety of tasks is influenced by the environmental settings, the type of external representations and other conditions, such as their motivation for navigation.

In each wayfinding task, the cognitive processes and resources differ with respect to the environmental situation, problem-solving strategies, perceptual input and the type of movement.

Several researchers have identified and classified different wayfinding tasks [e.g. Allen, 1999; Chown et al., 1995; Mallot, 1999; Franz and Mallot, 2000; Kuipers, 2000; Montello, 2005; Wiener et al., 2009].

For this, the researchers have classified the respective tasks according to relevant issues like complexity and memory requirements [Mallot, 1999; Franz and Mallot, 2000], shared comments for decision making, reasoning and planning [Montello, 2005] or have classified them by environmental familiarity, depending on whether wayfinding is performed in a familiar or an unfamiliar environment or if it is motivated by exploratory interests [Allen, 1999].

Allen [1999] presents a classification according to the wayfinder's knowledge of and their motivation for the journey. For this, he introduces three classes: wayfinding to a familiar destination, like travelling from home to work, wayfinding to an unfamiliar destination, like navigating with a map in a new city, and exploring environments, like cruising around a hotel area.

Furthermore, Allen proposes six means of wayfinding like fundamental navigation mechanisms such as oriented search, path integration to follow a marked trail, piloting between landmarks and habitual locomotion, up to knowledge retrieval processes like referring to cognitive maps. Other researchers like Passini [1984a] lay focus on a framework of wayfinding defined via procedure steps of wayfinding tasks.

Passini provides a conceptual framework of cognitive processes during wayfinding tasks [Passini, 1984a,b]. In his study, he collected analysed wayfinding protocols of subjects navigating in public buildings and categorised their wayfinding behaviour into three classes: cognitive mapping, decision making and decision executing (see Section 3.2).

Chown et al. [1995] presents another wayfinding model. Their *PLAN = Prototypes, Locations, and Associative Networks* model is composed into basic components of wayfinding: landmark identification, path selection, direction selection and abstract environmental overviews. *PLAN* is based on an elaborate cognitive mapping process. It distinguishes between landmarks recognition, route knowledge and cognitive mapping. Contrary to other technical systems, this system integrates the view of the agent.

A taxonomy proposed by [Wiener et al., 2009] integrates the main findings to a finer-grained and overall classification of wayfinding tasks in which the wayfinding tasks are classified by the existence of an external aid, a specific destination and availability of different kinds of spatial knowledge like landmark, route, and survey knowledge (see Figure 4).

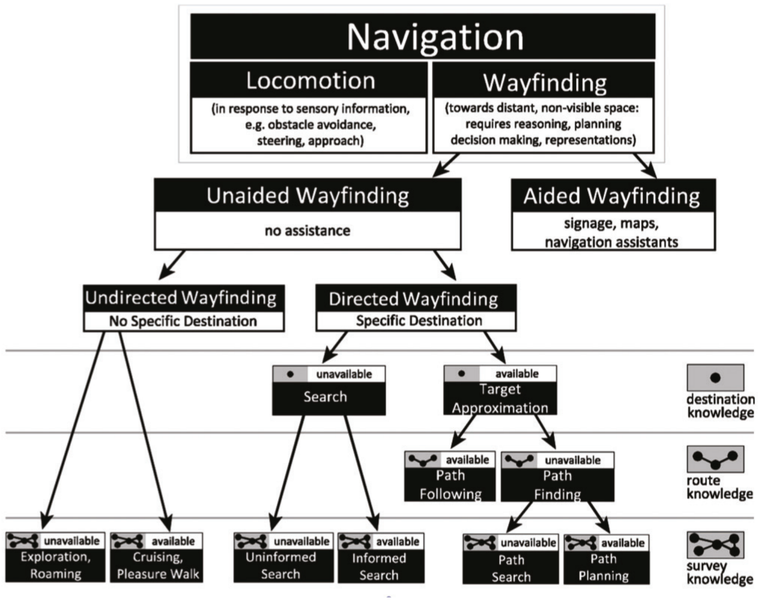


Figure 4: Taxonomy of wayfinding tasks (cf. [Wiener et al., 2009])

This taxonomy separates navigation into two components: locomotion and wayfinding.

It focuses on unaided wayfinding in environmental space directed to distant destinations which are not visible to the wayfinder from the starting point. Explicitly excluded from this taxonomy is wayfinding that is aided by external representations like maps, signs or route directions.

Unaided wayfinding is classified by motivation, depending on whether or not a predefined destination is to be reached.

If the wayfinders have no predefined destination and their wayfinding is undirected, they can either *explore* the environment for acquiring survey knowledge or *cruise* through it for leisure.

In the other case, wayfinding is directed and the wayfinders aim to reach a predefined goal. If the wayfinders have no knowledge of the location of their destination, they must *search* for the destination. If there is knowledge, they either know a specific route to their goal and can *follow a path*, or they must *find a path*.

In case the wayfinders have no route knowledge and no access to survey knowledge of this environment, they must *search for a path*. If there is survey knowledge of this environment, they can *plan a path* to their destination.

The above taxonomy is incomplete and lacks certain issues like background knowledge or heuristic search strategies, but it represents an initial step to systematically classifying wayfinding tasks.

2.3 WAYFINDING ASSISTANCE

Wayfinding assistance has a long tradition. There is evidence that people during the Early Stone Age used paintings and signs to communicate relevant locations to others.

The goal of any wayfinding assistance is to present useful spatial information just in time during wayfinding. Hence, it is essential to know which information is needed in which situation, and which assistance system delivers which type of information.

People need assistance to find their way when they do not know either their current physical location, the position of the starting point or destination of a route or in case they do not know the route at all.

Here, wayfinding assistance can either help to plan a route or to explore spatial information, or it can assist in following a specific route.

Any representation of spatial information which is used for wayfinding that was not created by the mind of the wayfinder or directly acquired by the environment is a form of wayfinding assistance [Schmid, 2010].

Classical examples of external representations for wayfinding assistance are maps and route descriptions.

Nowadays, spatial information has become ubiquitous—via different media like mobile phones, Internet mapping services and other common navigation systems that can be used everywhere. The usage of these media is changing the way people acquire, process and remember spatial knowledge.

The range of current external representations of spatial information for wayfinding assistance starts with oral or written route description to different types of maps like thematic maps, topological maps, route maps and mobile maps etc. to 3D virtual models or augmented reality.

Some of these techniques have a long tradition and are well-grounded in cartography, spatial cognition and cognitive psychology. Other new media like electronic mobile maps and 3D virtual models are often employed and bear certain advantages and new interaction forms like zooming, changing perspective, presenting multilayer information or adding non-spatial content to the environment. However, some of these new media lack understanding the interacting processes and do not take into account research results on the spatial conceptualisation.

In the following I will introduce taxonomy of wayfinding assistances by which assistances are being classified according to their function of presenting specific spatial information.

2.3.1 *Taxonomy of Wayfinding Assistance*

Chen and Stanney [1999] propose a taxonomy which organises wayfinding tools into five functional categories: (1) tools that display the current position of the user; (2) tools that present the current orientation of the user; (3) tools that log the movement of the user; (4) tools that demonstrate surrounding environmental information; and (5) tools that present an active guidance for the user. I will introduce each category by means of examples of technical wayfinding tools, nevertheless each category of wayfinding information can be given by humans or environmental features as well.

An antiquated example of a wayfinding tool that presents information of the current position is an astrolabe. This nautical instrument was used to determine the current position of a ship with the help of the stars. This day, GPS (Global Positioning Systems) are utilised for position determination. For this, to keep it simple, satellites send information of their current position, identity and time to the GPS receiver, then, by trilateration techniques the distance over three points can be determined, and the receiver can calculate the current position. Both are examples of the first category of this taxonomy.

Magnetic compasses are a classical example of tools of the second category. A person can determine their current orientation using a compass. GPS signals can also be used to for a person's orientation.

The third category is less common than the other categories. An example of a navigational tool that logs the movements of its user is currently found in shipping. For this, the current position is stored and recorded over time [Chen and Stanney, 1999]. Beyond that, due to innovative GPS techniques, it is now possible to integrate this technology into mobile devices like mobile phones and thus to keep track of an individual's movement and analyse it for further navigational assistance. In contrast to the preceding three categories, navigation tools of the forth category deliver surrounding information of the environment in a direct or indirect way. For instance, binoculars expand the view of the user and give direct access to spatial information of the surrounding environment. Maps, however, indirectly present pictorial spatial information of the surrounding even of large-scale spaces. Also, new technologies in the field of photography provide panoramic views of the surrounding environment, like, for example, Google Street View.

Finally, the fifth category differs significantly from all the other categories. Assistance systems of this category can employ or integrate any of the above categories and use the information derived from this to actively guide the user during a wayfinding task. This type of guidance ranges from signs that divert to an alternative route to navigational systems in cars or mobile phones, up to autopilots on airplanes.

2.3.2 *Cognitively Ergonomic Wayfinding Assistance*

In the field of wayfinding assistance, a number of researchers concentrate on cognitively driven spatial interfaces. Their field of research can be described as a subdivision of cognitive ergonomics. Cognitive ergonomics is a field of research concerned with the analysis of cognitive representations and processes in order to design applications that are natural to interact with, effective and satisfactory to the user [Wilson and Keil, 2001]. The aim behind cognitive ergonomics is to develop technological innovation that enhance human performance by taking into account the results of cognitive research by aiding, resembling and reorganising human cognitive activities through designing advanced technologies and applications.

Egenhofer and Mark [1995] infer from the fact that perceived space diverges from actual space that individuals have in mind a *Naïve Geography* to deal with the geographic world. "Naïve Geography represents a commonsense view of the world, complete with misconceptions and biases" [Hirtle, 2011, p.3]. The findings and conclusions taken from Naïve Geography can be employed as an inspiration for new approaches to wayfinding assistance.

Three main problems must be considered when it comes to designing adequate wayfinding assistance: the matching of the external representation to the internal representation and the environmental situation, the variety and complexity of indoor and outdoor environments, and the respective expectations of the wayfinder [Hirtle, 2011]. Depending on the type of wayfinding assistance, the complexity of the wayfinding task and its environment as well as the foreknowledge of the wayfinder, adequate assistance can differ significantly. For instance, a person who is partly familiar with a city can be directed to a familiar place and from there be guided to their destination [Tomko and Winter, 2006].

The interpretation of an external representation for wayfinding is not a trivial task. The user must transcribe and understand the given information of the external representation and translate this information into useful knowledge by reasoning and mapping the external representation onto the reality. Human interaction with external representations attracts intensive attention in the spatial cognition research community.

However, for one thing, most wayfinding assistance services provide spatial information without considering these findings. For another thing, many assumptions of Naïve Geography are related to well-grounded empirical studies without being integrated into an overall theoretical framework.

Nevertheless, some approaches aim to develop cognitively driven wayfinding assistance. I will introduce two approaches that integrate the concepts of spatial cognition into a technical application for wayfinding assistance.

Hirtle [2000] introduced a navigation system for assisting people in finding certain libraries on the campus of the University of Pittsburgh, termed LibLoc (Library Locator) [Hirtle and Sorrows, 1998; Hirtle, 2000]. This system is a web-based browser that assists the user in locating the 17 small libraries on the campus. The basic idea behind this application is the concept of a cognitive collage (see 2.1.2). Hence, this assistance system provides spatial information in a redundant manner via different external channels like a map of the campus or a floor plan of the buildings, key images along the navigational path, verbal instructions and the exact address of the library itself. For this, the LibLoc system integrates different design principles, such as presenting spatial information on different levels of detail, using different externalisations of spatial information, individual preferences of favourite externalisation, and overlapping and redundant information contents in the presented externalisations.

Another example of a cognitively ergonomic approach for wayfinding assistance is μMaps, as introduced by Schmid [2009]. Schmid develops a visualisation of spatial data for small display devices in the context of wayfinding assistance. For a visual compression of geographic information this approach exploits the prior knowledge of the user. The environment is subdivided into familiar areas which come compressed, and unfamiliar parts which are displayed in full detail. Consequently, μMaps consist of two different frames of reference—a personal and a geographic one. Schmid investigates how these different frames of reference can be integrated into and visualised on small devices, based on a concept termed mental tectonics which describes "a process that harmonises mental conceptual spatial representations with entities of a geographic frame of reference" [Schmid, 2009, p. 411].

2.4 SCHEMATISATION TECHNIQUES

Nearly every external representation presents spatial information in an incomplete and distorted way. Simplification, exaggeration or even omission of selected aspects in external representations directly influences the assisting performance during a specific wayfinding task. By intelligent selection and accentuation of the most relevant aspects in a given wayfinding task, the acquiring and processing of information from external representations can be facilitated for the user. This intelligent selection of relevant aspects is commonly termed schematisation and is central topic in this thesis.

The process of intelligent information selection, reduction or emphasis has several synonyms, starting from generalisation (see Section 4.2) to schematisation [Klippel et al., 2005b; Herskovits, 1998] to aspectualisation [Berendt et al., 1998]. Depending on the scientific field, like cognitive science, psychology, geography, artificial intelligence or linguistics, these terms has a slightly different interpretations and foci.

In cognitive science, most notably linguistics, Herskovits states that "Systematic selection, idealisation, approximation, and conceptualisation are facets of schematisation, a process that reduces a real physical scene, with all its richness of detail, to a very sparse and sketchy semantic content." [Herskovits, 1998, p. 149]. The core of Herskovits' ideas originates from Talmy [1983] who defines this process as "...a process that involves the systematic selection of certain aspects of the referent scene to represent the whole, while disregarding the remaining aspects" [Talmy, 1983, p. 225].

Berendt et al. [1998] introduced a computational approach providing a theoretical framework for developing a schematic representation with focus on identification and extraction of relevant aspects for a certain task. The resulting schematic maps present selected spatial knowledge for a certain task. Therefore, information or aspects are categorised into three classes: aspects which must be presented in an unaltered way, aspects that can or even should be distorted, and aspects which can be or should be omitted.

In the present thesis, I utilise the definition of *schematisation* given by Klippel et al. [2005b] and briefly introduced in 1.1.4. Klippel discuss schematisation from a cognitive perspective by emphasising the significance and relevance of schematisation to knowledge representation. As said before hand, he defines schematisation to be the process of intentionally simplifying a representation beyond the technical requirements in order to achieve cognitive adequacy [Klippel et al., 2005b]. His goal with schematising an external representation is to supports cognitive processes and to achieve a cognitively ergonomic and user-friendly interaction and reasoning with the external representation.

Hence a schematisation technique is implementation or realisation of a concept of schematisation. Schematisation techniques for certain external representations of spatial information are developed as an attempt to achieve the construction of legible and cognitively adequate representations. This means that by schematising the representation developers aim to enhance the interacting, processing, and extracting of relevant information from a given external representation. Thus, the focusing of the correspondences between internal and external representations and supporting the cognitive processes during the wayfinding task can enhance the wayfinding performance.

2.4.1 *Representational Complexity versus Cognitive Difficulty*

Schematisation aims at reducing and selecting intelligently the given amount of information to its essentials. Schematisation can be achieved using different methods with different effects. These methods may either address simplifying the representation as such or enhancing the information processing ability of the user or both. To clarify the distinction between these two methods, I introduce the terms *complexity* and *difficulty*. Richter discriminates complexity from difficulty by classifying their respective focus, stating that complexity is used when referring to structure, and difficulty, when referring to performance.

Analysing the complexity of a representation, one must consider two cases: firstly, an uninterpreted representation, where the structural complexity of the representation is crucial—and secondly, an interpreted representation, for which not only the complexity of the representation but also the mental processes of the user are essential. It happens that a complex representation is easy to process for a certain task, while a simple representation is hard to process.

Schematisation, as introduced, focuses on user information processing with the external representation. Richter [2008] distinguishes four different types of difficulties according to different informational processes: *navigational difficulty*, *descriptional difficulty*, *visual difficulty* and *conceptual difficulty*. To Richter, *navigational difficulty* is a difficulty with navigation as such, i.e., with the degree of difficulty in identifying the decision points, mapping the resulting turning action at the decision points and in matching it with the spatial situation. *Descriptional difficulty* concentrates on how a route is explained to the user. This kind of difficulty is particularly conceptualised for route descriptions.

Visual difficulty describes the difficulty to extract information from the visual representation, that is, the complexity of this representation according to its visual information presentation.*Visual difficulty* can be described by the concept of visual clutter [cf. Phillips, 1979; Rosenholtz et al., 2007]. *Conceptual* *difficulty* tackles all problems concerning the complexity of mental processes and mental representation, as well as the difficulty to conceptualise, form and build up an internal mental representation or reasoning with the help of the given external representation. The aspect of *conceptual difficulty* also reflects the bilateral way of making the conceptualisation parsimonious on the on hand and yet flexible to cope with situational changes or problems on the other hand.

The first two considered types of *difficulties* mainly depend on the environmental complexity and structure whereas the last two focus on the information processing of the user with the representation.

These difficulties describe both the complexity of the processes between the user and the external representation and the complexness of the processes between the user and their environment according to a certain task.

2.4.2 *Taxonomy of Schematisation Techniques*

Taxonomy of schematisation techniques has been introduced by Peters and Richter [2008]. This taxonomy scrutinises two main dimensions, the first of which concerns the question whether the schematisation approach that manipulated the representation of the spatial information is organised bottom-up or top-down, while the second dimension classifies schematisation according to which features or relations of space are manipulated.

The first dimension of this taxonomy can be subdivided into two classes: *data-driven* and *cognitive-conceptual approaches* [Klippel, 2004]. This differentiation is focused on the map-making process. The *data-driven approach* is a bottom-up approach and the *cognitive-conceptual approach* is a top-down approach [Klippel, 2004]. *Data-driven approaches* generate a spatial representation from a rich source of geographic data and create a representation which is schematic by systematic abstraction, i.e., cartographic generalisation. *Cognitive-conceptual approaches*, on the contrary, start by mental concepts, or primitives, to reflect human mental conceptualisation and enrich these representations by concretisation, combination, and contextualisation.

The second dimension of this taxonomy concerns the question which features of the representation are manipulated. Hence, it is distinguished between *object-schematisation* and *space-schematisation* [Peters and Richter, 2008]. In *object-schematisation*, the relevant objects are selected (e.g., landmarks) and for these objects an adequate representation is generated (e.g., by highlighting certain qualities of the objects or reducing unnecessary objects). The adequate configuration of objects and other properties of space are topics of *space-schematisation*. Schematisation techniques that can be classified in this category systematically modify properties of space, e.g., by altering angles, enlarging or shrinking distances, forming and/or highlighting regions.

2.4.3 *Schematisation Techniques for Maps*

It is a common practice to distort information according to technical needs when developing external representations of spatial (geographic) information. Developers of these representations decide to simplify certain aspects, exaggerate some and even omit other aspects. Specific distortions and the accompanying loss of information strongly depend on the type of representational medium.

Maps necessarily distort the presented information, not least due to their smaller scale, in order to maintain good legibility. This distortion and simplification due to technical needs is a result of cartographic generalisation (see Section 4.2).

The approach of schematisation is applied to different implementations of schematic maps, too. In this subsection I introduce some examples of schematic maps as prototypes of the categories of the introduced taxonomy and to introduce how schematisation intend to lower complexity or difficulty.

DISCRETE CURVE EVOLUTION MAPS Barkowsky et al. [2000] introduce a schematisation technique for simplifying shape information in map representations. With this schematisation, the developers aim to reduce the cognitive load of the map user by simplifying the perceptual shape or reducing information for presenting them on small-scale maps. This type of schematic map can be characterised by schematising objects based on *Discrete Curve Evolution* (DCE) algorithm [Latecki and Lakämper, 1999]. During the schematisation process, the least significant points of an object's geometry are removed until a certain significance threshold is reached. The significance threshold for a point is defined by the distance to and the angles between its neighbouring points. Hence, this method manipulates the geometry of a single object by modifying the boundary polygon, but it guarantees that the topology and the ordering of objects are being preserved. This is ensured by certain fix points (see Figure 5) which are excluded from simplification. During the schematisation process, all points of the map are categorised into three groups: fix points that cannot be removed and cannot be changed in their position, movable points that can be moved but not deleted, and removable points that can be deleted.

This schematisation technique is an example for a data-driven schematisation because the underlying algorithm works bottom-up. The originally given spatial data are simplified according to certain spatial constraints. Beyond that, it is an object schematisation, due to the fact that this schematisation applies all simplification to the shape of the objects [Peters and Richter, 2008]. The schematisation process aims at lowering the complexity of the map representation with the objective of reducing the *visual difficulty*.

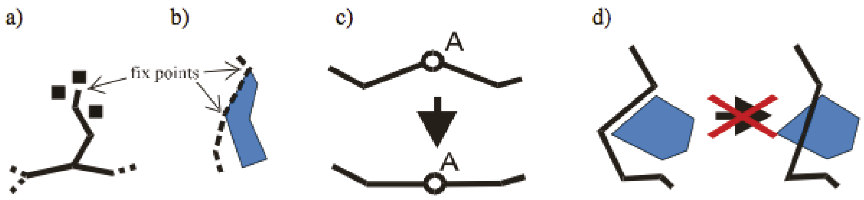


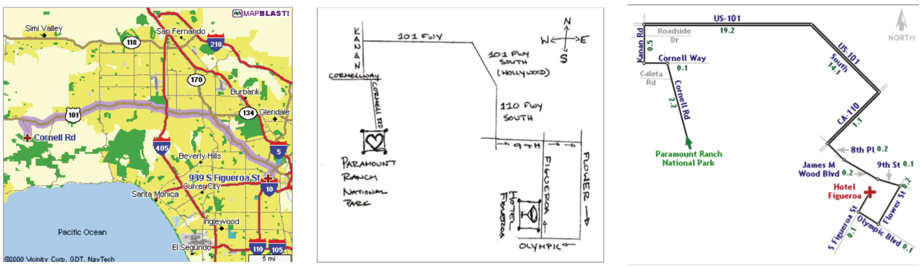
Figure 5: DCE Map: example cases that guarantee constant topology and ordering information; a.) Selecting fix points which cannot be eliminated; b.) Considering connectivity of objects and modify both; c.) Considering topological order (taken from [Barkowsky et al., 2000])

LINEDRIVE MAPS As I briefly introduced in Chapter 1, Agrawala and Stolte [2001] present a schematisation technique to improve the usability of routes which is based on cognitive studies of hand drawn sketches of route maps. This approach generates schematic maps by distorting the distances of roads according to the density of events along the route. Additionally this schematisation approach prototypes the angular information of the turning branches. This type of schematic map is termed *LineDrive* map. Concluding from the inspected hand drawn sketch route maps, Agrawala and Stolte infer that, during a route following process, one important event is the turning action at decision points. Due to this fact, areas where the density of turning events is high are presented with a higher level of detail, contrary to areas with a low density of decision points, which are presented in a scaled-down format. As a consequence, the map as a whole is not consistently scaled. LineDrive maps present long segments of routes without turning events (like, for example, straight highway segments of hundreds of kilometres) in a compressed format, so that these parts do not occupy much space on the map. On the other hand, dense event-areas in urban spatial situations (e.g. cities), such as the starting or destination point of a route, are enlarged and occupy large-scale space on the map. Figure 6 illustrates three versions of one route by comparing an example of a standard computer-mapping system, a hand drawn route map and the LineDrive map.

This schematisation algorithm is used for route following tasks for a car driver's wayfinding as, for example, as a feature of Bing Maps [2].

This example is categorised as a data-driven space schematisation [Peters and Richter, 2008]. This schematisation aims to lowering both the *cognitive difficulty* and the *visual difficulty*.

2 http://msdn.microsoft.com/en-us/library/cc514631.aspx



a.) b.) c.)

Figure 6: Sketch of the idea behind LineDrive Maps: a.) standard computer mapping system; b.) hand drawn route map; c.) LineDrive Map of the same route (modified from [Agrawala and Stolte, 2001])

FOCUS MAPS Focus maps aim to ease map reading by guiding the user's attention to the areas of current interest, i.e., in the case of route following, the route [Zipf and Richter, 2002; Richter et al., 2008]. This schematisation approach aims to increase the legibility of a map by visually highlighting the areas of interest. This is achieved by pale colouring of areas of little interest to the wayfinder, next to geometric clustering for line drawing simplification with increasing distance to the areas of interest on the map. An example would be the omission of colour information in areas remote from the route. Figure 7 presents an example of a focus map according to a specific route (illustrated via the black line).

This approach is an example for a data-driven space-schematisation [Peters and Richter, 2008]. This schematisation technique manipulated mainly by the colour properties of certain areas and intended to decrease the *visual difficulty* by highlighting the areas of interest.

CARTOGRAPHIC VISUALISATION OF LANDMARKS FOR MAPS This approach demonstrates a design concept for visualising landmarks on mobile maps [Elias et al., 2005]. Elias et al. use different types of visualisation of landmarks, such as well-known shops or buildings distinguished by visual characteristics, and they examine on which level of abstraction the landmarks should be visualised. The forms of abstraction range from photorealistic image presentation to drawings or icons to symbolic representation (see Figure 8).

This classical example for cognitive-conceptual object-schematisation is the replacement of an object by its symbolic representation [Peters and Richter, 2008]. Within this approach, buildings or features and functions of buildings

Figure 7: The focus map highlights a given route (black line) by highlighting the area around the route (taken from [Richter et al., 2008])

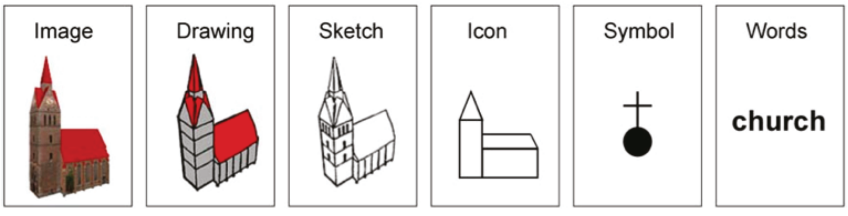


Figure 8: Level of abstraction of presented landmarks ranging from a photorealistic picture to an icon to labelling (taken from [Elias et al., 2005])

will be represented by symbolic representation, for example, a church by a cross, or a certain fast-food restaurant or gas station by is commercial brand name. These symbols or brand logos take the original place of the represented building on the map.

Figure 9 presents an example of the visualisation of landmarks by using a photorealistic picture, a drawn sketch, or the brand name of the restaurant.

Replacing the landmark information by its symbol or icon renders the representation more legible to the map user in certain situations by decreasing *cognitive difficulty* as well as *visual difficulty*.

TOOLKIT FOR ROUTE DESCRIPTIONS Tversky and Lee [1999] present a toolkit approach of constructing verbal and graphical route directions by spatial primitives. This toolkit approach is based on empirical findings of prototypical externalisations of wayfinding situations. They collected

Figure 9: Visualisation of landmarks by presenting a.) the landmark as photorealistic picture; b.) the drawn sketch or c.) the brand of a certain restaurant (modified from [Elias et al., 2005])

route directions (verbal and hand-drawn sketch maps) from passers-by on the Stanford University campus and analysed their structural similarities. From the results they infer a verbal and pictorial toolkit for the automatic generalisation of graphical and verbal route directions based on inferred spatial prototypes. They propose a common underlying conceptual structure of both the graphical and verbal route directions and conclude that these two externalisations are based on the same conceptualisation. These prototypes are sufficient for constructing route instructions. Figure 10 illustrates the pictorial and verbal toolkit.

According to the map externalisation, this type of schematic representation is a cognitive-conceptual space-schematisation [Peters and Richter, 2008]. This cognitively motivated approach fosters the legibility of the representation by decreasing the *cognitive difficulty* through emphasising the underlying conceptualisation.

Table 1 sums up the categorisation results of all the presented examples of schematisation techniques.

2.4.4 *Wayfinding Choremes*

In this thesis I present a transfer of the schematisation technique *wayfinding choreme* from a map representation to a embedding into a virtual environment. Therefore I will describe this schematisation here in detail.

This schematisation approach for map representations is based on the theory of wayfinding choremes introduced by [Klippel, 2004].

The concept of wayfinding choremes is inspired by the theory of chorematic modelling by Brunet [1987]. Klippel [2004] states that Brunet's ele-

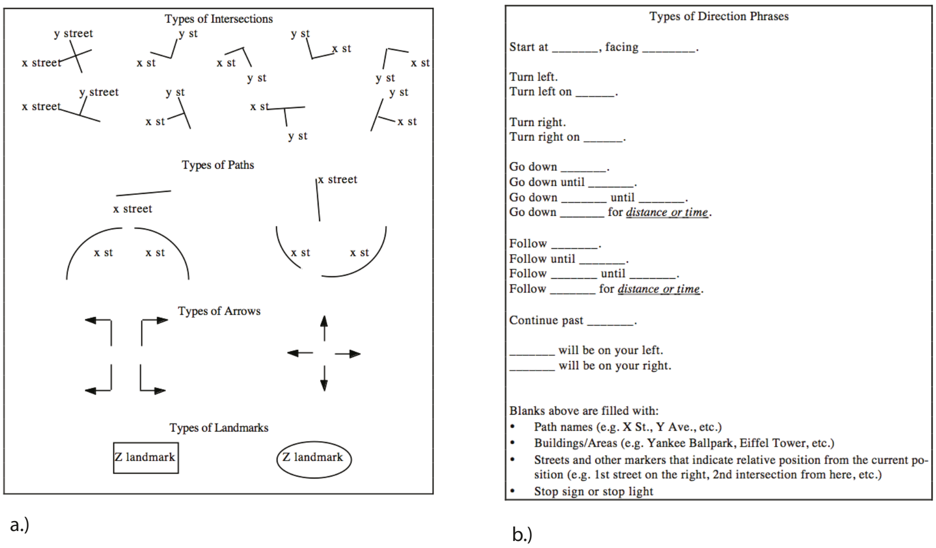


Figure 10: Toolkit for route descriptions: a.) graphical toolkit b.) verbal toolkit (modified from [Tversky and Lee, 1999])

mentary models describing graphical externalisations of spatial information, termed *choremes*, are the smallest possible entities, or primitives. The word *choreme* is a made-up word composed of the lexical root *choros*, the Greek word for space, and the suffix *-eme*, used analogously to the suffixes of phonemes for speech or graphemes for written language.

Inspired by the work of Brunet, Klippel developed wayfinding choremes as a cognitively adequate schematisation technique that is defined as an abstract mental conceptualisation of functional wayfinding primitives. He stated, "Wayfinding choremes are functional primitives of direction (turning) concepts at decision points" [Klippel, 2004, p.112].

Klippel distinguishes between structural and functional primitives, where structural primitives are linked to the spatial configuration at the decision point and functional primitives are connected to the conceptualisation of the action at a decision point. This distinction has a strong correlation to Richter [2008]'s distinction between complexity and difficulty in the context of wayfinding assistance.

Klippel empirically identifies mental conceptualisations of turning situations and terms this concept—verbally and graphically externalised—*wayfinding choremes*.

Figure 11 presents the sketch map results of the empirical investigation whose participants adhered to prototyping the turning action at a decision point [Klippel et al., 2005b]. Klippel states, "Wayfinding choremes—as

Table 1: Summary of presented schematisation techniques; categorisation of space or object schematisation, conceptual-cognitive or data-driven approach, and the effects on difficulty (visual or cognitive) or complexity

Method	Object/ Space	Cognitive/ Data Driven	Difficulty
DCE Map	Object	Data	vis. difficulty
LineDrive Map	Space	Data	vis.+cog. difficulty
Focus Map	Space	Data	vis. difficulty
Landmark Map	Object	Cognitive	vis.+cog. difficulty
Toolkit	Space	Cognitive	vis.+cog. difficulty
Choreme Maps	Space	Cognitive	cog. difficulty

a domain specific extension—are defined as mental conceptualisation of primitive functional wayfinding and route direction elements; their focus is on the actions that take place in environmental structures" [Klippel et al., 2005c, p.96].

Wayfinding choremes have a graphical and a verbal externalisation. In this thesis I concentrate only on the graphical externalisation.

The graphical externalisations of the concept of wayfinding choremes are prototypes of an angular configuration of turning actions on a wayfinding map. They reflect the conceptualisation of mental representation, reasoning and interacting at a certain decision point.

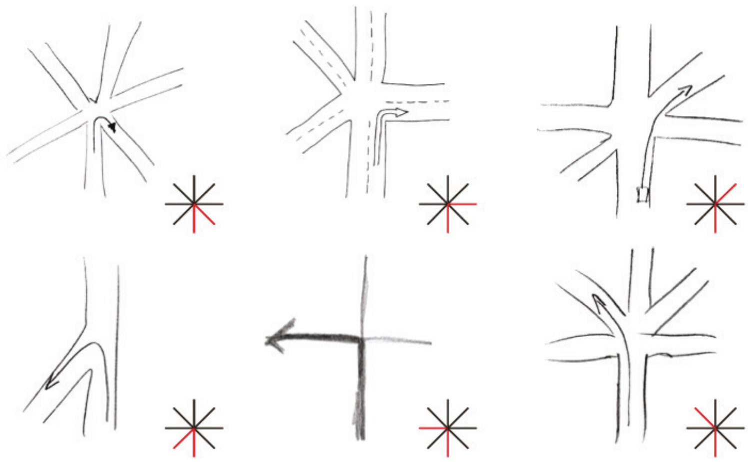


Figure 11: The experimental basis of wayfinding choremes. These six sketches present six basic wayfinding choremes without a wayfinding choreme for going straight on (modified from [Klippel, 2004])

Dealing with the graphical externalisation of wayfinding choremes, this graphical form requires a precise instantiation.

Klippel [2004] employs for the instantiation an 8-sector model, which allows calculating an 8-direction model. Each sector has an equal size of 45° for prototypical directions (see Figure 12).

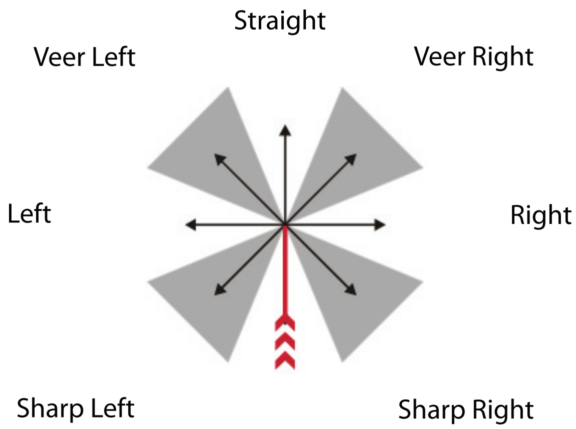


Figure 12: Applied eight-sector model to identify the according wayfinding choreme (modified from [Klippel, 2004])

Consequently, the route segments at an intersection are represented by the 45° prototype of the corresponding sector [Klippel, 2004]. To adjust the sector model, the incoming route segment is used as a reference direction due to the goal-directed movement, and the outgoing route segment is conceptualised according to its prototype. The seven possible wayfinding choremes are based on the direction of the sector model.

According to his empirical findings, Klippel [2004] defines seven wayfinding choremes: *straight*, *veer right*, *right*, *sharp right*, *sharp left*, *left*, *veer left* as illustrated in Figure 13.

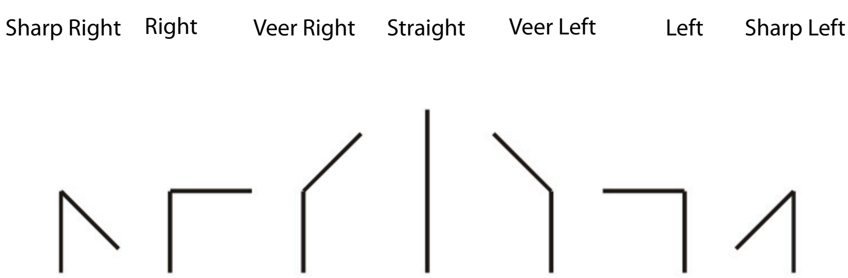


Figure 13: Prototypical turning action: seven wayfinding choremes (modified from [Klippel, 2004])

Basically, the wayfinding choreme schematisation can be broken down into three steps: firstly, analysing the decision points along a given route according to the angular situation of the intersections, secondly, replacing the functional part at each intersection by its wayfinding choreme, and finally, aligning the integrated wayfinding choreme according to the direction of travel along the route [Klippel, 2004].

This schematisation technique is applied to a map representation with a predefined route for a route following task with a map. This map is termed *wayfinding choreme map*. For the integration of the concept of wayfinding choremes into a map representation, all the intersections of the route have to be modified. The incoming branch of each intersection of the route is used to adjust the intersection to the direction model. The outgoing branch will be replaced by the corresponding wayfinding choreme of the sector that the original branch matches with. Hence, the angle between the incoming and outgoing branches needs to be calculated and classified according to the direction model (see Figure 12). This procedure must be repeated for all intersections along the route.

The replacement of the original outgoing route segment with its wayfinding choreme has consequences for the graphical representation of the whole route. Every replacement of the original outgoing route branch influences the connection of and the topology to the following intersection because the position of the following intersection needs to be shifted. To overcome this problem, all the intersection positions along the route are fixed and adjustments of the integrated wayfinding choremes according to the changes are done via Bezier curves [Klippel et al., 2005c]. When, consequently, schematising the route and also the road network according to the concept of wayfinding choremes, the route network is only locally manipulated.

Klippel [2004] claims that this schematisation has several enhancing effects on the wayfinding performance, such as easing the alignment processes of external and internal representations, and selecting the correct branch of the intersection during the decision process by replacing the original curve with its according wayfinding choreme. The decision points along the route are the critical part of the task for a wayfinder, and as a consequence, the wayfinder needs adequate support on this issue by the external representation intended for their assistance [cf. Daniel and Denis, 1998]. The graphical externalisation of wayfinding choremes turns the wayfinder's focus to the decision points and emphasises specific turning actions in a wayfinding situation.

This type of schematisation is a cognitive-conceptual space-schematisation [Peters and Richter, 2008]. The concept of wayfinding choremes simplifies the angular information of certain relations. This schematisation lowers the *cognitive difficulty* by emphasising the mental conceptualisation of turning actions at decision points.

2.5 VIRTUAL REALITY

The term virtual reality (VR) denotes computer-simulated environments that simulate the presence of a place in real or imaginary worlds. Many virtual environments are created as platforms for research application or training activities.

With the increase of computer power, computer simulations have become large-scale virtual worlds in which people can navigate and find their way in real-time.

In this thesis I focus on virtual reality applications that can primarily be experienced visually. The presentations of visual stimuli range from small displays like mobile phones to computer screens to large screens or even fully immersive caves.

Over the past 30 years, virtual environments have been applied to evaluate various aspects of human performance. These studies concerned themselves with a broad range of human aspects in the larger field of cognition, perceptual issues or motor performance.

Virtual reality as a medium gives research the freedom to change the limitations of reality, to easily measure and control the participants' behaviour and to minimise any influences of noise.

Numerous researchers have investigated the performance of wayfinding in VR and the influence factors of displaying spatial information [cf. Brooks, 1999; Nash et al., 2000; Slocum et al., 2006].

Nowadays, virtual environments are applied as wayfinding assistance services. Over the past 20 years, this type of spatial information representation has developed from an expert and experimental tool for selected applications to a platform that tackles the everyday needs of common users. Amongst other things, virtual 3D city models are employed to deliver spatial information for search, vacation planning or traffic information.

2.5.1 *Wayfinding in VR*

In recent years a number of researchers have attempted to investigate the understanding of wayfinding and navigation in unfamiliar environments by the use of virtual environments. Many studies on VR investigate various spatial activities and performances like moving, exploring, searching and building up of spatial knowledge in virtual environments.

In these studies, VR is used both as a direct source of spatial information and as an indirect source.

Subjects are able to find their way in virtual environments [e.g. Darken and Sibert, 1993, 1996a; Nash et al., 2000; Ruddle, 2001; Ruddle and Jones, 2001] or employ VR as a tool for wayfinding assistance [Münzer and Stahl, 2007] in the real world. They build up spatial knowledge of the virtual environment which is comparable to spatial knowledge acquired from real environments [Meilinger, 2008].

Regardless of whether spatial knowledge is derived from virtual or real environments, it is orientation-free, as compared to spatial knowledge acquired from maps [Montello et al., 2004]. However, if subjects learn routes in VR their knowledge will be strongly biased in the direction of the route, for example, when recognising landmarks as if learned in real world [Schweizer et al., 1998].

People are able to learn routes and build up survey knowledge in VR, but compared against real world survey knowledge, they tend to perform worse in pointing and distance estimation in VR [Richardson et al., 1999]. Nevertheless, with training the performance can be enhanced [Ruddle et al., 1997].

Several observations indicate that people have difficulty in maintaining spatial knowledge or orientating in VR [Darken and Sibert, 1993]. This is due to the fact that experiencing virtual environments differs from experiencing the real world as to certain characteristics, e.g., to the field of view, the accessibility of depth information, the quality of visual input (e.g., photorealistic details), sensomotoric feedback (treadmill) or other sensory modalities.

A factor affecting human performance is interface design. Ruddle et al. [1996] analyse differences in movement patterns of subjects navigating in an immersive (using a head-mounted display) or non-immersive (using a desktop setup) virtual environment.

Another influence factor is the movement control devices in virtual environments, such as keyboards and joysticks, or body controlled devices like treadmill VirtuSphere [3].

There exists a large variability in setups of virtual environments, like desktop presentations or immersive environments with head-mounted displays, which in turn generates a large variability in spatial knowledge acquired via VR.

In experiments in which subjects wear head-mounted displays and walk through space on their own, a better performance was yielded in survey knowledge tasks as compared to desktop setups [Ruddle and Lessels, 2006].

3 http://www.virtusphere.com/, retrieved January 05, 2012

2.5.2 *Enhancing Wayfinding Performance in VR*

Due to the fact that people have a number of difficulties with finding their way in VR without getting disoriented, several researchers have investigated which factors influence and enhance wayfinding performance in VR. For this, some researchers are trying to apply real-world design techniques to improve wayfinding in virtual environments, while other researchers get inspired by cognitive motivated techniques to enhance wayfinding performance.

I will concentrate on approaches which put focus on the visualisation of the spatial information but not the interfaces of virtual environments.

Darken and Sibert investigate in their studies a toolset of techniques based on assisting aspects derived from the real world that positively influence the performance [Darken and Sibert, 1993, 1996a,b].

For their study cases Darken and Sibert implemented a toolset which contained *flying, acoustic landmarks, breadcrumb markers, coordinate feedback* (presents current position), *visual synthetic landmarks, regionalisation* (drawn visible lines), *grid navigation* and *map navigation*. Additionally, they investigated the influence of global features by displaying an artificial sun or compass information.

The participants had to perform three navigation tasks: *exploration*, *naïve search* and *informed search* in a large-scale environment of open sea islands where they were searching for ships as their target.

From their findings Darken and Sibert concluded that missing directional and visual clues lead to disorientation. Furthermore, they propose that human beings tend to use environmental factors like coastlines or gridlines as paths during navigation. They examined that presenting an underlying grid in the VR improves performance by providing useful orientation cues.

In summary, Darken and Peterson [2001] present a review of enhancing techniques in VR like *using maps, integrating landmarks, presenting trails or footprints, giving directional cues,* and *implementing implicit and explicit sectioning*.

Another approach, inspired by Lynch's ideas of legibility with the essential components *path, edge, landmark, districts* and *nodes*, was introduced by [e.g. Ingram and Benford, 1995; Ingram et al., 1996; Ingram and Benford, 1996]. In their work they propose a set of general techniques that are applied to information visualisation. Their specific instantiation of these techniques results in a legibility system called *LEADS* which aims to enhance legibility. This system contains a set of algorithms for automatically creating or enhancing legibility like: clustering algorithms to create districts, creating edge objects to separate districts, setting in landmarks at central points of districts, and emphasising nearest neighbour nodes objects within districts and creating paths between them.

Ingram and Benford found that participants performed better in the *LEAD*-enhanced environment as compared to the non-enhanced virtual environment. Additionally, subjects also claimed to feel less disoriented in the enhanced environment.

The approach of Ingram and Benford aims to develop a virtual environment without any realistic copy. Other researchers purpose to apply Lynch's role model to a virtual environment which represents an existing real environment [e.g. Omer et al., 2006, 2005].

Omer et al. developed a method to highlight urban objects over a city orthophoto, in their case Tel Aviv. They follow the framework of Lynch's urban image theory and present an appropriate framework to facilitate transferring spatial knowledge from the real city to its virtual representation.

Other approaches for enhancing legibility in VR employ the ideas of *The social logic of space* written by Hillier and Hanson [1984]. They present a new perspective on architecture and urban design according to mutual influences of architecture and navigation in the environment. In their analysis of small villages in the South of France, Hillier and Hanson show that even small and simple unplanned urban structures have an "underlying order". They define measurements for the legibility, navigability, accessibility and awareness of urban space by analysing the relationships between local and global properties of space. The *Virtual City Builder* constructs virtual cities based on underlying principles of space syntax [Ingram et al., 1996]. By means of agent simulations, they test the effects of space syntax on wayfinding behaviour.

2.6 summary

This Section provides an overview of recent research on wayfinding and wayfinding assistance. In particular, human conceptualisation of spatial information is introduced, and its impacts on cognitively motivated wayfinding assistance systems are presented. Different wayfinding assistance approaches aim to employ the results of spatial cognition of wayfinding and conceptualisation in order to develop an adequate assistance for a certain wayfinding task. Hence, an intensive investigation of wayfinding tasks and their information needs is required to infer the type of information that need be presented by an external representation for performance assistance—next to an answer to the question how this information is conceptualised by the wayfinder.

The next chapter presents a detailed task analysis to inspect the informational needs of two route following tasks—route following with maps and route following from memory.

3 INFORMATION REQUIREMENTS OF ROUTE FOLLOWING

The development of cognitive ergonomic wayfinding assistance systems requires a thorough analysis of a potential user's informational needs for successfully performing a specific task. In this chapter I will introduce a systematic procedure to examine the informational needs of the two predefined wayfinding tasks as showcased: route following with the aid of maps and route following from memory.

This chapter starts with an introduction of the method of functional decomposition (see Section 3.1) to decompose complex systems.

In Section 3.2 I will employ the concepts of functional decomposition to a theoretical wayfinding model.

By the examples of *route following with maps* and *route following from memory*, in Section 3.3 I will functionally decompose these two wayfinding tasks. To the end of this chapter, in Section 3.4 I will use the results of this to extract the similarities of these two *route following* tasks.

3.1 FUNCTIONAL DECOMPOSITION

Functional decomposition, broadly speaking, is a process which breaks down a complex system into the functional relationships of its components. The process of decomposition can either be applied to gain knowledge about the internal components of the system or for the purpose of acquiring a representation of the systemic function at a certain level of abstraction. This approach is a fairly general approach for analysing complex systems in many fields of science, such as philosophy, mathematics, biology or computer science.

Reductionism is a philosophical school that exploits functional decomposition as a tool to understand and to investigate the nature of complex things by reducing them to their parts and interactions. Thus the focus of this approach is on causality. A famous example of this is the model depiction of a duck's organism as an automaton, as it was conceived by Descartes [1643](see Figure 14).

In the field of computer science for example, this approach is applied to different areas such as algorithms, knowledge representations, machine learning or programming languages.

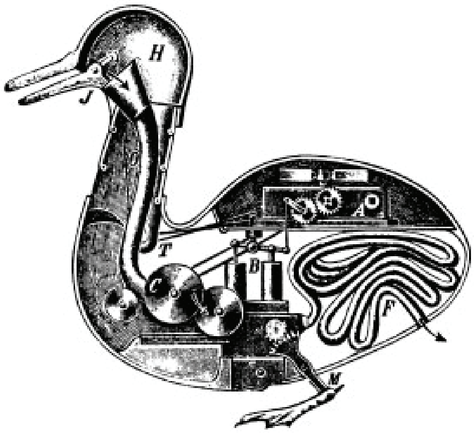


Figure 14: Descartes' picture of duck automaton (cf. [Descartes, 1643]

"Divide and conquer" is an algorithm design paradigm that is based on the concept of decomposing a problem into sub-problems. All "Divide and Conquer" algorithms recursively break up a problem into two or more sub-problems until the sub-problems become simple enough to get solved directly. Thus the solution for the main problem is based on a combination of the solved sub-problems. With this technique different kinds of problems can be solved, such as sorting, Fast Fourier Transformation, or other optimisation problems which deal with dynamic programming [Cormen et al., 2001].

Furthermore, in the field of computer science functional programming is a programming paradigm that is based on the concept of decomposing the computation into functions or modules—and not in states, as is the case with imperative programming languages.

In the area of machine learning, many approaches consisting of hierarchical models deal with functional decomposition, such as decision trees or hierarchical clustering [Zupan et al., 1997].

The idea of functional decomposition is also employed in cognitive science as a general approach to inspect cognitive systems. Influenced by philosophical assumptions inspecting complex systems by decomposition, researchers in cognitive science have applied functional decomposition to cognitive systems. Fodor [1983] for example has revived the discussion about the modularity of the mind. He postulates that modules are functionally specialised cognitive systems and that these modules must be domain-specific and must encapsulate information.

Taking these examples from philosophy, computer science and cognitive science as indicators for the extensive applicability of functional decomposition, the next part of this introduction will present the basic concepts and requirements for a functional decomposition analysis.

3.1.1 *General Idea*

The general goal of a decomposition analysis is to break up a complex system into smaller and more manageable or understandable parts. Therefore a system can be decomposed either by the categories or by the functions of its components. The following example will illustrate the differences between these two approaches by the example of a car. To simplify this complex system, only the engine, the wheels and the steering wheel will be taken into consideration. By categorising its components one can decompose a car by classifying every component by its material. Inferentially, all components consisting of a specific material would be grouped—all steel components, for example, would be separated from all plastic components. Finally, groups would be obtained which would contain all the plastic elements, or the steel elements, or the rubber elements.

Using the second approach, one would decompose the components of a car by their function. Following this idea, all the items which produce energy for the movement of the car, like the engine components, or all the items that execute the steering, or all the items that are in charge of the movement of the car would be grouped together. This process can be understood as a functional decomposition.

The advantages of a functional decomposition are twofold. On the one hand, the decomposition facilitates the identification of the atomic functions that build up the complex system, and on the other hand, it facilitates the identification of the internal structure and of information needed of these structures for solving the functions and the interplay of these functions.

While functional decomposition is a general and broadly applied approach, there are basic requirements on the complex system which is to be decomposed. The following paragraph introduces a set of basic requirements and assumptions about it.

3.1.2 *Requirements and Assumptions*

The decomposition of a complex system requires this system to have a hierarchical structure. Following the ideas of Herbert A. Simon, in the context of the architecture of complex systems a hierarchy means "...a set of Chinese boxes of a particular kind" [Simon, 1973, p. 5]. Understanding the analogy of a hierarchy to Chinese boxes, it becomes apparent that on opening the Chinese box one not only finds a single new box in it but a whole small set of boxes. These Chinese boxes are organised in a sequence of boxes in complete order which can be represented by a tree structure.

Simon [1973] stated in his paper that most of the complex systems that occur in nature show a hierarchical structure. Figure 15 presents the idea of Chinese boxes as an analogy of hierarchical structures.

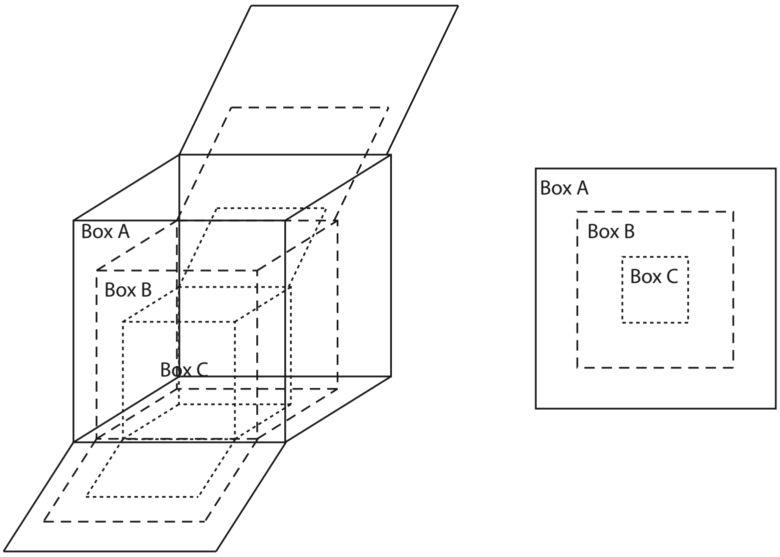


Figure 15: Schematic picture of Chinese boxes analogy: left, a schematic picture of open Chinese boxes; right, boxes in a hierarchical order

The hierarchical structure of the complex system is the basic condition for organising it into almost independent sub-systems which interact through an interface.

It is a necessary assumption for applying a functional decomposition that most interactions occurring in observed complex systems decrease in strength with increasing distance. This argument infers the hierarchical organisation of a complex system and provides an opportunity to identify and encapsulate specific functional modules and analyse them separately.

Additionally in these systems there often exists a loose horizontal coupling meaning that each sub-system is in some sense independent of the exact timing of the operation of another sub-system [Simon, 1973]. This independency of the single sub-system is due to the nesting of a sub-system inside another sub-system, so this encapsulation consequently relieves the sub-system of fluctuation of other sub-systems.

Nevertheless, most complex systems can only be analysed as near-decompositional systems. This is due to two reasons: Firstly, the dynamic interplay of the sub-systems cannot be neglected over a long period of time and leads to an overall behavioural equilibration, and secondly, sub-systemic interactions are often underestimated, while not all of the possible interactions of a complex system are analysed [Simon, 1962]. Consequently, functional decomposition analysis for the most part is a momentary observation of a complex system. This constraint must be taken into consideration when presenting the results and interpretation of the analysis.

3.1.3 *Decomposing the Mind*

Functional decomposition is a suitable and common method of analysis applied to cognitive science. Within the field of cognitive science, a general assumption is that a variety of cognitive mechanisms and processes underlying our mental life are organised domain-specifically and functionally independent. The idea of a modularly organised mind is based on philosophical ideas like Descartes' division of imagination and will or Kant's decomposition of sensation, judgement and understanding [Wilson and Keil, 2001]. The basic elements of the basic functional decomposition of a cognitive system are: the sensory organs, the reasoning/memory unit and the effectors (see Figure 16).

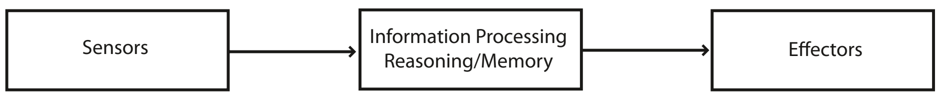


Figure 16: Schematic presentation of information processing. First step: Input given via sensors; second step: Information processing unit; third step: action performance via effectors

The organisation of the brain and its mental processes reflect a modular and hierarchical structure. An example for the modular organisation of the brain is the classification of brain areas into their functions. Broca determined a modularity of the brain by analysing its dysfunctions and came to the conclusion that cerebral areas must exist which correspond to discrete mental functions [Wilson and Keil, 2001]. Wernicke proceeded on this course and by clinical observations concluded that three brain centres associated with language production and use must exist [Wilson and Keil, 2001]. The results of his work can be seen as a functional decomposition for language.

Another example for applying functional decomposition is the analysis of the memory system. Following common opinion, at least two distinctive memory sub-systems exist. A distinction is made between short-term memory and long-term memory. But this is not the only possible or recent decomposition model of the memory system. In the field of cognitive science the results of memory experiments have led to a variety of explanation models of the memory system, including distinctions between working memory, declarative memory, semantic memory and sensory memory. Currently there is no consensus of an appropriate model that concludes the entire range of memory phenomena [Wilson and Keil, 2001].

These two examples of applications of functional decomposition follow the fundamental ideas of information processing systems in cognitive science. Cognitive science describes a cognitive system that processes information derived from perception, recognition, encoding, decoding, saving and memorising as well as reasoning, problem solving, action planning and executing and language [Strube et al., 1996]. Cognitive systems can be seen as complex systems and are investigated on three different levels: the level of computational theory, the level of representation and algorithm and the level of physical realisation [Marr, 1982]. The level of computational theory focuses on determining which computations are necessary for mapping the input information to output information. On the second level the definition of information processing operations is highlighted, and on the last level the physical implementation of the cognitive system is focused. Functional decomposition is allocated on the level of representation and algorithm. Following the information processing approach, cognition is declared as a process of symbol manipulation. A fundamental thesis of cognitive science is the physical symbol system hypothesis: "A physical symbol system has the necessary and sufficient means for general intelligent action", as stated by [Newell and Simon, 1976, p. 116]. Information is processed in the system by syntactic operations on formal symbols.

Simon and Newell continue these theoretical considerations in their work, a General Problem Solver (GPS) [Newell and Simon, 1963]. Here, solving a problem means finding a way in a given situation to turn to a desired situation or goal [Wilson and Keil, 2001]. The General Problem Solver is a computer programme developed for implementing a universal machine in order to solve problems. Separating its knowledge of the problems from the chosen strategy, GPS was the first computer programme with a single strategy for solving problems. GPS is based on the idea of problem reduction according to which problems are either decomposed into smaller sub-problems or an initial problem is transformed into a known and solved problem.

The method a GPS works with can be considered as a functional decomposition. Thus the problem space presents the complex system with hierarchical structures in which the solver tries to find the solution for the problem. The solution is a product of the sub-solutions of the sub-problems. To solve a sub-problem by itself, it must be independent from other sub-problems. Due to this structure the system of hierarchical ordered sub-problems satisfies the criteria of loose horizontal coupling.

3.1.4 *Critique and Limitations of Functional Decomposition*

Up to this point the advantages of utilising functional decomposition to a cognitive system have been discussed. At this point, however, it must be mentioned that each approach also has its drawbacks. Fodor [2001] himself states that not all processes in the mind must necessarily be modular. He claims in fact that the ideas of modularity, informational encapsulation and domain specificity were taken too far.

First of all, the mind examined as complex system is not as such a system that works in a vacuum—it is embedded in the human body. Researchers from the fields of philosophy, psychology and cognitive science have termed this field of research embodied cognition or embodied mind theory. Functional decomposition analysis mostly neglects this issue, and the mind is seen independently from the body. This simplification enables researchers to investigate even a complex system. Nevertheless, these results are to be critically studied in the context of embodied cognition.

Furthermore, the mind can only be seen as a near-decompositional system because the sub-systems of this complex system do not work independently. The assumption of independency of certain sub-systems can only be regarded as valid as long as the respective problems are being investigated within a short period of time.

However, seeing the concept of modularity as a tool to inspect this complex system, this approach has the great advantage that it provides a starting point for investigating complex systems. The implications on the theory of mind are useful in that these assumptions are fruitful and inspiring.

3.2 Decomposing Wayfinding

In cognitive science, wayfinding is considered as spatial problem solving [Passini, 1984a]. A person in a wayfinding situation has to solve the problem of finding a way to reach their destination, on a cognitive as well as on a behavioural basis.

Passini [1984a] introduced a wayfinding model which is based on three steps, focussing on decision steps. These three steps are grounded in the informational processing step and are termed as cognitive mapping, decision making and decision executing. Cognitive mapping is understood as generating information, meaning that the information received from the world around the person is understood via direct perception and integrated into the internal representation of knowledge. The second step is decision making, which means structuring decisions according to the information received from the cognitive mapping step, and planning an action and structure in order to create a wayfinding plan. The third step is decision execution, when the decisions that were made are transferred into a behavioural movement pattern and will be executed.

Figure 17 presents the functional decomposition of the general wayfinding model.

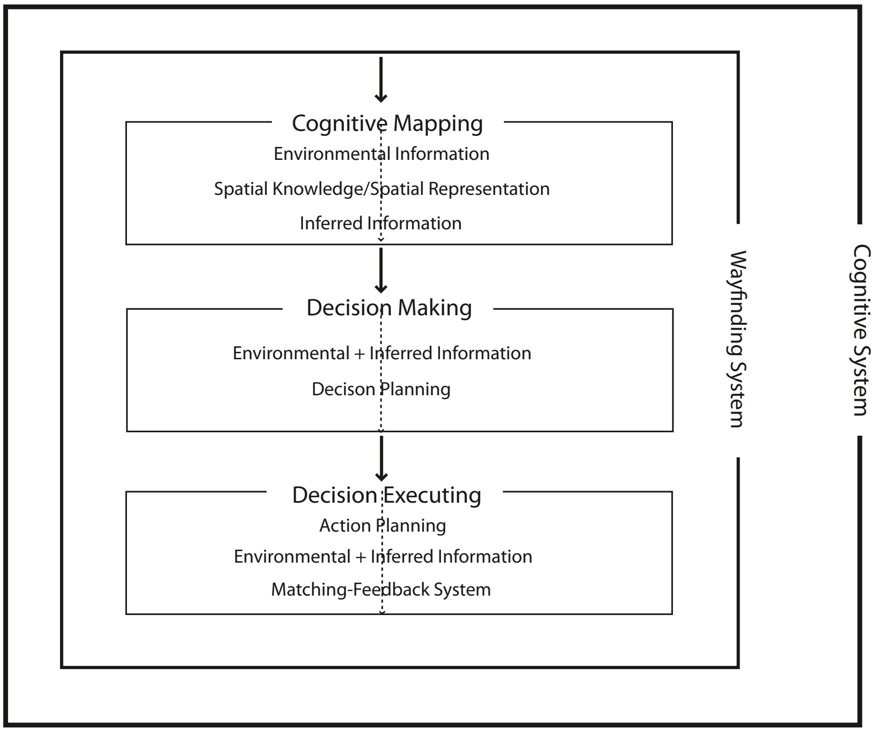


Figure 17: Adopted model of Passini [1984a], functional decomposition of wayfinding. Three steps: Cognitive mapping, decision making and decision executing

Upon closer examination of spatial problem solving, the first wayfinding decision is made when a person defines the destination of their journey in their mind. This decision is based on spatial aspects which describe the destination in a spatial context. It can be vaguely or incompletely described in spatial knowledge and spatial representation. Usually a spatial problem cannot be solved by a single decision but rather a series of decisions is needed. All these decisions require information from the environment, directly perceived in the spatial setting, or inferred information received either by previous experiences or by the combination of solving other spatial problems.

Decisions alone do not lead to a physical goal. A decision must be executed through an action in a specific place in the physical environment. For executing a decision environmental information and inferred information for spatial representation are needed as well.

Passini [1984a] described the decision execution as a matching feedback model which mostly operates on a subconscious level. Therefore, the expectancy of the decision maker is important. During decision execution a check of the expected environmental setting at a certain time will lead to an action. If this is not the case, decision execution requires reanalysis and becomes a task.

The decomposition of decisions is considered to be a hierarchical structure. A complex wayfinding task can be described as a hierarchical structure of sub-tasks which allows both the solving of manageable semi-isolated problems and yet taking into account the problem as a whole.

The functional decomposition of decisions fulfils the criteria of loose horizontal coupling. By encapsulating each sub-decision, the interaction and dependencies between sub-decisions can be reduced.

However, this complex system of spatial problem solving is not completely decomposable. A wayfinding system is a near-decomposable system. On the one hand, this originates from the neglected influences of several factors of this cognitive system. Its influences on the wayfinding system can be as manifold as the motivation behind the wayfinding task. A person under time pressure during wayfinding due to an emergency would react in a different way than a person in a leisure situation would react. Another issue is the spatial ability of the respective person. This overall influence on the wayfinding system results in a priority shifting in decisions. On the other hand, the interactions between the sub-systems of decision making in spatial situations can be changed over time. This can be caused by learning, adoption or strategy changes of a person according to the spatial situation and previous knowledge [Chen and Stanney, 1999].

For the introduced model, the factors which make the system a near-decomposable system will be observed in certain instances. Therefore in the following section I will introduce the spatial situation of and underlying motivation for the analysed model. Additionally it will be assumed that neither learning nor adoption occurs during the time span of the investigation which takes place on a fixed-hour level, and according to the comparable spatial situation no strategy changes happen. These factors will be discussed for both functional decompositions.

This model of wayfinding implicates the importance of the required spatial information received by the environmental setting and inferred by the internal spatial representation for solving spatial problems in general. The analysis focuses on the relations between spatial problem solving and the conceptualisation of spatial information in internal spatial representations.

Before the wayfinding tasks *route following with map* and *route following from memory* will be functionally decomposed, I will generally introduce *route following*.

3.3 ANALYSING ROUTE FOLLOWING

Everybody has experiences in navigating along a known or unknown route between, for example, the route from their home to work, and the route from a hotel to a sightseeing point in a new city. During this process a person has the goal to reach a known destination in an environmental space by navigating from a fixed starting point along a certain route. For this task route knowledge is required, which can be learnt directly by interacting with the environment or indirectly, provided, for example, by maps or verbal route directions. The process of *route following* can be decomposed into three sub-tasks: 1.) identifying a location, 2.) deciding for a movement that leads towards the goal and 3.) mapping this movement decision to the environment [cf. Daniel and Denis, 1998].

These *route following* processes can be mapped into of the Passini wayfinding model. Performing route following the wayfinder has to identifying a location in the cognitive mapping task, the decision making match with the movement decision task and the decision executing is in this task the mapping of the movement decision to the environment.

LOCATION IDENTIFICATION The identification of certain points during a *route following* process is essential for the success of the process. The wayfinder must identify the starting point, the goal and several points along the route at which the wayfinder has to decide which movement will lead to the goal. These decision points can be recognised, for example, by the specific form of an intersection, or by counting decision points, or by a certain landmark at a decision point.

People use different sources of spatial information for location identification like structural elements (e.g. shape of an intersection, arrangements of landmarks) [e.g. Meilinger, 2008; Mallot, 1999; Lee et al., 2002; Appleyard, 1970] or objects (e.g. landmarks, proximal or distal, visual or other sensors) [e.g Steck and Mallot, 2000; Sorrows and Hirtle, 1999]. A crucial point during this process is the saliency of the clues.

Usually a person remembers selected information from decision points better than other information along the segments [Lee et al., 2002; Janzen, 2006]. Imagine a straight route from home to work: Here, a person only needs to recognise the goal on their arrival but no further changes of direction during the route up to it because there is no additional decision point on the way.

Therefore the focus of *route following* is put on discrete locations and not on continuous processing of the environment [Mallot, 1999; Trullier et al., 1997]. During a route following task the navigators must know their current position at the decision points and which movement decision has to be made for the given situation.

movement decisions and movement mapping Given that a route usually contains more than one decision point, the process of *route following* typically is a sequence of location identifications and movement decisions. The combination of these two processes must be recombined several times to succeed in *route following* tasks. For example, at a specific intersection the wayfinder remembers to turn left at a church. The process of movement decision can therefore be decomposed into sub-problems: firstly, to decide on the movement direction at a specific decision point, which leads to the goal, and secondly, to map this decision to the current spatial situation and thirdly, to execute it [cf. Daniel and Denis, 1998].

The spatial situation in which the movement decision is embedded provides information of landmarks to anchor both the decision and the spatial configuration of the branches of a decision point intersection. In an urban environment, this spatial configuration is based on an intersection which contains different numbers of branches and different angles between these branches. The wayfinder has to map the movement decision onto one of the existing branches and has to execute the movement until the next decision point is reached [e.g. Richter and Klippel, 2005; Richter, 2008; Klippel, 2004].

Figure 18 presents the integration of the wayfinding task *route following* in the context of the introduced wayfinding model.

In the following two subsections I will introduce two different *route following* scenarios. First I will present the task *route following with map*. In this setting the person utilises a map as an external representation of spatial information. This external representation presents information of the route and the wayfinder must extract the route information and map it onto the current spatial situation. The second task is *route following from memory*, which contains a recognition phase and a recall phase. This wayfinding task has to be solved without external wayfinding assistance. Both wayfinding

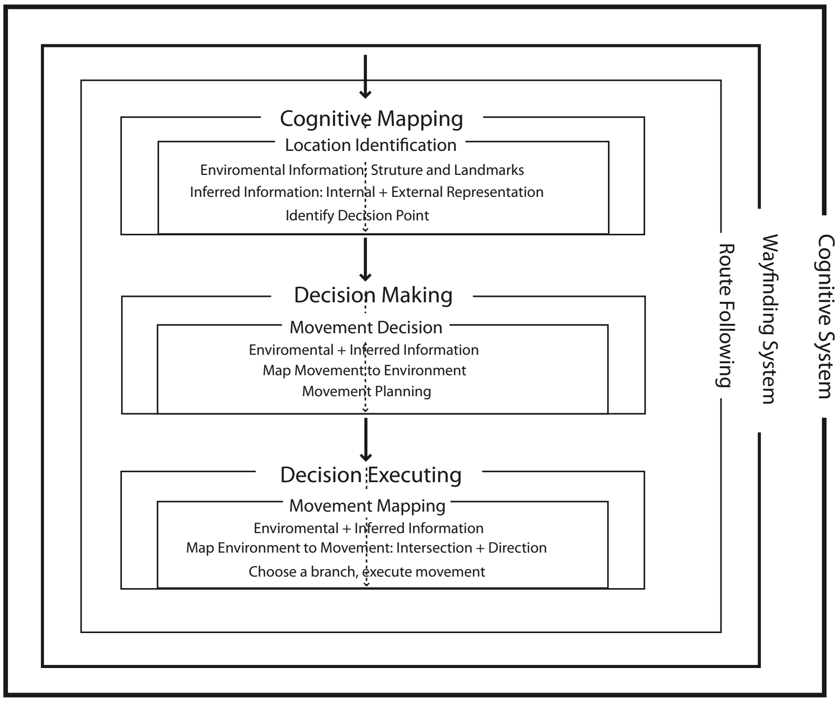


Figure 18: *Route following* embedded in the wayfinding model: Refinement of every sub-task. In *route following* during the cognitive mapping step a person has to identify the location; the second step is to map a movement decision during the decision making step and the last step is the movement mapping and executing in the environment.

tasks will be functionally decomposed. The result of the functional decomposition will be applied to analyse the similarity of the informational needs of both wayfinding tasks.

3.3.1 *Route Following with Map*

Using a map as external wayfinding assistance during a *route following* task is a common way to deal with an unknown environment. During this task people follow a predefined route which is planned and defined by the persons themselves, or given by other navigational services, like an external route description. The map highlights the route in a visual, graphical way and the map user must extract the information of the map to identify the route.

Maps have a long tradition in wayfinding assistance. This externalisation of spatial information is a traditional and comprehensible format to assist a person in wayfinding. In Chapter 4 I will explicitly present the qualities of maps and depict the kind of spatial information that maps contain and present. The theoretical considerations of the map as a medium are limited to static paper maps here.

A map user must read the map, understand the spatial information it contains and must infer the acquired information to their personal spatial knowledge and expectation and map it onto the spatial situation. In the following paragraph I will introduce the main cognitive subtasks of map reading and integrate it into the presented wayfinding model.

3.3.1.1 *Map Reading*

Anyone using a map must solve certain cognitive tasks such as symbol identification, object rotation, self-localisation, visualisation and the matching of a two-dimensional view provided by the map with the three-dimensional view the person experiences while navigating through their environment [Lobben, 2004]. The process of map reading can be decomposed into three parts: perceptual map understanding, abstract/symbolic map understanding, and cognitive treatment of the information received in a wayfinding situation. For the functional decomposition of *route following with map* I will concentrate on the analysis of the mental processing of spatial information received by maps. For a better insight into the whole map reading process the next paragraph will give a brief overview of perceptual and abstract/symbolic map understanding [further reading cf. Lobben, 2004; MacEachren, 1995].

PERCEPTUAL AND SYMBOLIC READING Perception in this context can be decomposed into mental processes of discrimination based on visual properties such as the shape, texture, colour and orientation of objects, form recognition and spatial arrangement. Basic visual processes analyse the visual scene and extract by active perceptual organisation and other perceptual rules like the Gestalt principles the informational content of a map [MacEachren, 1995]. Additionally, certain mental processes analyse the organisation of a scene by determining the depth information of scenic elements, separating foreground and background information and grouping the elements by criteria like visual properties and spatial relations.

The next step of reading a map is the understanding of the representation of spatial information on the map. In this representation, spatial information is presented in an abstracted way. Signs and symbols are central to information transfer. Sign information transfer is analysed by semiotic theory which refers to the function of signs. Semiotics is an approach on the communication of meaning and the interpretation of signs. It can be analysed by the syntax addressing formal and structural relations between signs, semantics tackling the meaning of signs to what they represent, and pragmatics concerning the relation of signs to their interpreters [MacEachren, 1995].

VISUALISATION,SELF-LOCALISATION,PATH INTEGRATION When analysing the process of map reading during a route following task three cognitive processes are essential to interacting and relating the acquired spatial information with the environment. These processes are visualisation, self-location and path integration [Lobben, 2004].

The map-reader must mentally integrate the extracted information of the two-dimensional map into a three-dimensional format of the environment and match their characteristics and objects, such as buildings, streets and intersections. The process of visualisation refers to the development of a mental representation of map information [Lobben, 2004].

In this context, visualisation is both the identification of patterns and objects to match the current spatial situation with the map content, and utilising the information of the external representation to make predictions for future spatial situations after a certain transformation or series of transformation—to predict, for example, the expectations that arise for the arrangement of the next intersection. Two sub-tasks for visualisation are the encoding of spatial information acquired from the map and then linking this information with the inferred information to the environment in order to determine movement consequences.

During the process of map reading, self-localisation takes place. This refers to a mental process of matching real-world clues of the environment with the map. The central question to be answered is, where on the map, relating to the current spatial situation, is the person located? For solving the self-location task two sub-tasks are important. Firstly, map readers must be able to determine their location on the map by identifying object features and spatial arrangements, and secondly, by aligning their orientation to the map orientation [Lobben, 2004].

Visualisation and self-localisation represent two ways of interaction with the two-dimensional map and the three-dimensional world. Visualisation is the information process that is concerned with matching a map to the environment, in contrast to self-localisation which processes information from the environment to the map. Both processes describe an interaction circle within map reading.

Both processes are essential to acquire the spatial information from a map to perform a route following task. For location identification as well as movement decision, the wayfinder has to map the route information which is presented in the map to the current environment (visualisation) and also has to map their current position to the corresponding position on the map (self-localisation). During location identification the wayfinder utilises the map to extract information about the next decision point. Accordingly, the wayfinder matches the presented map content to the environment by understanding the presented landmarks or spatial configuration first. The second step is self-localisation when the visible spatial scene is collated with the map content in order to figure out which object or other confirmation matches with the map content.

Having identified the respective location, the external representation of the movement decision can be extracted. Hence, in an urban environment, the map reader concentrates on the configuration of branches of an intersection displayed on the map to figure out which branch is to be to chosen in the real environment. Likewise, visualisation and self-localisation are needed for extracting the spatial information.

Integrating both cognitive sub-tasks into the *route following* model, as well in *location identification* task as in *movement decision* task the wayfinder has to perform both sub-tasks to first extract the needed information from the map and to locate themselves into the environment and acquires the necessary movement decision information at this point from the given external representation.

The process loop of *route following* comes to an end with decision execution, when the wayfinder moves to the next decision point.

The third process is path integration, which is independent of map reading as such. Path integration describes the process of maintaining a sense of direction and location in an environment [cf. Lobben, 2004; Franz and Mallot, 2000; Wang and Spelke, 2002]. A person obtains route information by self-motion and integrates this information over time to estimate their current position [Loomis et al., 2001]. This information is derived from movement and velocity as well as from turns and orientation information on relative location, as related to the origin. Their sense of direction or location sums this information up and allows a person to move effectively through the environment [Lobben, 2004].

Figure 19 presented the integration of *route following with map* into the wayfinding model.

3.3.2 *Route Following from Memory*

A common way of acquiring spatial knowledge directly from an unfamiliar environment is during *route following from memory*. In this situation the wayfinder must remember the route without help from external representations. During this process a person builds up route knowledge (see Section 2.1.1) for memorising the information that is necessary to succeed the *route following* task. This phase is termed *route recognition*.

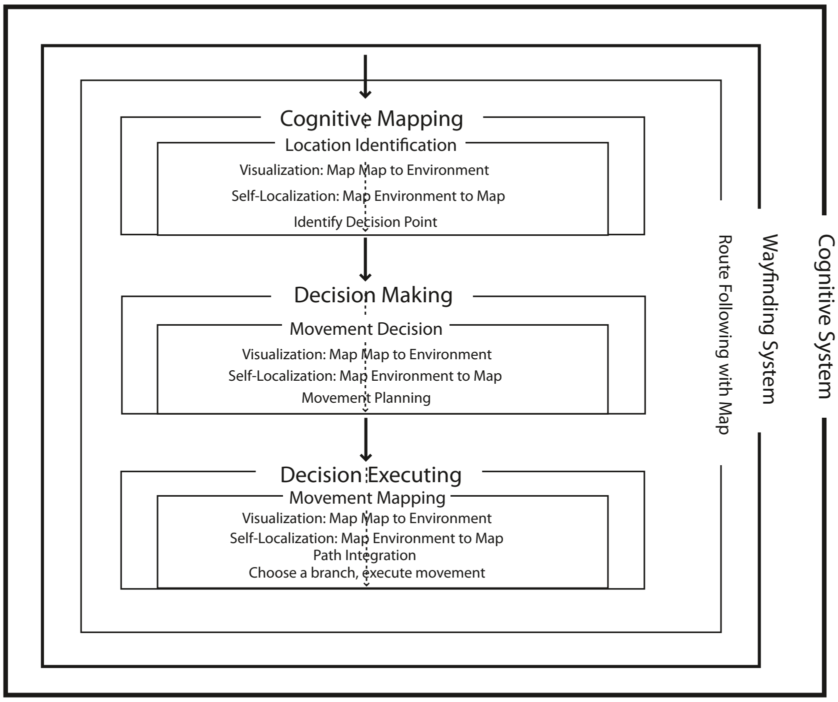


Figure 19: *Route following with maps* embedded in general *wayfinding* model: Integration of the sub-tasks visualisation and self-localisation and path integration

In the *route recall* phase the navigator must remember the route and utilise the route knowledge to successfully navigate along the route. Therefore the route must be remembered including all the necessary spatial information that defines the route, such as decision points, landmarks along the route, the configuration of intersections and movement decisions at certain decision points. Kuipers [1978] described in his TOUR model how three classes of representation are needed to solve this task: knowledge representation about a particular environment, representation of the current position, and representation for inferences between the other two representations.

Experiments of *route following from memory* tasks give evidence that route knowledge is parsimonious. There is no requirement for an extensive knowledge of the whole route for successful navigation [Gale et al., 1990]. Golledge et al. [1992] showed in their work that people could navigate a route correctly without being able to sketch it correctly. They proposed a parsimonious development of orientation, sequencing and topological arrangement of route components in route knowledge. Parsimonious selection is the reason for several errors in behavioural performance, like sketch mapping, distance estimation, orientation and sequencing. These erroneous results give an introspection of the inherent conceptualisation of certain aspects of route knowledge.

However, the question on which selected information is stored and which factors influence the choice of informational clues has not fully been answered yet.

The next two paragraphs present a functional decomposition of route recognition and route recall. For this analysis of *route following from memory* I set a scenario in which the wayfinder is unfamiliar with the environment and in which the route is highlighted in a special way during the *route recognition* phase, for example by signals in the environment. During the *route recall* phase the route is no longer highlighted. The navigator knows this circumstance beforehand and has to recall all route information from memory. The person has only one trail, and this procedure excludes any familiarity issues concerning the person and their environment.

3.3.2.1 *Route Recognition*

The *route recognition* phase can be understood as an active-memorising mode in which the navigator experiences the nearby and visible environment by perceptual focusing, body movements of head and body turning and travel effort [Golledge et al., 1995].

I define *route recognition* as a cognitive process of five sub-tasks. These five sub-tasks are: 1.) the recognition of a decision point; 2.) selecting relevant discrimination features for this decision point, which are salient for place recognition; 3.) creating an association pair of decision point and movement, which leads to the destination; 4.) path integration, which accumulates metric information of the segments between decision points; and 5.) the storage of the route information.

RECOGNITION OF DECISION POINTS During the navigation along a route, the wayfinder identifies decision points at which the movement direction is changed and a new direction is followed. In urban environments, such decision points are often intersections along the route. Furthermore, a decision point can also be a reference point to assure that somebody is still on the route at long segments. The identification of decision points is partly a conscious and partly a subconscious process. Franz and Mallot [2000] stated that *route following* can be explained as a recognition-triggered response.

FEATURE SELECTION At each decision point the wayfinder selects information to recognise the place again. Such clues can be objects or configurations in the environment. The salience of the respective clue determines if it is chosen as a landmark. Selection of landmarks is an issue of ongoing research [Peters et al., 2010]. Thus, the identification is partly a subconscious process; the selection of landmarks and other discrimination features is a subconscious process as well.

MAPPING MOVEMENT OF DECISION TO DECISION POINT After selecting a decision point and mapping a discriminating feature to this point, the wayfinder has to map the movement decision to the decision point as well. Therefore the wayfinder must determine which movement decision leads to the goal and how to memorise this decision.

PATH INTEGRATION Path integration, as was described in 3.3.1.1, defines the process of determining the self-motion of the wayfinder. The acquired knowledge of metrical and topological information can be integrated in route knowledge to store information about the segments along the route.

STORAGE OF ROUTE KNOWLEDGE The final step during *route recognition* is the storage of all acquired information in route knowledge in order to remember this information during the *route recall* phase. This combination of different information will be integrated and parsimoniously saved in memory. Figure 20 presents the advanced wayfinding model.

3.3.2.2 *Route Recall*

During the *route recall* phase, the wayfinder identifies the route only from memory. Therefore two cognitive processes, location identification and movement decision (described in Section 3.3), are necessary to succeed the wayfinding task. In comparison to *route following with map*, these two processes receive their information only from memory of the route knowledge and from the inferred information of route knowledge and the current environment.

LOCATION IDENTIFICATION Following the assumptions of Section 3.3, the wayfinder has to identify several decision points along the route—the starting point with the original heading of the wayfinder, the decision points along the route at which the movement direction is changed, and the destination. On the one hand, these points are identified by mapping the current spatial situation—with memorised environmental configurations and salient objects —in ones internal route knowledge. On the other hand, the information thus stored might be manipulated or inferred by expectations of a spatial situation due to preceding memorising processes in which certain spatial situations were prevailing and formative of the wayfinder's behaviour or reaction to them. Additionally, during the storage of spatial information

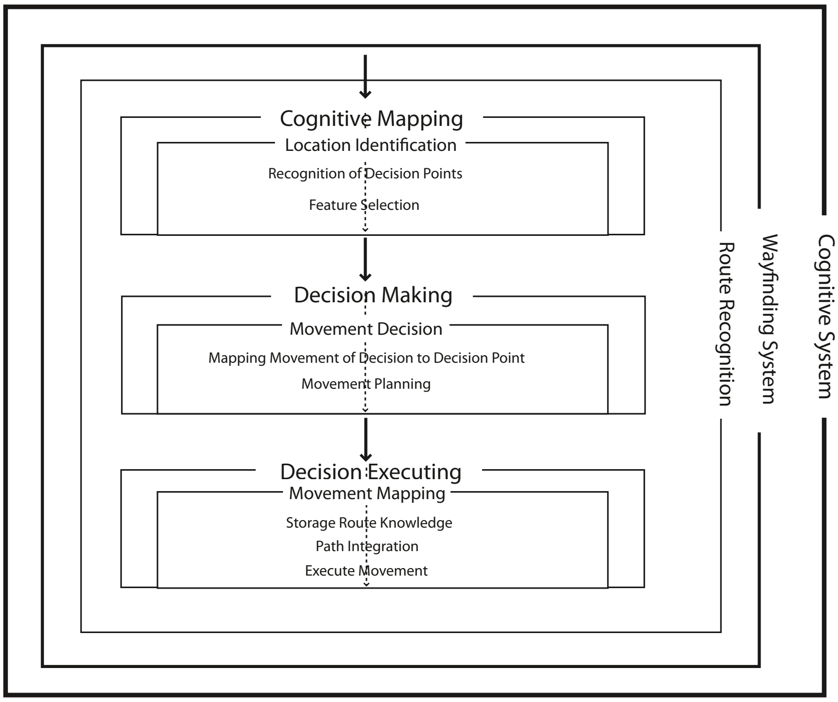


Figure 20: Embedding of *route recognition* in wayfinding context. Integration of each sub-task to the general model.

(see Sections 2.1.1 and 3.4.1) in route knowledge, this information is mentally processed to build up a spatial representation. This conceptualisation results in emphasising certain aspects of spatial information. Therefore the wayfinder must map the conceptualised and memorised information to the current spatial situation and compare the stored information with the current point in order to recognise the decision points. In case the navigator identifies a decision point, a movement option needs to be chosen.

MOVEMENT DECISIONS AND MOVEMENT MAPPING The second step during *route recall* is the movement decision at a decision point. Here, the wayfinder has to match the decision point to a movement direction, for example, 'go left at the intersection with the church on the right hand side'. The execution of a movement decision requires the navigator firstly to decide which movement direction leads to the destination, and secondly, to map this movement decision to the current environmental situation. Most commonly in an urban environment the wayfinder, after deciding for a movement direction, must chose a branch at an intersection. Figure 21 presents the cognitive sub-task of *route recall* in the context of *route following*.

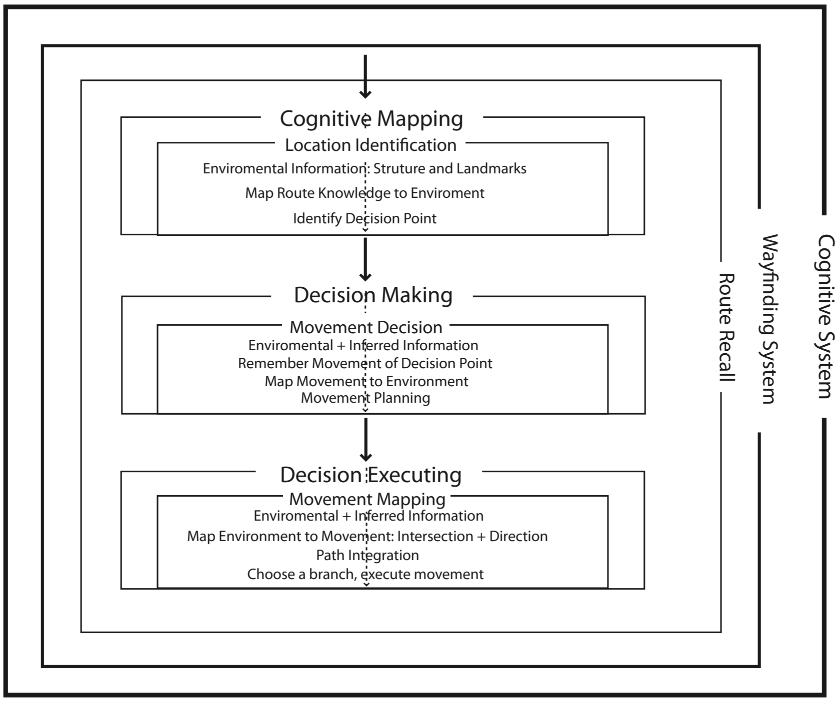


Figure 21: Embedding of *route recall* in the wayfinding context. Integration of every sub-task to the general model.

3.3.3 *Comparison of Sub-Tasks*

For the comparison of the two wayfinding tasks, I will use an urban setting in which the wayfinders perform their *route following* task in a street network, for example, in a city. The two tasks mainly differ according to their usage of external representations as a source of spatial information or internal representations. As is the case with *route following with map*, the wayfinders acquire information of the route by reading a map that presents route information. In *route following from memory*, the wayfinders first have to extract the useful spatial information from the environment, in order to store the route information into an internal representation in the *route recognition* phase. Hence, the wayfinders have to build up an internal representation of the route. This route knowledge has to be retrieved in the second phase, the *route recall* phase. In this second phase the wayfinders must remember the route from memory. For this the wayfinders have to identify via memory the salient clues at decision points to recall the movement decision needed to follow the route. To solve the route following task, in both of the cases the external representation or the internal representation must contain necessary spatial information. Comparing the two *route following tasks*, for *route following from memory* I focus on the *route recall* phase. In the *route recall* phase the learnt, integrated and stored spatial information in the internal representation is used to identify environmental features in order to remember the route. Figure 22 illustrates the comparison between *route following with map* and *route following from memory*.

During the cognitive mapping phase, in both wayfinding tasks the wayfinders have to identify their own current location. For this the wayfinders analyse either the external or internal representation to determine or remember salient spatial features first and then align these features to features at their current position. Within this step in both cases the wayfinders have to identify the decision points along the route by analysing the external or internal representations.

In the next step, in both tasks the wayfinders have to determine which movement decision leads to the goal of the route. For this the wayfinders in the *route following task with a map* have to interpret the graphical representation of the street network on the map and must identify the correct intersection. In *route following from memory*, this step has to be performed from memory. The wayfinders have to remember the correct movement decision at the respective intersection. Afterwards, in both cases the correct movement decision has to be planned.

In the last step, in both tasks the wayfinders have to execute the planned movement decision. Hence, the wayfinders have to select the correct branch at an intersection to execute the planned movement decision. The correct branch is to be selected by aligning the planned movement decision to the current intersection. Thus in the case of *route following with map* the map is used to clarify which branch is the right one whereas in the case of *route following from memory* this decision has to be made by remembering the correct branch. Then, in both cases the wayfinders have to perform the movement and move on to the next decision point.

The inspection and the comparison of the two *route following* tasks demonstrate that certain similarities can be detected.

3.3.4 *Information Requirements of Route Following Tasks*

Performing a specific wayfinding task, wayfinders need spatial information to solve this task successfully. This information can either come from external representations, like maps, or from verbal descriptions or memory given by the internal representation and from the environment.

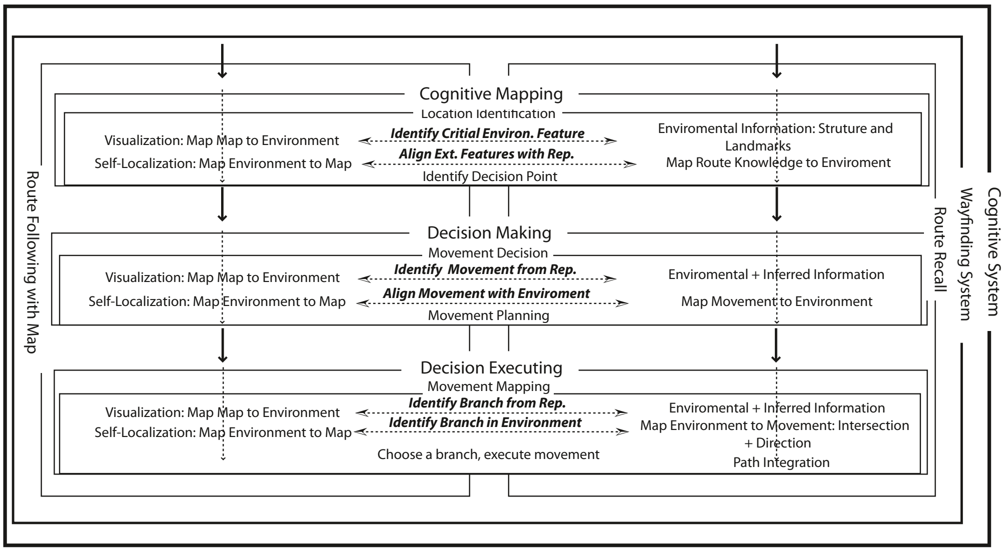


Figure 22: Comparing *Route following with Map* and *Route Following from Memory*. Identify differences and similarities.

Certainly, depending on the complexity of the route and the complexity of the environment, the information requirements for following a route are heterogeneous.

Following a route with two turning actions like ”turn left at the second intersection and then at the next turn right”, the needed information is given in this single sentence. With increasing complexity of a route—according to the length of the route, the number of turning actions, the number of branches at its intersections and the arrangements of branches [cf. Richter and Klippel, 2002; Mark, 1985]—wayfinders need more information to solve the wayfinding task. Hence, many researchers [e.g. Duckham and Kulik, 2003; Mark, 1985] have investigated the issue of determining the ’simplest’ route. Thus not only the complexity of a route as such but also the complexity of the route description is taken into account [Richter and Klippel, 2005]. Depending on the externalisation of an external representation of spatial information, the complexity of route descriptions may vary.

Additionally, environmental complexity can increase the requirement for information significantly. A monotonous urban environment with uniform street configurations together with uniform landmarks at the decision points can ambiguously affect wayfinding decision making—in that people need more information to identify decision points at all [Schmid et al., 2010], just as complex urban environments with unusual intersection configurations necessitate more distinct information during wayfinding.

These complexity considerations open up a large field of investigations and research questions. I narrow my inspections of the information requirements for *route following* down to a preselected 'average' route in an 'average' environment. Both *route following* tasks are performed in the same environment and on the identical route.

For the two wayfinding tasks to be analysed, *route following with map* and *route following from memory*, the available spatial information differs significantly.

route following with maps On *route following with map*, the wayfinders acquire the necessary information both from the map and from the environment. During the wayfinding task, the wayfinders must identify the necessary spatial information presented by the map and match this information with clues from their current environment. The graphical presentation of the spatial information must be decoded by the wayfinder in order to match the external representation with the environmental situation.

For identifying each next decision point, the wayfinders must reorientate and localise their respective position on the map. Therefore the starting point has to be highlighted on the map, and the wayfinders must align themselves with this representation. During the task, the map representation delivers information of the overall street network and its configuration. This information is needed to identify the decision points at which the wayfinders have to perform a turning action. At these decision points, the wayfinders need adequate information from the map to identify the points by matching the display configuration of the street network and the current environmental situation.

The next step is the readout of the turning action. Depending on the visualisation of the route and assumed that a line displays this route, the information of the turning action is given by the course of this line. The wayfinders have to detect the direction change of their course of the 'route' line at the respective decision point and match this change of direction to a qualitative turning concept like, 'go left'.

In the last step, this acquired turning concept must then be matched with the current environmental situation, i.e. a decision must be made which branches at the intersection must be taken. Hence, the wayfinders need information for matching the external representation and the current environment to solve this task. Similar to the first step as mentioned above, the map presents information of the configuration of this intersection as well as its landmark information. The wayfinders must select the branch which matches with the selected turning action.

ROUTE FOLLOWING FROM MEMORY In the case of *route following from memory*, both the built-up internal representation and the environment deliver the necessary information for the wayfinders. During the *route recognition* phase of *route following from memory*, the wayfinders have to actively select the necessary information in order to remember the route again. The wayfinders navigate along the route only once and afterwards have to perform the *route following* task. Thus no familiarity issues or 'long-time experienced environments' artefacts are considered.

Therefore the internal representation must trigger the remembrance of any necessary information for *route following* while actively navigating along this route. This is a critical point—because the internal representation is parsimonious, i.e. only a minimum of incomplete and not directly accessible information is stored and can be triggered by specific environmental features. The idea of parsimoniously storing information in an internal representation is described as "knowledge in the head" vs. "knowledge in the world" [Norman, 1998].

In the first step of *route following*, the decision point has to be identified. The first decision point is the starting point at which the wayfinders have to orientate themselves in order to align with the direction of the route. During this step the internal representation has to deliver the information needed to adjust the wayfinders to the route. In contrast to a map, the internal representation is multi-modal information source.

In the next step, the wayfinders have to remember which turning action must be performed at a certain decision point. At this decision point the information delivered by it can trigger the wayfinder's selection of the turning action [Franz and Mallot, 2000] subconsciously—or the wayfinder actively remembers a sequence of turning actions and consciously knows the correct solution.

In the last step, the determined turning action has to be mapped to the current environmental situation in order to select the correct branch. Therefore, as comparable to *route map following with maps*, the wayfinders have to map the concept of the turning to the respective configuration of branches of the current intersection.

After performing the selected turning action, the wayfinder starts the process of decision point identification over again and again until the goal is detected.

As to their information requirements the two tasks, *route following with maps* and *route following from memory*, can be compared. For successfully performing either task, comparable information must be delivered by map representation as well as by internal representation.

It is difficult, however, to answer the question if the wayfinders in the two tasks need similar information.

Yet in order to inspect the information needs for certain wayfinding tasks or sub-tasks, more information is needed. Therefore I will present an error inspection to deliver a deeper view of these *route following* tasks.

In the next section I will introduce an indirect way of analysing the information needs by analysing the observable wayfinding errors both during route following and in recall of information from route knowledge.

3.4 similarity of conceptualisation

People acquire spatial information to solve wayfinding tasks like *route following* via several different sources of spatial information. This can be done directly, by interacting with the environment, or indirectly, by the assistance of external representations of spatial information such as maps or verbal descriptions. A direct source of spatial information is a non-symbolic source and is acquired directly via sensory-motor experiences from the environment. All symbolic external representations which present spatial information of the real world transmit this information indirectly.

With the help of this information, a wayfinder builds up an internal mental representation of the route which is defined as route knowledge. Route knowledge is not an exact copy of all the presented or experienced spatial information where just random errors occur. In manifold studies [e.g. Thorndyke and Hayes-Roth, 1982; Montello et al., 2004; Tversky, 1981] researchers have analysed the wayfinder's performance during route following, and in post-tests after the route following tasks have tested the route knowledge by recall, pointing, distance estimation, sketch map, timing and retrospective reports. They found that the errors observed were systematic and thus distorted spatial knowledge.

However, it is impossible to determine which information is directly integrated in route knowledge [Montello et al., 2004] and what are the information needs of a wayfinder during route following. The navigator cannot consciously explain which information the wayfinder selects, integrates and distorts parsimoniously during the route following process. Therefore the identification of informational needs for *route following* can only be indirectly determined or estimated. The observed errors have shed light on the selection, conceptualisation and storage of spatial information (see Section 2.1.1). Depending on the way of acquiring spatial information—direct or indirect acquirement—distortions and errors may vary according to the respective interaction, while some distortions and errors occur in both cases whether the spatial information is represented in figural, vista or environmental spaces [Richardson et al., 1999].

In the following subsection, I will first present typical errors appearing during *route following with maps* and then introduce certain errors that are characteristic for the process of building up route knowledge via direct experiences during *route following from memory*. Finally, systematic errors will be considered that can be found in both route following tasks. I will finish this section with the conceptualisation of a specific systematic error which occurs under both conditions.

3.4.1 *Errors of Route Following with Maps*

Maps provide the route follower with a survey impression of their environment by depicting qualitative spatial relations of places and features. Maps can be both an indirect and a direct source of spatial information for the wayfinder. Once a person gets to know the environment only with the help of a map and recalls the acquired information on this map, it is considered a direct source. In our case, the navigator uses the map as a representative for the real world why in this case it is an indirect source.

Route knowledge acquired from maps is orientation-dependent [Montello et al., 2004]. Maps are usually on hand and are comprehended in a north-oriented way (reference direction). Caused by this fixed orientation of a map systematic errors occur by pointing experiments or drawing sketch maps, for example [cf. Tversky, 1981; Byrne, 1979; Golledge et al., 1995; Richardson et al., 1999]. In these experiments, the participants' pointing error variations correlate with both the originally experienced directions and the time of detecting a feature, depending on differences between the original directions in the map and current directions. This effect can be reduced by multiple views when using maps.

Route knowledge acquired from maps show distorted angle information towards right angles, and streets are remembered as straighter [Lynch, 1960; Byrne, 1979; Tversky, 1981]. Also, distance estimation is influenced by regionalisation. This means that people believe distances to be short within a certain region, for example a political region (a state or suburb), and remember them to be larger when they cross a region [Friedman and Montello, 2006]. Not only regionalisation but also perceptual organisation can bias human estimation of distances [Klippel et al., 2005a]. For example, distances are estimated shorter when locations are connected with lines. People who navigate with the assistance of a map are better at estimating direct distances between two points (beeline) [Richardson et al., 1999] and do worse in pointing to imagine points than a person who has learnt the route.

3.4.2 *Errors of Route Following from Memory*

Directly learnt route knowledge is also orientation-dependent, because the navigator usually experiences the route in one direction. This orientation-dependence is influenced by the main direction of the route but not from any cardinal directions, for example. This effect vanishes as soon as the navigator learns multiple views during the route-following task [Montello et al., 2004].

Route knowledge is not a continuous reflection of spatial information during route following. It is rather stored sequentially, and it focuses on decision points. People have a better memory for objects or configurations at decision points than they have within segments [Lee et al., 2002; Janzen, 2006]. Directly learnt route knowledge lets people make less pointing errors by pointing to imaginary (non-visible) objects [Montello et al., 2004].

A navigator, having learnt the route directly, estimates segment distances more accurately than people who use a map [Richardson et al., 1999] and does worst in direct distance estimation [Montello et al., 2004]. Also, distances of a route with more landmarks are estimated to be longer than other route distances [Golledge, 1995a]. This is also reflected by path choice, as people often use a different route on the way to a destination than on the way back to the starting point [Golledge, 1995a].

3.4.3 *Common Errors of both Route Following Tasks*

Both previous paragraphs present systematic errors which shed light on the route knowledge acquired either by specific interaction with an external medium or by direct experience.

This paragraph focuses on errors which may occur under both the above conditions in order to infer similarities of the respective information needs required for solving a route finding task, and to deduce similarities in the conceptualisation of information during the respective process of acquiring route knowledge. The assumptions thus made will be taken as a basis for further analysis of external representation for assisting people during route following.

Route knowledge under both conditions is orientation-dependent, but in the case of *route following with maps*, the internal route representation is being aligned to the original orientation of the map. In *route following from memory*, there is an alignment towards the direction the route has been experienced in.

Irrespective of the mode of acquiring knowledge, people tend to externalise streets or rivers in urban environments as straighter than they actually are when sketching them [e.g. Byrne, 1979], or they memorise borders between countries straighter when these were learnt from maps [Stevens and Coupe, 1978]. However, this systematic error of memorising streets straighter than they really are does not directly influence the performance of route following. Sketch map studies give evidence that people memorise the segments between decision points much less than they memorise the decision points themselves.

It is another systematic error that can be observed in *route following with maps* as well as in *route following from memory* that the branches at intersections are distorted towards 90 degrees (right angles) [e.g. Byrne, 1979; Gillner and Mallot, 1998; Lynch, 1960; Tversky, 1981]. This distortion occurs in the course of directly experiencing an unfamiliar environment and in environments learnt from maps even when a person draws sketch maps to explain a route to someone else [Klippel et al., 2005c; Tversky and Lee, 1999].

People who have learnt the route directly also tend to distort angles to right angles when externalising their route knowledge in sketch maps [cf. Klippel, 2004; Tversky and Lee, 1999].

This systematic error significantly influences a wayfinder's performance during route following.

3.5 SUMMARY

In this chapter I introduced functional decomposition as an adequate method for analysing the information requirements of two *route following* tasks. These two route following tasks are *route following with maps* and *route following from memory*. After introducing functional decomposition as a method to analyse complex systems, I presented the necessary requirements of a complex system to be functionally decomposable. Furthermore, I inspected this method as being grounded in spatial cognition.

As a next step I decomposed both route following tasks into their sub-tasks. For this I integrated each proposed sub-task in the introduced hierarchical wayfinding model and compared both wayfinding tasks according to their sub-tasks and information requirements.

Finally, I presented an additional analysis of the informational requirements by indirectly analysing the information needs on the basis of observable systematic errors and inferred for these results the similarities between the two tasks that could be found according to their corresponding conceptualisation.

The analyses of the two wayfinding tasks, *route following with maps* and *route following from memory*, by means of functional decomposition have shown both the comparability of their information requirements and an overlapping conceptualisation of the spatial information acquired during the tasks.

4 INFORMATION ANALYSIS OF EXTERNAL REPRESENTATIONS

For the assistance of a person during a wayfinding task, an external representation should highlight essential information, enriched with additional information that is helpful but not necessary, and neglecting information which is ambiguous or even misleading.

Defining the information requirements of a specific wayfinding task is the first part of the process of developing a wayfinding assistance system (see Chapter 3). The second part of this process is an analysis of the information included in the external representation, accompanied by an inquiry into the way this information is represented in the external spatial representation. This analysis allows us to draw a conclusion on whether a specific external representation contains all necessary information to successfully perform a wayfinding task, and if the externalisation presents this information in an adequate way.

Furthermore, this analysis facilitate to compare two different types of external representations, maps and virtual environments, according to the information they provide, respectively, for certain wayfinding tasks.

In this chapter, the focus of the analysis will be put on the information content on the basis of two external representations for wayfinding assistance: street maps and virtual environments including pedestrian view. For this I will utilise the results from Chapter 3 to concretise this information content analysis by reference to the wayfinding task of *route following*. The present chapter concludes with a comparison of maps and virtual environments according to the information they display that is required during route following.

4.1 EXTERNAL REPRESENTATIONS FOR WAYFINDING

The aim of this chapter is to identify which information is represented in a certain external representation according to the wayfinding task of *route following*. External representations vary in their information content and in the format or externalisation of the information they display. Introducing, I will present the representation-theoretic requirements for an analysis of external representations in general (see Section 4.1.1). The two external representations will not only be inspected under representation-theoretic assumptions but I will also analyse the different representations according to their psychological and cognitive qualities of external spatial representation.

4.1.1 *Representation Theory*

Representation, as briefly introduced in Section 1.1.2, can be described as a model that reflects certain aspects and relations between a represented world and a representing world. The representational system defines the correspondence between objects and relations in the represented world with objects and relations in the representing world. For the encoding and acquiring of information from a representation a user must know these correspondences of this system. Often reasoning and interacting with these representations is easier than it is with the represented world itself [cf. Palmer, 1978].

4.1.1.1 *Representational System*

In this section I will introduce a representational system according to the theoretical considerations of Palmer [1978].

A representing world, or representation, is usually utilised for a certain purpose—in place of the represented (real) world. For this, in order to solve a specific task, certain processes that operate within this represented world must be defined and then presented within the representation. These processes produce and define certain operational relations, so that an informed user is able to interpret the representing world. This is termed interdependence between representation and itÕs processing. A representation would not contain any useful information without knowledge about operational relations within this representation.

Figure 23 gives an example for a representational system. Here, the represented world contains three three-dimensional objects: two different cuboids and a ball. For this represented world there exist three representations. The first representation (ii) displays the two-dimensional form of the frontal view of each object of the represented world. The relation *taller than* of all objects is presented in the second representation (iii). The third representation in (iv) shows the classification between cuboidal form (black dot) and non-cuboidal form (white dot).

4.1.1.2 *Representational Equivalence*

Representations can differ as to objects or relations that they present but nevertheless contain the same information. For the comparison of two representations one has to analyse their information content to find out if the selected representations are *informationally equivalent representations*.

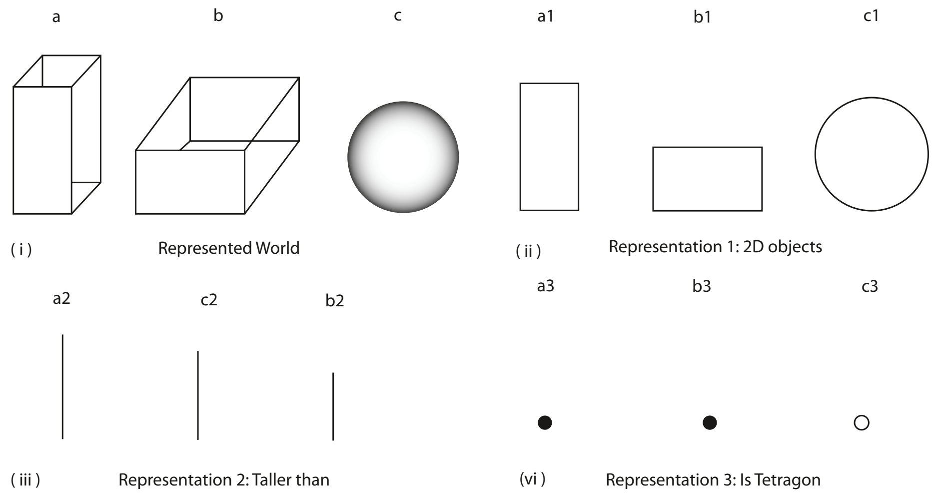


Figure 23: Examples for representational systems: (i) represented world with three objects (two cuboids (a + b) and one ball (c)); (ii) 2D frontal view representation of all objects; (iii) representation of the *taller than* relation of all objects; (iv) representation of a classification off all object in cuboid form (black dot)(a+b) or not (white dot)(c)

Comparing two representations, the information types that are transported in the representation, their resolution, and their uniqueness must be determined [Palmer, 1978]. The type of information refers to operational relations that are reflected—for example, whether it is only unary relations of facets[1] like height, length and size, or binary relations relative (like $a > b$), or if it is even higher-dimensional features that are presented by a representation.

Two representations may still display the same facets but can vary as to their resolution, just like one representation may only be equipped with two categories of size—is cuboid or not—while another representation may spread out over ten different size levels.

Even if the facets and the resolution of two representational systems are the same, the respective system has not been *informationally equivalent representations*.

These two systems can differ as to their uniqueness. Here, the term uniqueness is used analogously to its use in measurement theory, and it describes the differences between representations according to their dimensional comparison [Palmer, 1978]. For example, a dimension is called nominal if the characteristics of this dimension are only qualitative without ordering function. Otherwise, dimension is ordinal which means that this dimension can be functionally ordered.

1 [Palmer, 1978] utilises word dimension instead of facet

These three criteria—type of information, resolution, and uniqueness—are the basis for comparing two different representational systems. However, this comparison omits an analysis of the relations to the represented world. Two further criteria extend this comparison, which take the represented world into account. The first of these distinctions is whether the relations of a representational system are intrinsic or extrinsic, or mixture of both. A relation is intrinsic if it follows the same form of logical structure as those of the represented world. A simple example of an intrinsic relation is, when the same relation between the heights of two objects holds in both the represented world and the representing world. If the inherent structure of the relation is arbitrary it is termed extrinsic [Palmer, 1978].

Additionally, a representation can be direct or derived. A representation is called direct if its relations are basic operational definitions according to the represented world and do not need further computation; otherwise, it would be derived.

4.2 MAPS

One of the most prominent external spatial representations is a map. "Maps are powerful tools, and have been for centuries, because they allow us to see a world that is too large and too complex to be seen directly." [MacEachren, 1995, p. v].

A map is a specific form of an external spatial representation that provides spatial information about a portion of the earth's surface by using a visuo-spatial layout. This kind of visualisation employs various colours, symbols and labels to represent environmental features indicating variations in terrain, representing street networks and houses, etc. The term 'map' is characterised as a type of pictorial representation which presents spatial information in a two-dimensional way and which applies symbolic depiction, represents geographic entities and transports information about spatial relations of the represented world by the localisation of these symbols [Berendt et al., 1998].

For almost any purpose there exists a specific map. The respective maps particularly differ in their presentation of for example for objects, image resolution, and colour scheme—depending on the information needed for solving a certain task. As an example, a different type of information is required when looking for a friend's house in a big city than you need when going hiking in the Alps. In other words, both the task and its context are essential for designing a map. Thus, maps may vary in format, scale and purpose.

Depending on the purpose, a map-maker must select the key aspects to serve this purpose and decide on which level of detail they shall be represented. Therefore, maps vary in scale. Some maps show large areas of the earth, such as continents or the planet as a whole—as opposed to maps that present smaller selected areas of the earth, such as views of cities or neighbourhoods. With the map scale, both the resolution and the object image properties vary: A river on a world map is represented in a completely different way than a river on a city map.

Geographic maps can be categorised into two main classes: topographic maps and thematic maps. Topographic maps are designed to represent geographic information on a specific environment, e.g. the shape or the siting of land, information on distance between cities, information on terrain elevation or on water areas. Based on topographic maps, thematic maps are intended to show data which is attached to geographic data, e.g. demographic information, health issues or climate information for a certain terrain, land or city. In my thesis I focus on topographic maps.

A map as a representation of spatial (geographical) information of the real world must necessarily distort the represented information due to the legibility issues.

Maps do not only present a geometric projection of the environment but also integrate symbolic representations of processing spatial information [Barkowsky et al., 1997]. Geometric images as well as symbols require the same space on the map. Both present relevant information for the map user: Symbolic information depicts relevant information, and with the help of geometric information this symbolic information is located; or the shape information is given, or the spatial relations to other items are presented [Barkowsky et al., 1997]. Consequently, these two concepts compete for the same space on a map and interact with each other so that a map can be seen as "...a geometric projection in which the projected entities are replaced by symbolic interpretations of these entities." [Barkowsky and Freksa, 1997, p. 349]. The correspondence between signs and maps and the meaning of these signs is either explained by a given legend that is presented on the map or it must be inferred by the general cartographic understanding of the map reader.

This phenomenon of reducing information in the context of transforming cartographic representations is a subject of cartographic generalisation [cf. Hake et al., 2002; Müller et al., 1996; Weibel, 1997]. The modification of spatial data is based on the respective availability and quality of geographic data on the one hand, and on the presented scale on the other. Due to smaller scale and the reduction to two dimensions, the objects presented in a map would overlap or even be mapped to the same position and would become undistinguishable for a map reader. Therefore, a selection must be made from the items to be displayed, and some must be removed or omitted.

Nowadays, the presentation medium of maps has changed dramatically from paper maps to electronic maps, and due to this fact interaction with maps is changing. Electronic maps have the advantage of dynamic interaction, like zooming in and out and panelling. This type of map is often presented on a small screen such as on a mobile phone or in a car navigation system but also available via the Internet, e.g. in Google Maps.

Due to the high variability in maps, I will concentrate on maps designed for pedestrian wayfinding in my further considerations. Those maps typically display street networks and the outlines of buildings within an urban spatial context. They are created for pedestrian navigation assistance and the wayfinding task of route following in particular. My survey will then be carried out on static maps, using the example of paper maps, as well. Figure 24 illustrates an example of map presenting a route from train station to the university in Bremen.

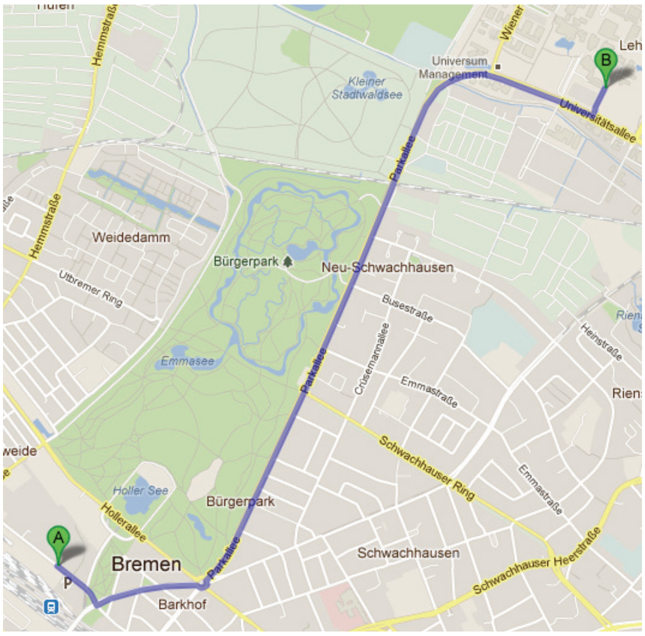


Figure 24: Presenting a route from the train station to the university in Bremen (taken from www.maps.google.de)

4.2.1 *Representational System of Maps*

"The representational nature of maps, however, is often ignored—what we see when looking at a map is not the world, but an abstract representation that we find convenient to use in place of the world." [MacEachren, 1995, p. v].

In the following section I will focus on the representational system of maps. The information content of this representational medium cannot be determined without specifying the purpose or the task the medium was designed for. Hence, I will limit my analysis of the representation system to the information needs of route following.

The process of map-making is a result of human conceptualisation of geographic space. However, this process has not yet been completely understood in formal terms [Barkowsky and Freksa, 1997]. To design a map, its maker must decide on several demanding design questions and also regard the properties of paper as the underlying medium which does not always fully meet the requirements of spatial representation. The map-maker's main goal is to design a map that adequately communicates the relevant aspects of the represented world to the user. Assuming that all geographic data are available, it is necessary to modify these data to ensure an effective communication process. Consequently, the original data are no longer directly accessible—and the common map user has no insight into which data form the basis for a specific map. Obviously, therefore, for analysing the representational system of a map one has to take into account both the map maker's intentions when designing the map and the map user's interpretation of the spatial information acquired from the map in equal measure. Three main difficulties in formalising the representational approach can be recognised: a loss of information by the transformation of the underlying geographic data, the fact that cartographic generalisation is not yet fully formalised, and the fact that the map user is not informed of the generalisation processes taken by the map maker [Barkowsky and Freksa, 1997].

In consequence of these facts, a map as a representational system does not achieve all the requirements listed in Palmer's representation theory [Barkowsky and Freksa, 1997]. According to Section 4.1.1, one requirement of a representation is that there must be full knowledge of the correspondence between the aspects to be represented (e.g. the spatial relation between entities) and the components of the representing world—which, as mentioned above, is not the case.

Even with this lack of communication, nonetheless, people works with maps quite successfully, and maps are one of the oldest communication and navigation assistance and systems in the world.

To explain this discrepancy, I follow the ideas of Barkowsky and Freksa [1997] who briefly describe the representational system of a map as a triple: a set of entities (E), a set of relations that hold between these entities (R) and meta-knowledge (M) which transforms the spatial representation to a usual understanding of the map. Concluding, a map can be seen in two ways: as a non-interpreted pictorial medium consisting of a set of entities and a set of relations and as an interpreted medium where the meta-knowledge represents the connection between the underlying spatial knowledge and the map. The meta-knowledge can be understood as a body of knowledge that covers every possible reference between displayed entities and spatial relations between the represented objects. Thus, this meta-knowledge represents relevant correspondences between the representing world of the map and the represented world. Figure 25 illustrates the correspondences between representing world, represented world and the meta-knowledge of the user to build up an internal representation.

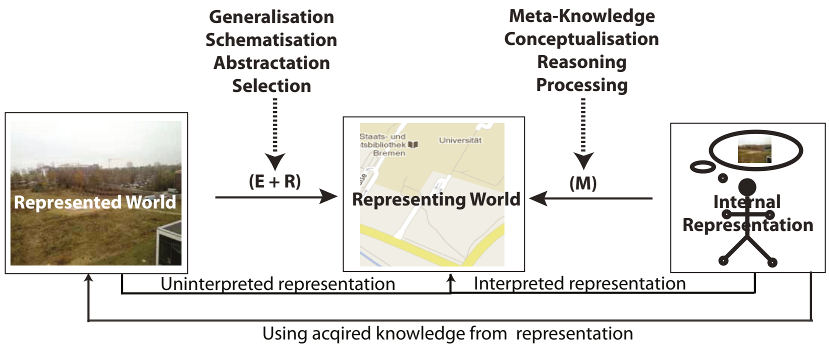


Figure 25: Correspondences between representing world, represented world and meta-knowledge.

Narrowing the discussion down to the type of maps I am focusing on in this thesis, the map is a representational system, where the real world is equivalent to the represented world. A map user does not only obtain distance and topological information but also information on objects and labelling information via the map.

4.2.2 *Maps for Route Following*

Focussing the discussion on maps for *route following*, I will narrow this discussion down to maps for pedestrians in urban environments, such as cities. Such route maps have in common that they display information that is necessary to follow a certain route.

Designed for *route following with map* of pedestrians in a city, maps have a resolution of 1:5.000 to 1:20.000, which reflects the correspondence of distance information between the representing world and the represented world. Buildings are reduced to their 2D simplified layout. Line segments represent streets. These line segments are straightened and classified by coloration and width in different street types, such as highways or minor roads. Certain areas like parks or rivers are also highlighted by coloration.

Another important issue to be considered is the use of signs and symbols, i.e. the labelling of places or buildings in a map. City maps are highly structured by symbols and signs. As in every map, the presented information can be categorised as predominantly sign and symbol information or predominantly spatial information [Berendt et al., 1998].

In the following section I will focus on three relevant information aspects during a *route following* task: landmarks, decision points and the configurational embedding of the route.

Most information on landmarks in maps is transported via symbols and signs. For example, a church can be represented by the symbol of a cross, or by a label bearing its name. Typically, depending on the purpose of a map, only selected landmarks are addressed, however. City plans usually display information on landmarks as building information, using symbols, labels or information on a region, e.g. its city districts, parks, or other geographic entities such as rivers. A map certainly cannot convey all information on salient landmarks but features a selection. The selection of useful and salient landmarks for an adequate route description, verbal as well as graphical, is ongoing research [cf. Winter, 2003; Duckham and Winter, 2009; Peters et al., 2010].

Following a route, a wayfinder must identify certain decision points along the route (see Section 3.3). Therefore a route is visually highlighted to identify each decision point by indications of direction changes of the route. For urban spatial situations, a route consists of a sequence of street segments and their intersections, where the route may take a turn into a new street.

Consequently, the embedding of a route is the spatial embedding of the streets that are part of the predefined route. A map user can gain knowledge of the way their route is embedded in the environment with a single glance at the map—due to an allocentric overview of its setting.

Angular information is central to the knowledge transported via maps. In every map, angular information is displayed explicitly by the spatial arrangement of geographic entities and their cartographic relations. However, there is a vast variety of depicting angular information in maps, starting from precise angles to a preciseness of 8-sector orientation to a 4-sector orientation to no orientation information [Barkowsky and Freksa, 1997].

In city plans, angular information is usually presented precisely. Angular information is usually directly presented in a map by the angle between the branches of an intersection.

Depending on a user's application of meta-knowledge, the user tends to over-interpret the angular information. Therefore, the user must be told to choose the correct level of meta-knowledge for every aspect at any time in order to correctly interpret and successfully use the map as an assistance tool during the wayfinding task.

Applying the analysis method of Barkowsky and Freksa [1997] to the angular information in city maps, the entities are the line segments which represent the streets. These line segments display the street network of a represented sector of the city. The underlying relations between the represented world and the representing world are identical in the case of angular information, depending on its resolution, the map represents the angular information in a more or less simplified or distorted way. The meta-knowledge of the user is applied to understand the representational system of the map. This meta-knowledge is based on their own conceptualisation of angular information in map reading. People tend to prototype angular information to 8-direction model. Therefore one must be aware that during navigation people usually do not perceive angular information as in survey presentation.

4.2.3 *Psychological or Cognitive Classification of Maps*

In the following section I will classify maps according to psychological and cognitive aspects. Hence, I investigate the reference frames, scale of space and delivered assisting wayfinding information. Maps as a wayfinding assistance system during *route following* are an indirect pictorial source of spatial knowledge (see Section 3.3.1). The perspective in which spatial information is presented via a map greatly influences cognitive performance and certainly how people build up spatial knowledge acquired via maps.

FRAME OF REFERENCE Usually maps depict information of the earth surface directly as viewed from overhead, i.e. using a vertical perspective. It is a common way to align maps to cardinal directions, usually to the north, or to align the map orientation to the first presented leg of the route. Thus, when displaying a route via map, according to this reference frame the route is presented in an aligned form.

Therefore, maps are encoded within an allocentric reference frame. Along the *route following* process, the map user must transform every single movement decision to this reference frame (see Section 3.3.1) and back again to the egocentric reference frame of the user.

SCALE OF SPACE Maps can present information about spaces starting from one's immediate surrounding environment up to the entire planetary system. According to Montello's classifications of different scales of spaces the representational system of a map for *route following* transports knowledge about environmental space by means of the depiction of objects in figural and pictorial space [Montello et al., 2004].

type of assistance Classifying maps into categories according to the taxonomy I introduced in Section 2.3.1, maps are the most popular wayfinding assistance systems of category 4 [Chen and Stanney, 1999]. This category presents information on the surrounding environment to the user in a wayfinding situation. Depending on the resolution of the map and the sector that is being presented, the surrounding information starts from the near environment and broadens to the entire planet surface depending in case of *route following* on the length of the route.

4.3 virtual environment

In this section I introduce virtual environments (VEs) as an external representation of spatial information. This medium of external representation of spatial information is a dynamic one. A user acquires knowledge of their environment by 'directly' navigating in it.

The world of virtual environments has expanded over the last 20 years to a wide range of different formats of virtual environments: from virtual environments that are presented on a computer monitor up to flight simulators on hydraulic platforms.

A virtual environment is usually an interactive, real-time, 3D graphical rendering external representation of spatial data (see Section 2.5). Subjects have a first-person egocentric view of the scene, as if the scene was viewed through their own eyes, and they control the interaction by motion devices or by their own physical motion. Therefore, a computer-created simulation of a particular place or environment appropriately responds to the respective motor commands of the user. The user acquires information on the environment sequentially and integrates this information over time into a mental representation of the environment. Their moving through the virtual environment shall give the user the impression that they navigate through a 'real' environment. Due to technical improvements, the visual appearance of environmental features has been dramatically enhanced over the years—up to virtually photorealistic computer modelling. Yet they remain 'virtual' environments, in their appearance as well as in that the user still interacts with the medium of a computer system.

Virtual environments differ in manifold ways as to their presentation and the user's experiencing of the represented world. Here, differences can be found concerning the field of view, the level of photorealistic details, additionally presented modalities, such as sounds or smell, and interface or interaction modalities. Setups range of virtual environments starting with display VE on a desktop screen to large projection displays up to augmented reality and fully immersive systems [cf. Nash et al., 2000; Montello et al., 2004; Hunt and Waller, 1999]. Depending on the setup, the field of view and other criteria may change dramatically. Some VE setups put a stronger focus on the visual presentation of virtual environments and therefore present the VE on wide screen to ensure a wide field of view.

As an example, head-mounted displays (HMDs) offer a direct way of interaction with a VE. On wearing a HMD, a computer system tracks the user's head orientation and, depending on the system, their body movements as well. Yet due to the tracking system, this setup can only provide proprioceptive information according to the user's head orientation, and the user must use a motion device like a keyboard or computer mouse for locomotion. More sophisticated systems track the complete body movement of the user without any additional motion device for translation or rotation. Systems like these allow the user to walk freely through the VE as if it were a real environment. Such virtual environments systems are called immersive VEs. Typical drawbacks are their sprawling setups like a large walking room to prevent the user from walking into walls. In other VE setups, treadmills or other walking devices provide for wide walking spaces.

Contrary to this, VEs can also be displayed on a flat CRT screen, in front of a stationary observer. Here, the field of view of the virtual environment is narrowed to a comparatively small desktop. Interaction with the VE, mainly the locomotion, is usually restricted to the use of motion devices like keyboard or mouse.

In different virtual environments, not only do their setups differ in quality but their visual stimuli vary widely too—from simple geometric box worlds up to photorealistic 3D copies of real-life scenery.

Besides, the increase of applications of 3D virtual environments demonstrates that this type of application has developed from an expert tool to a platform addressing the common users, and dealing with their everyday needs [Glander et al., 2009]. This tendency is influenced by rapid technical improvements and an easier handling of the setups of VEs. Home users need a VE setup which runs on standard hardware or home entertainment devices, like a PC or a large TV screen.

Due to the vast variability of VE, in my following considerations I will pick out and concentrate on settings of virtual world designed to train people acquiring route knowledge. I focus on VRs which are presented on projective large screens and with which the users interact with a gamepad to navigate in the virtual world. Those virtual worlds typically display information of the street network in pedestrian view so that all buildings are presented in realistic high and the users navigate along the streets. Exemplary, Figure 26 illustrates this virtual environment.

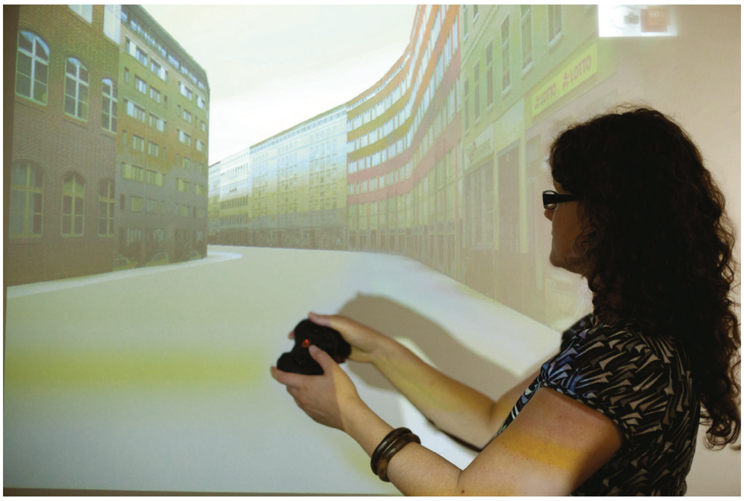


Figure 26: Presenting participant navigation in a virtual city

4.3.1 *Representational System of Virtual Environments*

Virtual environments have an intrinsic dual nature according to their representational system [Montello et al., 2004]. This kind of external representation is a representation of a specific environment on the one hand—and an environment on its own on the other. Therefore in my discussion I have to distinguish between VE as a representation and VE as an environment.

In the following paragraph I will discuss the theoretical considerations of the virtual environment as a representational system. According to the young age of this type of external representation, the theory is not quite elaborated as far as the representational nature of this medium is concerned. Due to this reason, I will take the theoretical assumptions for maps (see Section 4.2.1) as an example to explain this representational model, and based on the results of this I will facilitate a comparison of the two representational systems. For my analysis of the theoretical considerations I will as well focus on the information that is needed for *route following* task.

Similar to maps, VEs are man-made external representations. Thus, on the one hand their designers have created virtual environments dependent on the accessible data, and on the other hand their creation is subject to a defined purpose of the representation. The technical possibilities for VE have expanded dramatically over the last 20 years. Assuming the accessibility of high-standard 3D model techniques, it is now possible to represent physical spaces through photorealistic and immersive VE.

However, a VE is not a video film of the real word. Not only does the user of VEs often have the freedom to navigate 'freely' through the environment and decide by them what to see, but the medium also provides the possibility to enhance certain environmental aspects by visually accentuating them. There is an on-going discussion whether a highly realistic virtual environment must actualise an objective view of this area, or if a schematised version might provide an adequate assistance for a person in a certain task.

Advantages of highly realistic representations of spatial information are that their users see what they naturally expect to see in the environment, and its representation provides all the information the users need. However, an external representation of the real world can also be aimed at selecting relevant aspects for a certain task in order to ease the problem solving process, as maps usually do. This selection on the one hand and the reduction of information on the other hand is a common process in designing maps—depending on the medium of representation as well as on its intention to support the user beyond the technical need. This approach can be adopted for the development process of a VE.

Similar to maps, the representational system of VE is not yet completely understood, formally. Also for VE, a lack of knowledge concerning its correspondences can be detected. For an analysis of a VE, it must be taken into account what its developer had in mind intentionally to serve a specific purpose, and how the user interprets the represented information depending on the respective task. The user of an external representation is usually not informed about the underlying data nor the applied generalisation or distortion of these data. In contrast to maps, however, VEs present spatial information that need not be consciously interpreted by the user to the same extent as a map, as the more abstract representation, must be interpreted [Hunt and Waller, 1999].

Consequently, the requirements of a fully formal representational system according to Palmer are not fulfilled because this kind of representation does not deliver a complete communication of all correspondences between the represented world and the representing world.

Nevertheless, many studies have shown that people are able to learn the spatial layout of a VE and that they are capable of performing tasks such as route learning successfully [e.g. Ruddle and Jones, 2001; Nash et al., 2000; Darken and Sibert, 1996a]. Viewed from a cognition scientific point of view, a virtual environment (VE) "...offers the user a more naturalistic medium in which to acquire spatial information, and potentially allows to devote less cognitive effort to learning spatial information than by maps." [Montello et al., 2004, p. 275].

Additionally, studies give evidence that people can not only learn to perform a wayfinding task in a VE, but they can also transfer spatial knowledge, which is acquired via the virtual environment, to real environments [e.g. Münzer and Stahl, 2007; Peruch et al., 2000; Wallet et al., 2009].

To shed light on the question how the users deal with the missing knowledge of correspondences, I will again employ the model of Barkowsky and Freksa [1997] (see Section 4.2.1). The application of meta-knowledge is a central point in explaining how a user bridges the missing information of these correspondences.

4.3.2 *VE for Route Following*

As to maps, I concentrate in the discussion of VE on the wayfinding task *route following*, too. Therefore I take only VEs into consideration which present spatial information of urban environments, such as cities, in a pedestrian perspective. The presented virtual city should present buildings and the street network in a realistic matter. The buildings can be textured with façade pictures to deliver landmark information to the users. For example, simple geometric boxes can be textured with photorealistic façades representing the building in this virtual world.

The users navigate through the environment via motion controller like a gamepad, keyboard or mouse, constantly keeping a pedestrian's view on the presented scene.

Due to the fact that the users can only experience this VE from the perspective of a pedestrian, these VEs can be denominated as a 2.5 dimensional representation.

In these VE users have to train a specific route. Therefore the route must be highlighted by any visualisation technique. For example, in order to highlight a predefined route in this VE, at each intersection the direction can be displayed by arrows.

I focus on the presentation of landmarks decision points and configurational embedding of the route, as relevant information aspects of *route following*.

In contrast to map representation there is no need of interpreting symbols or colour coding because in the introduced virtual city the spatial information is displayed in a naturally realistic way. Faç ades pictures solely give landmark information. Hence, the navigators must select by themselves which façades information provides salient landmark information. There is no pre-selection done as it is in maps.

Certainly in this urban situation, decision points along the predefined route are located at intersections in the street network. However, the users of this VE experience these decision points in a completely different way. They must sequentially integrate their knowledge about the spatial embedding of a decision point in order to navigate through it. This also holds for the complete embedding of the route. No overview is given here, and the integrated spatial information of the route only exists in the users' mind.

The presented environment is spatially embedded in an underlying realistic map; nevertheless the users have to acquire this knowledge by integrating the experienced movement in this environment. The participants must infer every distance information or angular information, which is integrated stepwise via the optical flow and use of the movement device. This spatial information builds up the route knowledge. Accordingly, the presented information of a VE can be subdivided into a visually dominated part and an integrated information-via-movement part.

For example, angular information in this virtual city is precisely represented via the display of the street network configuration. The underlying map embeds equally precise angular information as the introduced city map. However, this angular information cannot be obtained at a glance like in a map; it must be experienced and inferred from the movement commands and visual flow instead. For my further analysis I apply the Barkowsky and Freksa [1997] model to the angular information.

In the case of angular information the presented intersections and buildings, bordering the intersection, are the entities. The buildings can emphasise the angular information, but at the same time restrict the vision of the users to acquire the necessary information. The relations for angular information are physically identical to the relations in the real world. The users apply their own meta-knowledge to understand and conceptualise the given angular information. Similar to the introduced conceptualisation of angular information in 3.4.3, studies have given evidence that these systematic errors also occur in spatial knowledge acquired via VE [Montello et al., 2004]. People tend to prototype angles of 45 or 90 degree even if the VE embeds the precise angular information.

4.3.3 *Psychological or Cognitive Classification of Virtual Environments*

The virtual environment is in this case a direct source of spatial information. The wayfinder can navigate freely through the environment and acquire knowledge to perform a *route following from memory* task. As for maps, I will present a psychological and cognitive perspective of analysing this external representation.

FRAME OF REFERENCE The introduced VE presents spatial information in an egocentric reference frame. Users have a first-person view of the presented environment and acquire their spatial knowledge of it sequentially via navigating through the VE with a gamepad.

SCALE OF SPACE Classifying this virtual city according to Montello [1993], this external representation (see 2.1.3) is attributed to pictorial space, vista space, and environmental space. A VE is a special case for classifying into the presented scale of space. On the one hand, this VE presents the representing world on a large screen but smaller than reality, which classifies this external representation as pictorial space. On the other hand, VEs are a part of vista space and environmental space because the user directly acquires spatial information of the presented environment and must integrate this information sequentially.

type of assistance Like maps, virtual environments belong to the fourth category of the taxonomy of navigation assistance systems. VEs present the surrounding information of an environment, but at a smaller scale than a map. Via this VE the user acquires the vista space of the surrounding and has to integrate this knowledge by himself.

4.4 comparison of map and virtual environment

In this section I will compare the two spatial information sources according to their representational details, their scales or spaces, their frames of reference and types of assistance in order to present an overview of the extent to which these external representations have something in common and the issues in that they distinguish themselves.

Table 2 presents an overview of the comparison.

4.4.1 *Comparison of the Representational Systems*

I will start with a comparison of the two representations as to their representing worlds. The applied criteria are the dimensions of operational relations, resolution, and uniqueness.

Maps and virtual environments differ as to their dimensions, their operational relations and the uniqueness of these dimensions. Each representation includes a variety of unary, binary and higher dimensional relations.

A city map usually has a given resolution of 1:5.000 to 1:20.000. The introduced virtual city represents the world on a smaller scale but, depending on the display, is perceived in nearly the same resolution as reality is perceived. However, compared to reality the navigation speed in VE is often increased.

The resolution influences both the form of appearance and the frequency of landmarks. In the investigated map, landmark information is usually given by signs or symbols, such as the symbol of a church or the name of a building. Contrary to this, in the virtual city every building is presented via a picture. The users must thus select the salient landmark by themselves.

In an urban context like a city, decision points are usually intersections along the route. Due to the resolution, the street network of a map is repre-

Table 2: Overview of comparison of two external representations: map and virtual environment.

	Maps	Virtual Environment
Representational System		
	Not Formalised	Not Formalised
Resolution	1:5.000-1:20.000	approximately 1:1
World Rep	intrinsic	intrinsic
Knowledge transfer	derived	direct
Route Following Issues		
Landmark		
	Symbolic,Labeling	Photorealistic façades
	Pre-Selected	Unselected
Decision Points		
	2D Intersection	3D Intersection
	overview	integrated
Spatial Embedding		
Entities (E)	Street Network	Intersection + Buildings
Relations (R)	Directly Given	Indirectly Acquired
Meta-Knowledge (M)	Prototyped Angle	Prototyped Angle
Cognitive and Psychological Issues		
Frame of Reference	Allocentric	Egocentric
Scale of Space	Figural, Environ.	Figural, Vista, Environ.
Type of Assistance	Surrounding Information (C4)	Surrounding Information (C4)

sented differently than it is in a virtual environment. Maps display the street network in a two-dimensional overview. A map user acquires knowledge of the configuration of a decision point almost at a glance. The angular information is directly given by the embedded intersection. The different resolution and viewpoint of the user in VE result in a different acquirement of spatial knowledge. The users have to integrate the information sequentially. The configuration of a decision point must be integrated via movement, given as optical flow. Here, the users increase their spatial knowledge of the route stepwise. Thus the virtual environment delivers the information in a higher resolution with much more details than a map, but at the same time the user needs to select the relevant features by themselves.

Representations can also differ in the way they present the presented world. Accordingly, I will discuss the qualities of maps and VE in comparison to the world they represent: the real world.

Either representational systems, be it map or VE, contain mainly intrinsic relations because they transport information by using the comparable relations as can be found in the real world.

Indeed, the two representing worlds differ in the way they transport knowledge of the representing world. The introduced virtual city can be classified as a direct form because its relations and basic operational definitions accord with those of the real world. The format of maps is rather derived, due to the two-dimensional medium and as to its signs and symbols. However, people are trained in dealing with city maps.

4.4.2 *Comparison of Cognitive and Psychological Issues*

frame of reference A map is a classical example for a representation with an allocentric frame of reference, whereas the virtual city is based on an egocentric frame of reference.

scale of space Both representations present overlapping scales of spaces. They can both be classified as figural and environmental space, but only the introduced virtual city displays vista space.

type of assistance The type of assistance is identical on both representations. Maps as well as virtual environments provide surrounding information for the user and can therefore be classified as category 4 type of assistance.

4.5 SUMMARY

In this chapter I presented an analysis of two external representations: maps and virtual environments. Therefore I inspected either representational system as to their given relations and represented entities. I limited this inspection to essential information of *route following*: landmark information, decision points and configurational embedding of the route.

These two representational systems show differences in some of the main criteria but also have many points in common.

The results of both analyses showed that maps and virtual environments differ in many aspects concerning the way either medium transports spatial information.

However, essential similarities between the two representations can be found in the meta-knowledge employed by the users in either of them, in order to gap the miscommunicated correspondences. For both the representational systems I have stated that this meta-knowledge of the user compensates the missing communication of correspondences.

An example for this overlapping meta-knowledge is the conceptualisation of angular information. Users of either external representation conceptualise angular information in similar ways. The analysis of the angular information given at decision points gives evidence of the comparability of the meta-knowledge applied in either representation. In both cases the respective angular information is prototyped by the user.

This meta-knowledge or conceptualisation of spatial information presents a bridge between the user and the external representation. This conceptualisation depends on the task on the on hand and on the medium of the external representation on the other.

One approach that uses the conceptualisation of an external representation to the user is *schematisation*. This technique emphasises cognitive conceptualisation in order to simplify the information processes inherent in an external representation. Furthermore, applying the results of my task analysis (see Chapter 3) and the above analysis of the two representations, I will present in the next chapter the requirements needed to transfer a schematisation technique from a map to a virtual environment.

5 TRANSFER OF SCHEMATISATION TECHNIQUES

In this chapter the theoretical requirements for successful transferring schematisation techniques are presented.

First, I will introduce a spatial context model for wayfinding assistance to analyse the deep interplay between a certain wayfinding task, the environment, the wayfinder and utilised external representation (see Section 5.1). Therefore, I will employ the results of my detailed wayfinding task analysis of *route following* in Chapter 3 and the results of comparison of the two external representations of Chapter in4.

Furthermore, in this Section I am going to infer from these correspondences the theoretical requirements that must be achieved to successfully transfer schematisation techniques. Hence I inspect the influences of schematisation on all correspondences of the context model.

In Section 5.2 I will introduce a candidate—wayfinding choreme—who fulfil the theoretical requirements of a transfer and I will first present the ideas of this exemplary transfer of schematisation techniques.

By reference to this particular example, I will then be able to discuss the theoretical requirements of generalising a schematisation technique, putting the focus on cognitive processes and the way these processes are supported.

Closing this Chapter, the technical realisation and implementation of the transfer of the schematisation concept *wayfinding choreme* is shown. Hence, I introduce the algorithm that embeds the *wayfinding choremes* into the virtual environment as well as the virtual environment itself.

5.1 TRANSFERRING SCHEMATISATION TECHNIQUES

In my present thesis I employ the term schematisation as simplification beyond its technical needs to support both interaction and legibility by means of a schematised external representation (see Section 2.4).

To inspect the influences of employing a schematisation technique on acquiring wayfinding information from external representation, I employ a spatial context model.

Therefore, I am going to introduce a spatial context model, termed *TEAR*, which takes a process-oriented view of spatial context, in order to analyse the correspondences between the task (T), its environment (E), the agent (A) and the representation (R). Furthermore, I discuss the strong influence of schematisation on these correspondences. This analysis will be taken as a basis for determining the theoretical requirements of transferring the schematisation techniques of one type of external representation of spatial information to another.

5.1.1 *Context Model of Wayfinding Assistance*

Depending on the respective task, a user requires different information from the environment and the external representation to solve a certain wayfinding task. Both the structure of the environment and the type of external representation have an influence on these requirements of spatial information and also influence the way this information is processed by the user.

For developing an effective wayfinding assistance system, one has to analyse the interplay and correspondences of an environment, an agent (i.e., the human user) and an assisting external representation in relation to each other in answer to a certain wayfinding task. By this method, it is possible to deduce from their interdependences the requirements of a cognitively adequate external representation.

In the following section I am going to introduce a spatial context model developed by Freksa et al. [2007]. This model defines context as the interactions of the components of a cognitive architecture, which is a rather orthogonal way of defining context [cf. Chen and Kotz, 2000; Dey and Abowd, 1999; Dey, 2001]. This model focuses on the processes to characterise the context specifically *spatial context*. This operational definition of spatial context provides the basis for a better understanding of the effects and requirements of external representations. The model describes context as a trilateral relationship between an environment, a cognitive agent and an external representation and, beyond that, it describes the interaction between these three entities according to a specific wayfinding task. I employ this model to analyse the influences of schematisation on the correspondences between the entities. This analysis will be the basis for inferring the representation-theoretic requirements of a specific schematisation technique to make it transferable between different externalisations.

External representations that aim at supporting a wayfinder during a wayfinding task are context-dependent in that they depend on the depicted environment, the selected information and the intended task. Traditionally, the term *context* has been defined by a list of factors that parameterise a supporting system to achieve a context-adaptive behaviour [cf. Chen and Kotz, 2000; Dey and Abowd, 1999; Dey, 2001]. Researchers have often defined context by enumerating examples of context [e.g. Schilit et al., 1993] or describing it as "...the set of environmental states and settings that either determines an application's behaviour or in which an application event occurs and is interesting to the user" [Chen and Kotz, 2000, p. 3].

The introduced context model named *TEAR* is a process-orientated model. The name of this model derives from the correspondences between its entities. The representation-theoretic characterisation of spatial context is described as the correspondences between the environment (*E*) in which the wayfinding task (*T*) takes place, the agent (*A*)—which can either be a person or an artificial agent—that accomplishes the task, and the representation (*R*), which is an external representation supporting the agent during the wayfinding task (*T*). The wayfinding task (*T*) influences all the correspondences by having certain information needs and conceptualisation constraints. Figure 27 depicts a diagrammatic view of this approach.

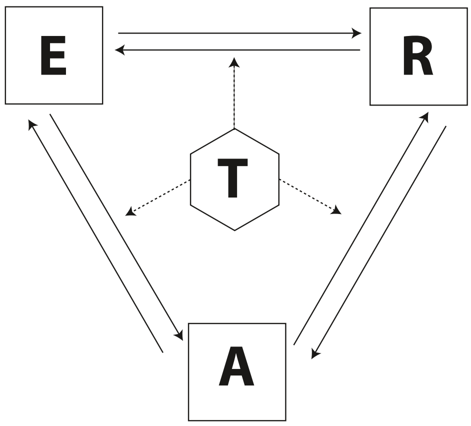


Figure 27: Process-oriented context model *TEAR* (modified from [Schmid, 2010])

Between these three entities, all processes determine the interaction proceeding to solve a given wayfinding task. For example, while using a map for a wayfinding task (*T*), the user must read the map (A × R) and interpret the information in order to be able to apply it in the environment (A × E).

5.1.2 *General Influence of Schematisation on TEAR*

One way of intentionally manipulation all correspondences of this system in order to achieve an enhancement of the wayfinding performance is schematisation (see Section 2.4). Schematising an external representation as exemplified by this system of correspondences influences all the correspondences involved and achieves an enhancement of the specific information processes between the entities. All these processes are determined by the given wayfinding task. The designer of an external representation selects and schematises certain aspects according to this wayfinding task. Analysing the correspondences of this context model allows the inspection of the interdependences between the entities. This is the basis for the feasibility to transfer different types of representation in order to support a certain wayfinding task.

By schematising the representation R_s, the correspondences between the environment and the external representation are often manipulated according to the schematisation technique be it the displayed objects and/or the relation which are modified ($E \times R_s$) in that other aspects are selected or highlighted on the representation. Caused by a schematisation agent also inspects and deals with the presented information of the representation in a different way ($A \times R_s$). For example highlighting certain objects like prominent landmarks may lead the agent to remember these landmarks easier or distorting distance information may lead the user draws different conclusions for their interaction with the environment ($A \times E_s$) than the agent had made it with an undistorted presentation.

In applying this $TEAR$ model I try to answer the following two questions:

- When is an external representation useful for supporting a certain wayfinding task?
- Under which circumstances can a schematisation technique be transferred?

Each schematisation technique specifically manipulates some correspondences intentionally, and, due to prevailing interdependencies, the schematisation technique usually influences the whole system. Hence, schematisation techniques can lower the complexity of an external representation and also concentrate on decreasing the interaction difficulties between the agent and the external representation. Lowering the complexity of the external representation can lead to a more legible presentation, thereby enhancing the agent's interaction with the representation. This enhancement is often achieved by map designers through reduction of both complexity (structure of representation) and difficulties (interaction with representation) (see Section 2.4.1).

Inspecting the influence of a specific schematisation on the correspondences of the $TEAR$ model, a new perspective is given on the topic by analysing and comparing different schematisation techniques.

From clarifying the influences of schematisation on the correspondences of the $TEAR$ system I can conclude whether the same schematisation technique works adequately for another type of external representation and has the same effects on the model. For this, firstly I must prove whether the other representation meets the preconditions, i.e., make sure that the replacing representation delivers the necessary information for the respective wayfinding task. The next step is to integrate the representation in the *TEAR* system and check if this schematised representation influences the correspondences in a similar way to its object of comparison.

In the following section, I will thus present the theoretical requirements for transferring a schematisation technique. For this purpose, I discuss the preconditions first and then analyse the theoretical requirements.

5.1.3 *Requirements for Schematisation Transfer*

The aim of this thesis is to investigate if and under which conditions a knowledge transfer of one schematisation techniques to another can be performed. To analyse the theoretical requirements for such a transfer I am using the example of transferring a schematisation technique developed for map representation to another external representation, more precisely, to a virtual environment. Applying this example, I propose in the following section the theoretical requirements for the transfer of schematisation.

To investigate the theoretical requirements for a successful transfer I start with inspecting the preconditions. The first precondition is the necessity to prove that the new type of external representation for wayfinding assistance which now employs the schematisation technique of the original representation delivers the necessary information content for solving a specific wayfinding task. I firstly illustrate the type of information that is required by the selected wayfinding task and will then demonstrate that this information is being communicated in the replacing representation.

The second precondition is to analyse if the user of the external representations employs similar meta-knowledge for certain aspects which are in the focus of the schematisation.

After demonstrating that the replacing representation fulfils these preconditions, I will introduce the theoretical requirements for the transfer of a schematisation technique.

task For the test case I selected the wayfinding task of *route following*. Chapter 3 presents two examples of this wayfinding task, next to which I investigate the general information requirements for *route following*. As examples of *route following*, I inspect *route following with map* and *route following from memory* and investigate the informational needs of these tasks. These two *route following* tasks were deliberately chosen according to the two selected external representations. In case the external representation is a map, I selected the task of *route following with map* for my analysis. For the virtual environment, however, owing to the properties of this external representation, I naturally cannot use the same wayfinding task. Therefore, I decided to use the wayfinding task of *route following from memory*. The analysis in Chapter 3 shows that these two tasks also have overlapping information needs.

Aside from that, by using the task of *route following from memory*, I can inspect more directly how this external representation influences the internal representation and the wayfinder's performance—due to the fact that in this case, environment and representation collapse.

EXTERNAL REPRESENTATION Using the information from Chapter 3 for analysing the information needs of the *route following* task, I investigate if the two selected external representations can adequately communicate this information required for solving the tasks. In Chapter 4 I compare map and virtual environment as external representations according to the representation-theoretic and psychological/cognitive considerations and their types of assistance. The comparison undoubtedly presents that these two external representations are highly different—not only with regard to the change of the frame of reference but also to the representational resolution and to other issues. According to the selected wayfinding tasks, both representations present the required information content as to the information needs of the respective wayfinding task. However, the representational systems of both external representations are not completely formalised. Yet the analysis of the meta-knowledge offers valuable clues that the meta-knowledge applied in the two cases strongly corresponds. Dealing with missing correspondences, the user applies their meta-knowledge to bridge the communication gap. Meta-knowledge can also be seen as a conceptualisation of extracted spatial information. This conceptualisation, or meta-knowledge, reflects the way spatial information is interpreted and processed by the user which influences their performance on solving a wayfinding task. Both misinterpretation and legibility of an external representation result from the matching of the conceptualisation and the external representation. If an external representation presents spatial information in a cognitively adequate way, this leads to enhanced legibility because the presented necessary information matches with the meta-knowledge.

META-KNOWLEDGE AND CONCEPTUALISATION The analyses in Chapters 3 and 4 have demonstrated that some types of spatial information are conceptualised in similar ways. Despite the many differences between the two selected external representations, these two external representations overlap in the user's conceptualisation. In both representations, the user bridges the communication gap by using their own meta-knowledge. This meta-knowledge is a mixture of previously learnt knowledge on how to interact with external representations and an internal conceptualisation of certain aspects of spatial information.

CONSEQUENCES FOR SCHEMATISATION In this Chapter I demonstrate that schematisation manipulates and influences all the correspondences in the $TEAR$-model. This manipulation of the correspondences is achieved in different ways. Beginning with the deliberate manipulation of a schematisation technique, this manipulation can be either data-driven or cognitive-conceptual. This differentiation indicates whether the schematisation approach is a bottom up (data-driven) approach starting from the available data, or a top down approach (cognitive-conceptual) starting from the conceptualisation of the user. Every schematisation process manipulates the representational system of the represented world (E) and the environment (R). By this manipulation of the correspondences between the environment (E) and the representation (R), inflicted by certain effects of schematisation, the correspondences between the representation (R) and the agent (A) are likewise affected. As schematisation usually aims to make the representation legible, it can both lower the *visual difficulty* and/or the *cognitive difficulty* of a representation. *Visual difficulty* is strongly connected to the visual clutter of an external representation. Therefore, lowering the visual complexity of a representation also positively affects its *visual difficulty*. However, the *visual difficulty* of an external representation is highly dependent on the type of externalisation. A decrease in the *cognitive difficulty* can be achieved by a cognitively adequate schematisation reflecting the internal conceptualisation. In the current test case where the conceptualisation, or meta-knowledge, of two different types of external representations bear resemblance to each other, it can be assumed that a schematisation which influences or affects this particular conceptualisation has the same (performance-enhancing) effects on either of the representations.

5.1.4 *Theoretical Requirements*

I propose in this thesis that the schematisation technique is transferable if both preconditions are fulfilled and the schematisation manipulates the correspondences between representation (R) and agent (A) on a cognitive level, i.e., it lowers the *cognitive difficulty* by reflecting the same conceptualisation of the spatial information for either of the two representations.

Therefore, the focus of the analysis is on the correspondences between the external representation (R) and the agent (A). As a requirement I quote the intended reduction of *cognitive difficulty*. In contrast to the *visual difficulty* which are strongly connected to the type of representation, the *cognitive difficulty* can be lowered by reflecting mental conceptualisations of specific aspects. Schematisation techniques that support underlying cognitive processes or structures, to realise a cognitively adequate representation, especially focus on this aim. A specific aspect of these external representations is their cognitive-conceptual way of schematisation, that is, they manipulate in a way that is consistent with human conceptualisation.

To transfer a cognitively motivated schematisation technique, the conceptualisation intended to be supported by this schematisation of specific aspects of the information required for a specific task must be applied to both of the external representations—the primary as well as the replacing one.

Hence, before transferring a schematisation technique from one external representation to another it must be ensured that the aspects to be modified by the schematisation are conceptually similar in both of the external representations.

5.2 TRANSFER EXAMPLE: WAYFINDING CHOREMES

I select the schematisation technique *wayfinding choremes*, introduce in Section 2.4.4, as a transfer candidate. The concept of *wayfinding choremes* can be integrate in route maps to enhance the wayfinding performance during a *route following task*.

Wayfinding choreme maps are developed to deliver cognitively adequate support for a *route following with map* task.

I will present a transfer of this schematisation concept from a map representation to a virtual environment representation. The wayfinding task in the virtual environment will be *route following from memory*.

The process of transferring the wayfinding choremes schematisation can be subdivided into three parts: firstly, the analysis of the concerned wayfinding task according to the information needed, presented in Chapter 3, secondly, the comparison of the two different types of representation, presented in Chapter 4, and thirdly, the analysis of the correspondences of the *TEAR*-model which I will present in the following section.

5.2.1 *Instantiating TEAR to Wayfinding Choremes*

To answer the raised questions on the correspondence of the *TEAR* model on the example *wayfinding choreme*, I will first introduce the entities I am dealing with, then analyse the correspondences between these entities and finally discuss the influences of this schematisation technique on these correspondences.

In my thesis, the wayfinding tasks (T) are located in an urban environmental setting, precisely, in a city (virtual or real), and are performed by the cognitive agent (A), who in this case is a human user.

Due to the case of using a virtual environment as an external representation (see Section 4.3.1), the entity environment (E) and the entity representation (R) must be analysed under special circumstances. In the case of a map as an external representation, the environment is the real world (E), and the agent interacts with both the real environment and the map to find the route. However, in the case of a virtual environment as an external representation, both entities can collapse to one entity in which the agent must solve the wayfinding task. For analysing the correspondences of ($E \times R$) I need to distinguish strictly between virtual environments as an environmental entity by itself on the one hand (E_{VR}) and as an external representational entity (R_{VR}) on the other. If an agent uses a virtual environment as a direct source of spatial information, the two entities, environment (E) and representation (R), collapse into one entity. In the other case, if the virtual environment is an indirect source of spatial information, the two entities exist disjointedly. To conclude, in this thesis the virtual environment is a direct source of spatial information for the agent, hence the environment (E_{VR}) and the representation (R_{VR}) coincide with regards to all the correspondences between the agent and these entities. For my analysis of the correspondences between $E_{VR} \times R_{VR}$, I distinguish between the two entities by employing the representation-theoretic considerations (see Chapter 4), where the virtual environment remodels (R_{VR}) the real-world settings (E). It has to be noted that in this thesis, in order to avoid familiarity effects on the participants (see Section 5.2.5), the virtual world is based on real-world data but does not remodel an existing real-world scenario.

The representation (R) in this thesis is either a map (R_M) or a virtual environment (R_{VR}), and the applied wayfinding task (T) is a *route following* task. In the case of the map as an external representation, the *route following* task (T_{map}) can be specified as *route following with maps*, whereas in the case of the virtual environment it is a *route following from memory* task (T_{memory}).

In the following part I discuss the correspondences between the entities of the context model $TEAR$ according to the task analysis in Chapter 3 and the representation analysis in Chapter 4.

correspondences between E and R_M The correspondences between the real world (E) and the map (R_M) are based on their representational system [e.g. Palmer, 1978]. In Section 4.2.1 I analyse the representational system between the real world and a map. This system describes the objects from the real world which are represented on the map and the relationships that are applied between these objects. Depending on the wayfinding task

(T_{map}), the analysis focuses on key information like landmarks, decision points along the route, and the configurational information of the decision points, according to the movement decision at a particular decision point.

CORRESPONDENCES BETWEEN E AND R_{VR} Analogous to what was stated in the previous paragraph, the correspondences in this case illustrate the representational system between the environment (E) and its representation as a virtual environment R_{VR}. The correspondences between the remodelled real city (E) and a virtual city R_{VR} are explained in Section 4.3.1. As it was discussed in Section 4.2.1, the analysis focuses on selected aspects that are considered necessary or important with regard to the wayfinding task (T_{memory}).

CORRESPONDENCES BETWEEN R_M AND A In Section 3.3.1, I examine the way a map user solves a route following task. Here, the correspondences between the agent (A) and the map (R_M) refer to map reading on the one hand, and to interpreting and reasoning processes as to the presented information on the other hand. Important steps in the process of interpreting and reasoning are the information visualisation and self-location of the user by means of the information that is presented on the map. Both these cognitive processes concern the user's information processing based on the presented information on the map, to acquire knowledge of the environment in order to either extract spatial information from the map, or using the map to adjust or align the information that was acquired from the environment. Furthermore, to use the representational system of the map and the real world, the agent must employ their meta-knowledge to overcome the non-communicated correspondences of the representation. The correspondences between the map (R_M) and the agent (A) reflect the way information is communicated to the agent and how the agent conceptualised the acquired information. Section 4.2.1 presents how maps represent the essential information according to the task to the map-reader.

CORRESPONDENCES BETWEEN A AND E Freksa et al. [2007] refer to the correspondences between the agent (A) and the environment (E) as more or less hardwired. In the direction from the environment (E) to the agent (A), the interaction with the agent is determined by the structure and legibility of the environment [e.g. Lynch, 1960; Hillier and Hanson, 1984]. In the other direction, the correspondences are based on the agent's perceptual/cognitive machinery—like experiencing the environment, reasoning about the next step and including their previous knowledge and expectations. Therefore, the human agent cannot distinguish between subsistent information in the environment and all such information that is built up, biased or even distorted by either conceptualisation or previous knowledge. The focus of the cognitive processes is on creating, inferring and matching the internal representation of the agent with the environment.

CORRESPONDENCES BETWEEN E_{VR}/R_{VR} AND A In the case of using a virtual environment as an external representation, the two entities E_{VR} and R_{VR} collapse into one entity (E_{VR}/R_{VR}) when analysing the correspondences between the environment (E_{VR}) and the representation (R_{VR}) in the direction of the agent A. However, in the opposite direction, both entities and their correspondences have to be considered and analysed. In Section 4.3.1 I demonstrate how a virtual environment represents spatial information perceived by the agent. Here, as opposed to the case of using a map as an external representation, the agent must acquire spatial knowledge sequentially and integrate this information to solve the wayfinding task (T_{memory}). In Section 3.3.2 I present the cognitive processes of *route following from memory*. *Route following from memory* can be subdivided into two phases: *route recognition* and *route recall*. In the former phase, the agent builds up an internal representation which will then be used in the latter, so the given route can be remembered. Comparable to the use of meta-knowledge in maps, the agent also utilises meta-knowledge to bridge non-communicated correspondences.

INFLUENCES OF WAYFINDING CHOREMES ON TEAR The schematisation technique *wayfinding choremes* influences all correspondences of $TEAR$. The schematisation technique *wayfinding choreme* intents to lower the *cognitive difficulty* of the external representation (see 2.4.4). Integrating the *wayfinding choremes* into a map, the correspondences between $E \times R_M$ are modified according to angular information. This schematisation technique replaces the original angular configuration by a prototypical angle. The correspondences between $R_M \times A$ are positively influenced because the displaying of prototypical angular information. This presented angular information supports the agent acquiring the correct turning action from the external representation. Furthermore the correspondences $A \times E$ are manipulated caused by the enhanced mapping processes of the agent who easier select the correct turning branch at an intersection.

5.2.2 *Validation of Theoretical Requirements*

In this thesis I present *wayfinding choremes* as a transfer candidate. This cognitive-conceptual schematisation technique intents to lower *cognitive difficulty*. It supports mapping of external and internal representation on the level of angular information.

This schematisation focuses on the conceptualisation of angular information in a turning situation at a decision point. Comparing the two *route following* tasks—*route following with maps* and *route following from memory*, the analysis in Chapter 3 demonstrates that each subtype of *route following* requires similar angular information at a decision point. This angular information is transported by both of the representations, the map and the virtual environment, albeit in completely different ways, presented in Chapter 4. A map shows angular information by presenting an overview of an area. Angular information is given by the presented line segments that are representative of a street or a building. Their configuration represents the angular information.

In the case of the virtual environment, the angular information is not given explicitly like it is in a map. A user must rather integrate their knowledge of the angle information by directly experiencing the area and integrating this spatial information.

Despite all these differences the analysis presented that users of these external representations apply similar meta-knowledge and conceptualisation of angular information. Both analyses illustrated that angular information is conceptualised for both external representations in a similar way (see Section 3.4.3 and Section 4.4).

5.2.3 *Transfer the Concept Wayfinding Choremes*

The transfer of the concept of wayfinding choremes into a three-dimensional virtual city is based upon the two-dimensional representation. It integrates the two-dimensional realisation into a three-dimensional virtual environment by applying the concept of wayfinding choremes to a virtual environment representation. This is achieved by locally modifying the angular configuration along the route at the decision points. For this purpose, the branches of the intersection are classified into their respective specific wayfinding choremes. To intensify the representation of the angular information, not only the branches of the intersection are changed according to the applied wayfinding choremes but also the buildings at intersections are locally adjusted. Figure 28 shows a sketch of the idea of wayfinding choremes embedded into the virtual environment.

The angular configurations of the building blocks in the virtual city are modified according to the applied wayfinding choreme. The choremised buildings were to highlight the angular situation at a specific intersection in order to ease the mapping process as well as the action decision-making process.

Consequently, following the two-dimensional concept of wayfinding choremes, the incoming branch is used to adjust the whole intersection

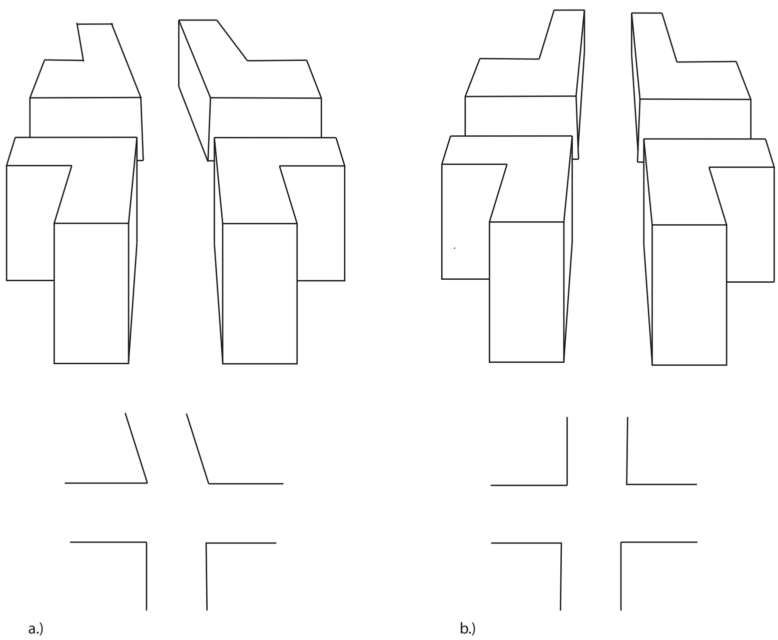


Figure 28: Illustration of the basic idea of 3D wayfinding choremes: (top) a.) the original intersection and b.) the same intersection with the integrated wayfinding choreme; (bottom) a.) two-dimensional representation of the intersection and b.) schematic picture of according two-dimensional wayfinding choremes

to the direction model in order to classify the outgoing branch into its corresponding wayfinding choreme.

Figure 29 presents the basic idea of the realisation of the wayfinding choremes.

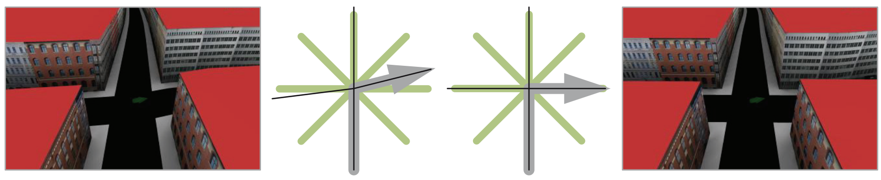


Figure 29: Schematisation of an intersection, (left) original intersection; (middle) analysis of the intersection; (right) wayfinding choremes integrated in a virtual environment (taken from [Glander et al., 2009])

As stated in the introduction, the hypothesis of this research is that the three-dimensional realisation of the concept of wayfinding choremes has similar positive effects as its two-dimensional equivalent on the wayfinding performance by emphasising the angular situation at a decision point. The expansion of the concept of wayfinding choremes to the three-dimensional realisation eases the wayfinder's alignment between the internal representation and the experienced virtual environment. Additionally, the action decision-making process is eased by the integration of the three-dimensional wayfinding choremes due to the prototypical external representation of the turning situation that matches with the cognitive-conceptual idea.

5.2.4 *Embedding of Wayfinding Choremes into a Virtual City*

In the following I introduce the implementation of the wayfinding choreme integrated into the virtual city[1]. This virtual city will be used in an experiment to evaluate the influences of schematisation on the wayfinding performance.

5.2.4.1 *Deriving Topology*

Prior to introducing the schematisation algorithm of wayfinding choremes, I am going to present the general structure of the topology of the virtual environment. In this virtual environment, the street network is an arrangement that intersects all parsed line features $L = \{l_i\}$ (see 5.2.5.2) in order to build up a half-edge data structure $G = (V, E, P)$ with vertices V, edges E, and polygons P, which are required for all further processing regarding the topology [Glander et al., 2009]. A half-edge data structure stores instead of the edges of the mesh the half-edges, meaning constructed by splitting an edge down its length into to components [de Berg et al., 2008]. This data structure is directed and the two edges of a pair have opposite directions.

$$L = \{l_i\} \xrightarrow{arrangement} G = (V, E, P) \tag{5.1}$$

Due to the fact that the route is defined before the street network is parsed and created into a half-edge data structure, the geometric route features $r = \{r_1, \ldots, r_n\}$ with $r_i = (x, y), x, y \in \mathbb{R}$ have to be aligned with and mapped to the topological street network representation.

$$(G, r) \xrightarrow{alignment} r_G = \{v_1{}^r, ..., v_m{}^r\} \text{ with } v_j{}^r \in V \tag{5.2}$$

For the alignment, all geometrically near and connected vertices in the created half-edge structure of the according street network are to be searched. Finally, the route is integrated into the graph structure the derived topological representation in the form of an ordered list of connected nodes.

1 . This implementation and technical realisation of a virtual environment was executed in cooperation with the Computer Graphics Systems group of the Hasso-Plattner Institute (Potsdam, Germany). Parts of it have been published in [Glander et al., 2009]

```
applyChoremes(G, r_G){
  for each v_i^r ∈ r_G, i > 1 do {

    if (degree(v_i^r)>2){                // consider only intersections
      Bins[4] bins4
      bool isOverlap
      bins4, isOverlap ← sortAngles(v_i^r)

      if (isOverlap = true){
        Bins[8] bins8
        bins8, isOverlap ← sortAngles(v_i^r)

        if (isOverlap = false){
          transformIntersection(v_i^r, bins8)      // use 8 sector model
        } else {}                        // leave intersection unchanged
      }else {
        transformIntersection(v_i^r, bins4) // use 4 sector model
      }
    }
  }
}
```

Figure 30: Pseudo code of schematisation according to wayfinding choremes for the virtual city (modified from [Glander et al., 2009]).

5.2.4.2 *Wayfinding Choreme Schematisation*

The schematisation of wayfinding choremes is based on the created graph, with contained the information of the street network with integrated route information. Every intersection along the route is to be schematised, which means that each intersection must be geometrically transformed. For this, all the nodes with a degree greater than two are transformed. The transformation of the half-edge structure of the street network according to the schematisation concept depends on the predefined route, $(G, r) \xrightarrow{chorematisation} G'$. The result is a schematised street network G' according the predefined route r. The direction of the route defines the incoming branch for the transformation process. This incoming branch has to be kept unchanged, whereas the other branches of each intersection along the route can be modified to conform to the direction model (see Section 2.4.4). To fulfil the above requirements, the algorithm iterates over all the nodes of the route list, starting with the first node, and transforming all intersections along the route to the goal node (see Figure 30).

At first, at every intersection, all existing outgoing street branches are evaluated in order to compute their angles relative to the incoming branches. By virtue of the graph structure, neighbour edges of vertices can easily be queried and their position is determined [Glander et al., 2009]. This step of the evaluation results in a numerical representation of the intersection, containing the angles of each outgoing branch. These results then undergo a stepwise sorting—vertices are first sorted into bins with a fixed size of 90°, i.e., a four-sector model. If there are multiple legs within one bin, the sector model is further refined up to eight sectors, into 45°-sized bins. In case that one bin still contains two branches after the second run, no angular modification at this intersection will be done, on the grounds that this intersection is too specific for a generalisation.

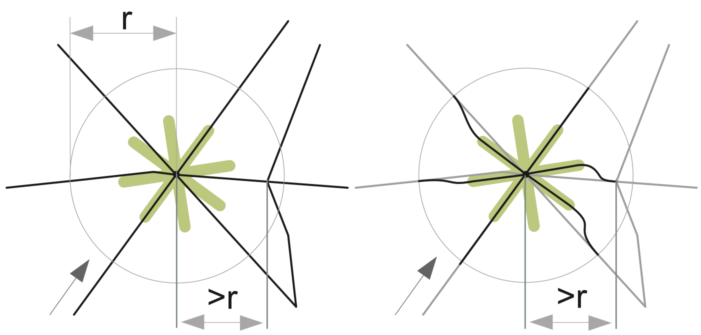


Figure 31: Schematisation transformation applied to an intersection. The grey circle visualises the local effects of schematisation. In green, the superimposed direction model. First, the original situation with the incoming street branch map with the direction model. Second, the shifted streets, aligned with the direction model and smoothly integrated with Bezier curves into the street network (taken from [Glander et al., 2009]).

The next step is to slightly rotate the outgoing street segments in order to align them with respective one of the seven wayfinding choremes. Executing this step, there are several implications to consider: To keep the overall geometry, the applied schematisation manipulates the street network only locally, that is, within a radius r. Hence, other positions of the intersection remain untouched by this transformation (i.e., kept fix), while along the modified branch new vertices must be inserted for aligning it with the selected wayfinding choreme. For enhancing the appearance of the embedded wayfinding choreme, this algorithm exposes the desired length of the choremised branch to $r/2$, that mean the wayfinding choreme modification will be extended to a length of $r/2$ if no other following intersection lay in this radius. The length cannot be guaranteed for every outgoing street segment if the following intersection is within the desired length, as shown in Figure 31 (if > r). In this special case the length of the expansion of the wayfinding choreme is determined as half the way to the next intersection. The last step is to smoothly integrate the modified intersection into the global street network. To achieve this, inspired by Klippel et al. [2005c], the modified outgoing street segments are connected and smoothed by application of Bezier Curves (see Figure 31). When all the intersections along the route have thus been processed, the algorithm stops.

Figure 32 shows a visualisation of the process of embedding the wayfinding choremes into the virtual environment.

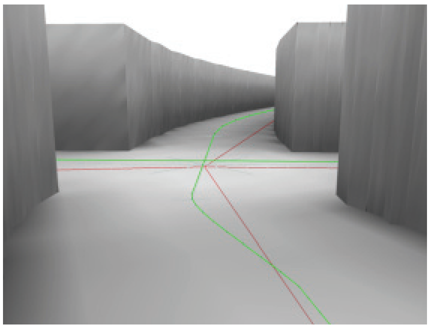


Figure 32: Process of embedding the wayfinding choremes. The red line illustrates the original angle configuration, and the green line displays the schematised version.

5.2.4.3 *Computational Complexity of Schematisation*

The complexity of the computation of the *wayfinding choreme* schematisation I present here briefly. The schematisation algorithm starts with the parsing and creation of the street network and the route in the virtual city. The computational complexity is linear dependent on the size of input data either the street network or the route. For computation of the schematisation according to the wayfinding choreme concept, the algorithm will compute along the predefined route at each intersection the new geometry of the affected branches. Therefore the algorithm iterate linearly through the route. Depending on the only local changes of the street network, the algorithm can stepwise modify each intersection independent from the other intersections and align the intersection to the respective wayfinding choreme as well as integrate this new geometry with the help of the Bezier Curve into the street network. Due to the fact that the computation is linearly dependent on the size of these two data components, the complexity of the schematisation of wayfinding choremes is $O(n)$. The complexity is not affected by other operations of the schematisation algorithm because all the following operational steps are based on these two components—street network and route. During the execution of the presented algorithm, all the intersections along the route are iteratively modified, and for each intersection, only the local topology including the nearest neighbours is processed.

5.2.5 *Virtual Environment for a Choremised Landscape*

The applied virtual environment which is designed to embedded the concept of *wayfinding choremes* represents a virtual city. The wayfinder can navigate through the street network of this virtual city only in the pedestrian mode and thus inspect the façades of the displayed buildings from a pedestrian's view. The buildings are organised in blocks like in inner city areas. Although the street network as well as the façade pictures are based on real world data, no existing city has been remodelled in order to avoid familiarity issues, such as recognition or familiarity-based responses.

The workflow for developing the virtual city starts with the processing of the input street network and the predefined route. In the case of the schematised version of the virtual environment, this route has to be manipulated according to the concept of wayfinding choremes. The schematised or original street network builds the basis for creating polygonal partitions as building blocks, which serve as footprints for every building in the environment. The buildings themselves are organised into blocks like in inner city areas. Each building is part of a represented three-dimensional block and every block of buildings has a different height, varying in a scale of usually building heights with four up to seven levels. The application that allows the setting of all parameters during the experiments is written in C++ and it uses the Virtual Rendering System for three-dimensional scene visualisation and interaction. The interface for the experiments is written in Qt; it offers the possibility either to choose or set all necessary parameters like schematisation, navigation velocity or subject number for the log files. Figure 33 presents the process pipeline.

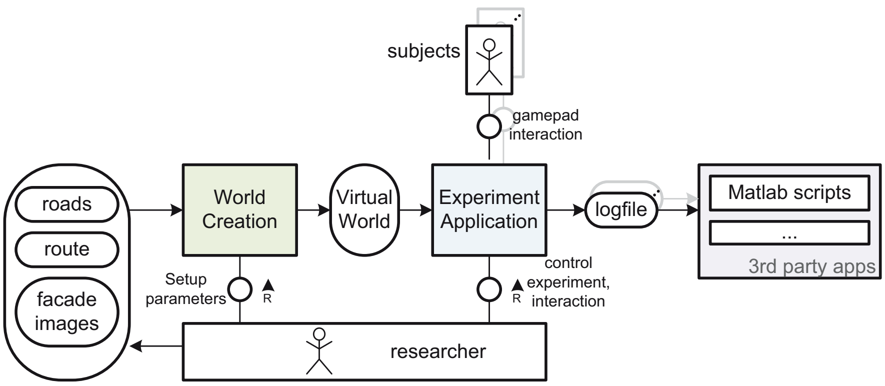


Figure 33: Overview of the designed experimental framework (taken from [Glander et al., 2009])

5.2.5.1 *Three-dimensional Geometry Creation*

To create an explorable virtual environment, a three-dimensional geometric model of this environment must be constructed. For this, based on the two-dimensional geometry of the very building footprints given by the underlying street network structure, which are to be further processed, the half-edge data structure is queried for the polygons. Here, in a first step, by applying two-dimensional Boolean operations, the street network is subtracted from the polygons to separate building space from street space. Subsequently, based on the footprints, the three-dimensional blocks are extended to building models of varying heights analogous to those in real urban areas, ranging from a specific minimum to a maximum value. Within this interval, randomly selected heights are assigned to each of the blocks. Finally, just as randomly, texture façades are allocated to each block from the façade texture pool (see Figure 34). Hence, the schematised version of the virtual environment should approximately have the same appearance as its original source. For further experimental work, this texture parameterisation can be stored. Figure 34 presents the above-mentioned procedure of façade selection.

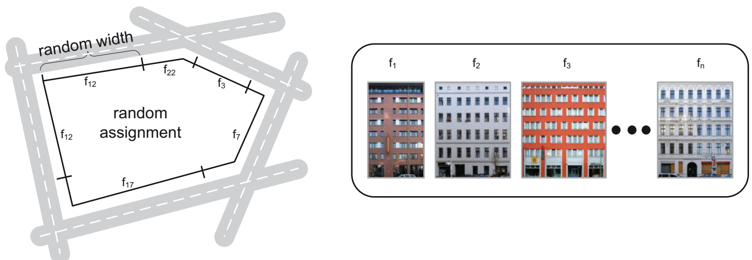


Figure 34: A block of buildings is defined by its surrounding streets. Every building has a randomly chosen façade. (taken from [Glander et al., 2009])

Users of this virtual environment navigate in it as pedestrian. They inspect during their navigation the urban-like environment consisting of building blocks which, in a final step, are pre-shaded to give the impression of a natural light shading during midday. However due to orientation issues the sun is hidden behind some clouds. To guarantee smooth and collision-free navigation of every user, a virtual collision geometry setup is calculated and stored. Consequently the wayfinder can only navigate along the street network and not run into buildings.

5.2.5.2 *Input Data*

The designed virtual city model integrates data from different sources. The data source for the geospatial data of the street network is provided by

TeleAtlas [2] and the OpenStreetMap [3] [Glander et al., 2009]. The route is predefined using a shape file. The shape file is then parsed by the application, extracting the line features representing the route, which are approximately aligned with the street network.

For designing a memorisable virtual city, its buildings must be provided with recognisable features in their appearance. For this purpose, distinguishable individual façades are used. These façades can serve as landmarks to guide the user and thus facilitate wayfinding. In a previous experiment, I investigated whether such photorealistic façades were used by persons as reference points to describe a route [Peters et al., 2010]. From the results obtained, there was evidence that people indeed describe a route with reference to façades.

Every building in the virtual environment has a randomly selected photorealistic façade. For creating a virtual environment, two design options are available: either a set of 38 different photorealistic façades or a set of façades to 126 different photos of façades can be applied.

Another (integrated) option is to present the virtual environment without any façades, so that the front of each building is white (see Figure 35).

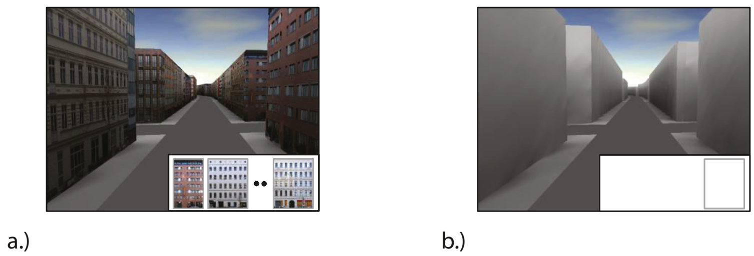


Figure 35: Two types of visualisation of the virtual environment: a.) environment with photorealistic façades; b.) environment with white façades. (modified from [Glander et al., 2009])

5.3 SUMMARY

In this chapter I introduced a spatial context model *TEAR* to analyse the correspondences between the environment, the external representation and the agent. By schematising the external representation, these correspondences can be intentionally manipulated to enhance the wayfinding performance. The context model provides the possibility to analyse the influences of schematisation on the complete system of correspondences. With the help

2 http://mapsby.tomtom.com/landingpage/index.php, retrieved January 05, 2012
3 http://www.openstreetmap.de/, retrieved January 05, 2012

of this analysis of the influences on the correspondences I proposed the theoretical requirements for the schematisation to be transferable.

Based on these facts, I selected a specific schematisation technique, termed *wayfinding choreme* and introduced a theoretical transfer from a map representation to its integration into a virtual environment. This particular schematisation technique prototypes angular information.

Furthermore, I present the technical realisation and implementation of the embedding of this schematisation into a virtual city and illustrated this virtual environment.

Within this virtual city, the transferred *wayfinding choremes* can be tested whether they enhance the wayfinding performance in this virtual environment, too.

6 WAYFINDING CHOREMES: STUDY IN A VIRTUAL ENVIRONMENT

This chapter concludes the transfer of *wayfinding choremes* by proceeding to the experimental investigation.

In this chapter I present a study to investigate if the *wayfinding choremes* embedded in this virtual environment actually enhance wayfinding performance.

By means of these experiments, I set the navigation performance as part of a *route following from memory* task in a schematised virtual city against the performance in a non-schematised virtual city.

The navigation performance of the participants in *route following from memory* is measured by errors during the participants' attempts to follow the route from memory, and by the time needed for navigating along the route.

My hypothesis is that participants who navigate in the schematised world make fewer errors during the task and need less time for succeeding in it.

Thus, in Section 6.1 I present two hypotheses on the enhancement of wayfinding performance with *wayfinding choremes*, which will be verified through the experiments. Then, I introduce the experimental setup which is the same in both experiments, and the parameterisation of the different virtual cities.

In Sections 6.2 and 6.3, experiment 1 and experiment 2 are illustrated, followed by a concluding discussion presented in Section 6.4.

6.1 STUDY AIMS AND GENERAL APPROACH

With this study, I investigate the question whether the transferred schematisation technique of *wayfinding choremes* when embedded in a virtual environment has a positive effect on wayfinding performance.

Klippel, who first established the concept of *wayfinding choremes*, states that the integration of *wayfinding choremes* along a predefined route enhance the orientation and mapping process for map users by emphasising turning actions at the decision points along the route, and consequently ease the decision making process.

Error rate and time serve as indirect indicators for determining whether the *wayfinding choremes* ease the mapping, orientation, and decision-making processes.

Two main hypotheses are formulated according to the proposed positive effects of *wayfinding choremes* on the participants' wayfinding performance.

Through this study I will confirm or contradict the following hypotheses:

- *Error rate* (H1): Integrating wayfinding choremes into a virtual city has positive effects on navigation performance, which results in a lower error rate during the *route recall* phase.
- *Time* (H2): Participants who navigate in a schematised world are faster at recalling and travelling the route than participants who navigate in an unschematised world.

6.1.1 *Experimental Setup*

For evaluating the transferred wayfinding choremes embedded in a virtual environment, a test scenario was created. In this virtual environment, the user can explore two different visualisations of the virtual city: a schematised version in the following termed *choremised* virtual city and a non-schematised world, which is termed *original*. The comparison between these two versions will allow investigations into the influences of schematisation on wayfinding performance.

Additionally, another factor is included in this experiment: the dependencies between the schematisation and the quality of the virtual environment according to its visual appearance. Hence, I created a visualisation of this virtual world with high quality photorealistic images projected on the façades, and another visualisation in which all the buildings have white façades.

6.1.2 *Presentation and Interaction*

The virtual environment was presented to the participants using a Sharp XG-PH50X beamer with a brightness of 4000 lumens. The projected image was 1.5 metres by 2 metres in size, and the image was presented with a resolution of 1280 x 1024, centred on the screen. All the participants were sitting 2.2 metres away from the screen. Navigation and interaction of the subjects in the virtual environment was realised with Logitech Dual Action Gamepad (Wireless).

Subject navigation by means of the gamepad was restricted to a horizontal plane, parallel to the virtual terrain, at a camera height fixed at 1.80 m. The maximum movement velocity was set to 8m/s. For the navigation through the virtual environment, a simple collision handling mechanism is implemented to prevent the subjects from running through buildings.

6.1.3 *Parameterisation of Virtual Worlds*

For the experimental investigation, two virtual scenarios were developed: one *small world* and one *large world*. These two worlds differ in terms of size, length of the predefined route and number of available façade textures. Both can be schematised according to the concept of *wayfinding choremes*.

SMALL WORLD The virtual scenario of the *small world* is a subset of the *large world*, with a size of 0.5 km^2. In this smaller environment, the predefined route environment has a length of 1.66 km and consists of 9 intersections including the starting point, but excluding the destination intersection. This route also is a subset of the longer route as part of the *large world*. The buildings in this smaller world are textured with samples of a set containing 38 different photorealistic façades pictures. Figure 36 gives an overview of the predefined route of the *small world* and the environment it is embedded in.

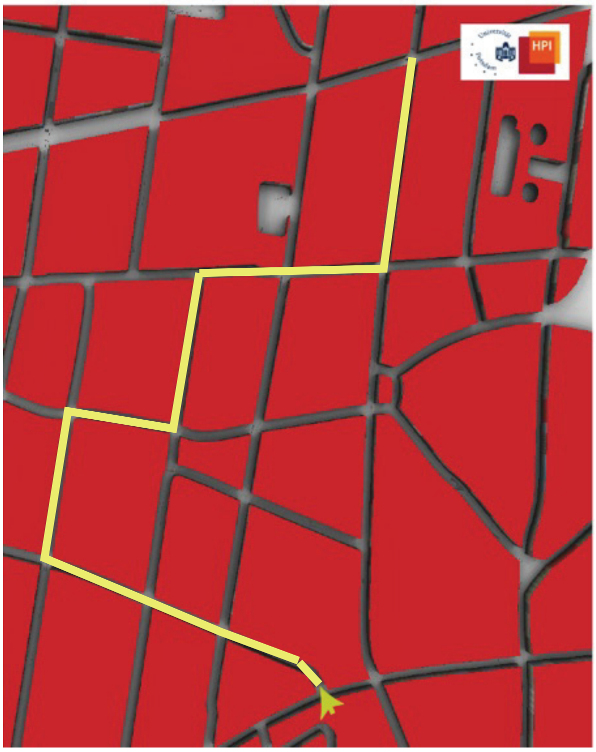


Figure 36: Overview of a section of the *small world*; the predefined route is highlighted in yellow, and the yellow arrow marks the starting point

LARGE WORLD The virtual scenario of the *large world* covers an area of 1.0 km^2. In this world, the predefined route has a length of 2.8 km, containing 16 intersections including the starting point, but excluding the destination intersection (see Figure 37). This world is equipped with buildings that are randomly textured with images from a sample set of 126 different photorealistic façades. Table 3 summarised the parameters of both worlds.

Figure 37: Overview of a section of the *large world*; the predefined route is highlighted in yellow, and the yellow arrow marks the starting point

ORIGINAL OR CHOREMISED ROUTE In both experiments, subjects are divided into two groups. Each group either experiences the original environment where the intersections along the route are displayed in a non-schematised configuration according to the underlying geospatial data, or the choremised environment where every intersection of the predefined route is schematised according to the concept of wayfinding choremes.

Table 3: Summary of parameters for small world and large world

	Small World	Large World
Area	0.5 km^2	1.0 km^2
# Façades	38	126
Route Length	1.66 km	2.8 km
# Intersections	9	16

photorealistic façades versus white façades Next to the option of choosing between the choremised world and the original world, in either case the experimenters can also opt between presentations of their virtual environment with either photorealistic textured façades or with façades that were left blank.

This latter option allows for evaluating the influence of visual features of the environment, given by either photorealistic textured or the white façades (see Figure 35), on the outcome of the experiment.

Through this parameterisation, the experimenters face a total number of 8 different parameterised worlds: The *small world* can either be choremised or not, and also be provided with photorealistic textured façades, or with white façades, i.e., left blank. Additionally, the same parameterisation options can be selected for the *large world*.

6.1.4 *Experimental Settings*

The general procedure is the same in both experiments. Either of them can be divided into two experimental phases. The first phase is the *route recognition* phase, and the second one is the *route recall* phase.

route recognition phase During the *route recognition* phase, a free exploration of the virtual environment is theoretically possible, yet for both experiments the subjects are instructed to follow the highlighted route. In this phase, the starting point of the route is highlighted via a yellow arrow. At every intersection along the route, a green arrow indicates the branch that is to be followed according to the predefined route. The destination is highlighted via a green shape of a soccer goal. Figure 38 shows the three main landmarks that highlight the route.

route recall phase In the *route recall* phase, the subjects are instructed to navigate along the learnt route from memory. For the registration of

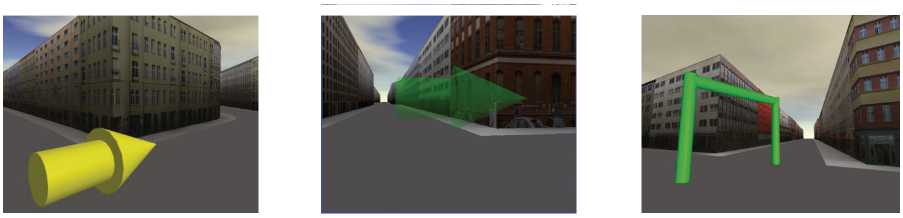


Figure 38: Landmarks marking the starting point (yellow arrow), the direction at every other intersection (green arrow) and destination (green goal)

navigation errors occurring in this mode, movements are restricted by the route through an invisible cage which bars the subjects from entering a possible but wrong intersection. Here, in the case of a wrong movement decision, a red light flashes up and a collision detector blocks the movement. Any such collision with this invisible blockade is registered as an error event in the log files.

6.1.5 *Log Files*

The log files store the user behaviour data as well as movement trajectories and heading information, next to the subject number, the current date and the visual parameter settings. Every second, independently of the respective phase of the experiment, the tracking system stores the position and heading of the subject in the log file. Error events are thus stored in binary code, replacing the absence of an error by 0, and 1 indicating an error occurrence. Additional data thus stored in the log file are the world parameterisation (*small, large; choremised, original; photorealistic façades, white façades*) and the current phase (recognition or recall) of the experiment.

6.2 EXPERIMENT 1

6.2.1 *Participants*

All the participants of the experiment were volunteers and students of the University of Bremen. Of 42 subjects volunteering altogether, 22 were female and 20 male, aged 19-42 (mean = 24). All of them were native German speakers and were paid for their participation. Two subjects did not complete the experiment due to simulation sickness and were therefore excluded from the analysis.

6.2.2 *Design and Procedure*

The experiment was designed as 2×2 factorial independent analysis of variance (ANOVA).

The all participants were randomly assigned to two groups of equal size, one of which only experienced the original world ($G_{original}$) while the other only experienced its choremised counterpart ($G_{choremised}$).

Additionally, each group was subdivided into two subgroups. The participants of all these groups learnt the route in a world with photorealistic textured façades alike, but in the recall phase, the groups were split in that one group ($G_{originalF}$/$G_{choremisedF}$) had to remember the route in the same world with façades information, whereas the other group was facing white façades ($G_{originalXF}$/$G_{choremisedXF}$). In terms of gender, all subgroups were fully balanced.

Experiment 1 was performed in the *small world* setting and is composed of the following three parts: a pre-testing phase, the main experiment that contains a recognition phase, a distraction task, and a recall phase, and a post-testing phase. The experiment lasts about 45 minutes altogether, pre-tests, instructions and post-tests included.

All participants receive the task assignments in the same order.

PRE-TESTS During the pre-test phase, each participant had to fill in two questionnaires. The first one covers questions on the participants' previous experience with virtual environments, gaming, and navigation assistance services. The second questionnaire is a German version of a self-evaluation of navigation performance, called Questionnaire of Spatial Strategies (FRS = Fragebogen Räumlicher Strategien) [Münzer et al., 2008; Münzer and Hölscher, 2011]. The factor structure of this questionnaire reflects different strategic aspects of spatial orientation, like allocentric or egocentric knowledge of directions and it includes different environmental settings, e.g., urban setting and natural setting.

EXPERIMENT The experiment is split up into four phases: a training phase, a route recognition phase, a distraction phase and a route recall phase. All phases are without timeouts and the participants themselves determine the flow time.

In the training phase, the participants get familiar with the setup and learn to navigate through the environment via gamepad. For this testing phase, a section of the virtual environment is chosen for navigation where no intersections with the route to memorise occur. As soon as the participants assure their familiarity with the setup and the navigation, the main part of the experiment is started.

During the route recognition phase, the participants are advised to follow a highlighted route and keep this route in mind. Every participant has only one trial for navigating along this route to memorise it.

A short navigation task was designed to intermittently distract the participants. During this task, the participants navigate along a verbally described route and are advised to draw a sketch map to enable them to return and walk back the route from their destination. The route in this task had the same starting point as the route for the *route following from memory* task but ran in the opposition direction of the route that was learnt in the outlying section of the environment.

After finishing the distraction task, the participants must return to the starting point of the learnt route in the route recall phase. The participants have to navigate along the learnt route unaided by highlighting or hints.

POST-TESTS Each participant had to answer several post-test questions. A first post-test dealt with the question whether the participants could memorise every intersection along the route only from considering a number of pictures showing the intersections from the perspective of the incoming branches. For this, a set of 32 pictures was presented to the participants, 9 of which showed different intersections along the actual route, excepting the starting intersection.

There were three options to choose from: The participants had to decide on whether or not they had come across the respective intersection along the route: yes, no, or maybe.

The following post-test focused on the question whether the participants could recall the sequential arrangement of the intersections they had seen along the route. For this purpose, pictures of the intersections had to be lined up in correct order. Hence, ten pictures of the experienced intersection were presented in random order and the participants had to sort these presented pictures.

Finally, the participants were randomly allocated into two equal-sized groups. Half of the participants had to draw a sketch map of the route they had learnt, while the other half was asked to mark the route they had learnt from a previously marked starting point in a given map. All participants had to answer a questionnaire on the complexity of the experiment they had participated in.

6.2.3 *Measures*

6.2.3.1 *Performance*

During the *route recall* phase, two measured variables are employed for determining the participants' wayfinding performance: the error rate and the overall time it takes to perform this task. For the analysis, the two groups, $G_{original}$ and $G_{choremised}$, are compared. Additionally, the two subgroups, $G_{originalF}/G_{choremisedF}$ and $G_{originalXF}/G_{choremisedXF}$, are considered in the analysis.

6.2.3.2 *Pre-Tests Evaluation*

frs questionnaire In the questionnaire, all participants must assess their own overall navigational performance. To evaluate this test the performance (error rate and time) and four different strategies (survey-based, landmark-based, direction-based and route-based strategy) in four different settings (a familiar city vs. an unfamiliar city, complex buildings vs. open space (nature)) are correlated and the Pearson's correlation coefficient are calculated.

6.2.3.3 *Post-Tests Evaluation*

discrimination of intersections from pictures This post-test was intended to shed light on the question whether the façades information helped the participants recognise the intersections they had passed along the route when being shown as image of the intersection from the perspective of its incoming branch. This test is analysed by the number of hits, false alarms, misses and correct rejections according to the signal detection theory [e.g. Swets, 1996; Green and Swets, 1989] to detect if and how the participant can recognise an intersection of the learnt route.

ordering of intersections In this post-test, each participant must put the intersections of the learnt route into correct order. To evaluate these sequences for every participant, the Levenshtein distance is calculated. This string metric measures the number of differences between two sequences. The correct sequence is defined as the order of intersections of the learnt route, while the compared string is the collocation as arranged by the participant. Allowed operations are the insertion, deletion, or substitution of a single character. To transform the given string into the correct sequence, each of these operations can be done, with every operation counting 1 (as for example, the Levenshtein distance between the string 'aba' and 'aca' is 1). All these operations are then summed up for transforming the given order into the original sequence. Here, the Levenshtein distance is the overall number of performed transformation operations.

EXTERNALISATION OF LEARNT ROUTE In this post-test, all the produced maps, hand-drawn sketch maps and routes drawn by hand into existing maps, are evaluated according to the displayed turning-action sequence of the respective route drawn on each map. That is, the (original) ordered sequence of turning actions on the learnt route was compared to the sequence of turning actions in the drawn route as arranged from memory. Thus, it can be analysed whether or not the latter was correctly arranged.

6.2.4 *Results*

For the analysis of wayfinding performance according to the *route following from memory* task, the data of all participants are considered. The pre- and post-tests are employed to complete the analysis.

6.2.4.1 *Experiment*

PERFORMANCE CHOREMISED/ORIGINAL WORLD Participants who were trained and recalled the route in a choremised world with integrated wayfinding choremes did not show a better performance.

Figure 39 illustrates that no differences can be detected as to the average *error* rate and *time* span between the $G_{original}$ and $G_{choremised}$ worlds.

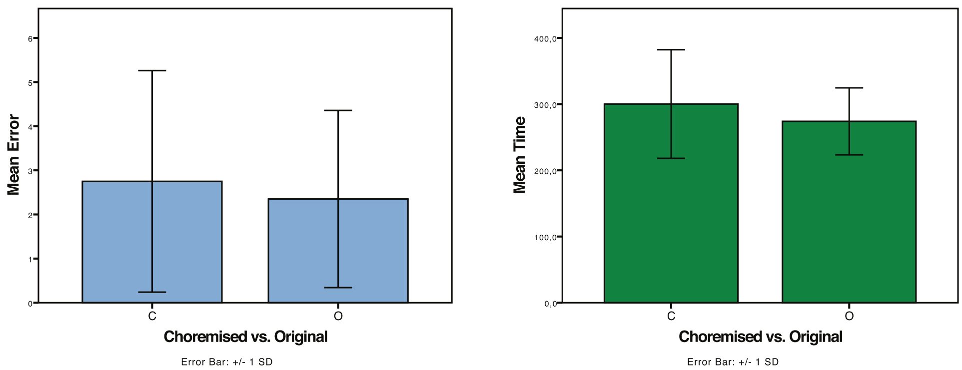


Figure 39: Error rate (left) and time span (right) of the recall phase of experiment 1. Means and standard deviation are shown.

Both ANOVAs indicate no significant differences between the $G_{orginal}$ and $G_{choremised}$ groups—neither as to the error rate nor the time span of the *route recall* phase, too. Also, no interaction effect could be found between the factors choremised/original world and a world with photorealistic façades pictures/with white façades.

PERFORMANCE PHOTOREALISTIC FAÇADES/WHITE FAÇADES Here, the ANOVAs, conducted for both wayfinding performance measurements, show significant main effects of the factor world with photorealistic façades/with white façades. For the error rate, the main effect is $F(1, 36) = 9.95, p > 0.005$, and for the time span, it is $F(1, 36) = 10.5, p > 0.005$.

Participants of the group tested with white façades information had an average effect of two fewer errors than their reference group; and their time span was 60 milliseconds shorter on average than was the time needed by the other group. Both of these results were independent of whether or not the virtual world was presented in a choremised version.

Tables 4 and 5 illustrate the average error rate and time span measured for each group ($G_{originalF}/G_{choremisedF}$ and $G_{originalXF}/G_{choremisedXF}$). On average, the experiment participants made 2.55 errors and needed 287 seconds (i.e., nearly five minutes) to perform the recall of the trained route.

Table 4: Result of the wayfinding performance (error) in experiment 1.

	photo. façades (F)	white façades (XF)	overall (C/O)
	mean (s.d.)	mean (s.d.)	mean (s.d)
choremised World	4.0 (2.76)	1.22 (.83)	2.75 (2.51)
original World	3.0 (1.89)	1.7 (2.0)	2.35 (2.0)
overall (F/XF)	3.52 (2.38)	1.47 (1.54)	

Table 5: Result of the wayfinding performance (time (sec)) in experiment 1.

	photo. façades (F)	white façades (XF)	overall (C/O)
	mean (s.d.)	mean (s.d.)	mean (s.d)
choremised World	334.43 (43.77)	258.28 (91.59)	300.2 (82.05)
original World	298.94 (50)	249.09 (39.04)	274.02 (50.6)
overall (F/XF)	317.53 (75.16)	253.44 (40.44)	

6.2.4.2 *Pre-Tests*

FRS QUESTIONNAIRE The FRS questionnaire is evaluated according to different strategies and to the participants' self-assessment of their overall wayfinding performance.

On analysing the data, the overall estimated wayfinding performance was negatively week correlated with the error rate ($r = -0.264, p < 0.1$). Furthermore, this overall correlation analysis revealed that there is a significantly strong positive correlation between error rate and time span ($r = 0.806, p < 0.001$).

6.2.4.3 *Post-Tests*

DISCRIMINATION OF INTERSECTIONS FROM PICTURES The results of the signal detection analysis revealed that there was a significant tendency for participants to tell the actual 'route' pictures from other pictures. This can be seen as evidence that participants memorise, even if unconsciously, the intersection along the learnt route ($d' = 1.1$ and $c = -0.1$). Therefore, all participants answered correctly as to more than 50% of all pictures, and without any conservative or progressive bias.

ORDERING OF INTERSECTIONS On average, the sequences arranged by the participants have a Levenshtein of 7.35 (minimum = 3; maximum = 10). This value gives evidence of the fact that, due to the high value of the Levenshtein distance, the participants cannot remember the correct sequential order of the intersections along the route.

EXTERNALISATION OF LEARNT ROUTE 15 out of 20 participants who had to draw the route into a map, externalised an incorrect sequence of turning actions along the route. In the map sketching task, 11 out of 20 participants drew sketch maps that displayed incorrect sequences of turning actions. No influences of the factors choremised/original world or tested with white façades/with photorealistic façades to the ordering performance could be detected.

6.2.5 *Discussion*

In this experiment, no major differences in the wayfinding performance of participants who were trained and tested in the choremised virtual environment and others who were trained and tested in the original world could be identified. These findings were unexpected because the wayfinding choremes were supposed to ease the wayfinding task.

However, almost all participants reported that the given *route following from memory* task was easy to accomplish. This is also reflected in the error rate of 3 errors on average, whereas a fraction of only two candidates registered eight or even nine errors without which the mean error rate sinks to 2.24.

An explanation for these findings is that the designed route was very easy to learn. Consequently, the participants made fewer errors, could easily recall the turning action sequences and did not require any performance enhancement through *wayfinding choremes*.

This explanation is supported by the observations that participants who were tested in surroundings with white façades performed significantly better. Whether a participant is tested in a world with photorealistic façades or with white façades has a great influence on wayfinding performance. Participants who performed the recall phase in the white world are on average significantly better than the other group. They make fewer errors (2 fewer errors) and perform the *route following* task faster (60 milliseconds).

Participants of white façades group could only make use of the sequence information of correct turning actions for performing their wayfinding task because no discriminable features like landmark information, as transported by photorealistic façades, were available.

No interaction effects can be detected. The results are independent of whether the participants navigated in the choremised or the original world.

It can be ruled out that all results may refer to individual differences or clustering effects like all participants preferring using survey knowledge in one group. The FRS (wayfinding performance self-estimation test) did not detect any correlation between the overall self-assessed wayfinding performance and the participation in a certain group.

The analysis of the post-tests shed light on the fact of the façades information. All participants are able to distinguish intersections they have seen along the route from those unfamiliar to them in a photograph, too. Here, the presented façades information delivered the information necessary for recognition, but when confronted with photographs of all the intersections they had seen along the route, none of the participants managed to successfully perform the sequential ordering test. This result can be used as an indicator of a lack of discriminable features in the photorealistic façades, i.e., the given visual stimuli fail to suffice as landmark information and thus cannot easily be matched with turning actions.

A reason for this may be the limitations of the volume of the underlying stock. In the virtual environment, a set of only 38 different photorealistic façades pictures was used, hence, the individual façades appear reiterated along the route (see Section 5.2.5.2). Such redundancy, i.e., iterative information, can lead to conflicting (overlapping) memory of the trained route.

Employing a more diversified set of façades pictures might solve this conflict problem.

Another reason for these findings might be that without distracting information, participants can better concentrate on the sequence of turning actions and therefore deliver better performance because their perceptions do not conflict with redundant visual information. This could also be an explanation for the good performance of the group tested with white façades information: The presented façades transport no salient or redundant information for the wayfinder.

The interpretation of all these findings should take into account, however, that the complexity of a given wayfinding task has great influence on the requirements of the external representation. To give an example, Meilinger [2005] presented a study in which in case of a simple route the participants showed better wayfinding performance in a *route following* task with a route description than they did in one with a map—and the explanation was that the written route description presented the necessary information in a compact and adequate way.

However, in the case of a more complex route, the written route description failed and the participants supported by maps show better wayfinding performance because the verbal description became too complex. I expect that in a more complex route, the *wayfinding choremes* will positively influence wayfinding performance, whereas the significant effect of the white façades will vanish while, with increasing complexity, the diversified façades information will be used as additional cues.

Due to the above reflections, I designed a follow-up experiment with an underlying longer route, and applying a broader range of photorealistic façades, to answer some of the open questions.

6.3 EXPERIMENT 2

The experiment 2 is a follow-up experiment to the first experiment and integrated two major parameter changes, the length and the complexity of the predefined route and the volume of photorealistic façades pictures.

6.3.1 *Participants*

30 participants attended this second experiment, with an equal number of men and women between 20 and 51 years of age (mean=24). All participants were native speakers of German, students of the University of Bremen and were paid for their participation. Five out of these 30 participants had to be excluded due to simulation sickness.

6.3.2 *Design and Procedure*

Experiment 2 had the same design as experiment 1, a 2×2 factorial independent ANOVA with the factors choremised world/original world and a recall phase with photorealistic façades pictures/with white façades.

All subjects were allocated to similar groups as in experiment 1, two main groups, $G_{original}$ and $G_{choremised}$, each of them consisting of two subgroups, $G_{originalF}/G_{choremisedF}$ and $G_{originalXF}/\ G_{choremisedXF}$. All partitions were fully gender balanced.

The second experiment took place in the *large world*, i.e., with a predefined route of 2.8 km and the environment was textured with 126 different photorealistic façades.

Experiment 2 followed the same experimental procedure as in experiment 1 (see 6.2.2) with one additional pointing post-test. The duration of experiment 2, pre-test, instruction and post-tests included, is 90 minutes. All of the participants were given the tasks in the same order.

pointing task post-test I added a pointing task to the post-tests of the experiment. In this task, every participant must navigate along the learnt route once again and at three intersections 5, 10, and 16, which divide the trained route into three segments of near-equal length, has to point back to the starting point of the route.

6.3.3 *Measures*

All measures were collected and evaluated according to the introduced methods of experiment 1 (see 6.2.3), except for the post-tests *discrimination of intersections via pictures* and *ordering of intersections*. Both tests were modified according to the settings of experiment 2. Additionally, I present the newly introduced pointing post-test to complete the evaluation.

6.3.3.1 *Post-Test Evaluation*

discrimination of intersections from pictures During this post-test, 32 pictures were presented to each participant. 16 out of the 32 presented pictures were images of intersections that the participants had passed along the learnt route. The procedure of this task followed the procedure in experiment 1 (see 6.2.4.3).

ordering of intersections According to the similar post-test in experiment 1, all the intersections of the learnt route excepting the starting intersection were now presented to the participants, adding up to a total of 16 pictures. The procedure was the same as in experiment 1 (see 6.2.4.3).

POINTING TASK This post-test should shed light on the question whether participants of the $G_{choremised}$ group built up a distorted internal survey knowledge, as compared to the $G_{original}$ group that had been trained to recall the learnt route in a non-schematised environment. For this purpose, every participant must navigate once more along the route and point back to the starting point at the intersections 5, 10 and 16.

6.3.4 *Results*

All data of every participant are considered in the analysis of the wayfinding performance of all groups. The pre- and post-tests are used to complete the analysis

6.3.4.1 *Experiment*

PERFORMANCE CHOREMISED/ORIGINAL WORLD In this experiment, the group of participants who navigated in the choremised world made fewer errors (3 fewer errors) but did not perform the wayfinding task faster than the other group. Figure 40 illustrates a comparison of the mean error rates and time spans between the two groups.

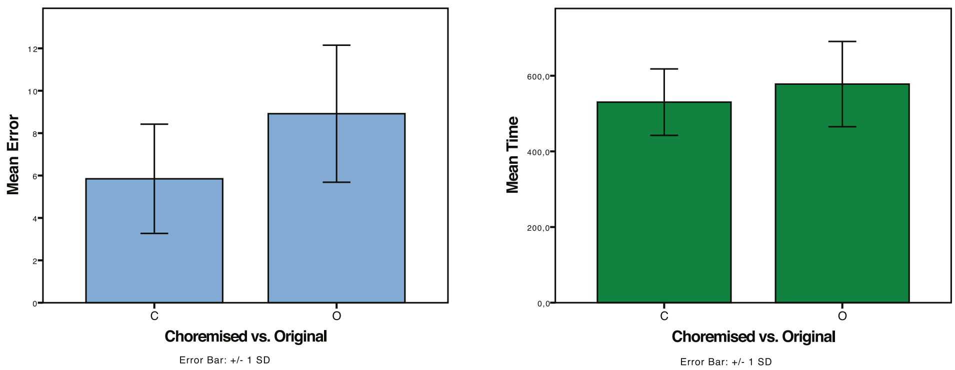


Figure 40: Error rate (left) and time span (right) of the recall phase of experiment 2. Means and standard deviation are shown

As to the error rate, the ANOVA showed a significant difference between the group who was trained and recalled the route in a schematised world $G_{choremised}$ and the group who experienced this in the original world $G_{original}$. The main effect was $F(1, 21) = 6.618, p > 0.05$ for the error rate. No significant differences could be detected as to the *time*, however. The $G_{choremised}$

group outpaced the $G_{original}$ group, albeit insignificantly. Additionally, no interaction effects with the factor photorealistic façades/white façades could be made out.

PERFORMANCE PHOTOREALISTIC FAÇADES/WHITE FAÇADES The ANOVA conducted for *error rate* and *time* detected no significant difference for the factor group $G_{choremisedFX}/G_{originalFX}$, recalled in the world with white façades, or the group $G_{choremisedF}/G_{originalF}$. No interaction can effect be detected to any group.

On average, the participants made 8 errors during the *recall phase* while it took them 9 minutes to complete this task (for further details, see Tables 6 and 7).

Table 6: Result of the wayfinding performance (error) in experiment 2.

	photo. façades (F) mean (s.d.)	white façades (XF) mean (s.d.)	overall (C/O) mean (s.d)
choremised World	5.57 (2.51)	6.17 (2.86)	5.85 (2.58)
original World	9.83 (2.99)	8.0 (3.45)	8.92 (3.23)
overall (F/XF)	7.54 (3.43)	7.08 (3.18)	

Table 7: Result of the wayfinding performance (time (sec)) in experiment 2.

	photo. façades (F) mean (s.d.)	white façades (XF) mean (s.d.)	overall (C/O) mean (s.d)
choremised World	518.69 (77.7)	543.55 (104.25)	530.16 (87.83)
original World	631.63 (120.0)	524.167 (81.34)	577.9 (112.71)
overall (F/XF)	570.82 (111.6)	533.86 (89.72)	

6.3.4.2 *Pre-Tests*

FRS QUESTIONNAIRE The correlation analysis showed a weak negative correlation between the overall estimation of the individual wayfinding performance and the error rate during the experiment ($r = 0.190, p < 0.5$). Furthermore, a positive strong correlation between the error rate and the duration of the *recall phase* was found ($r = 0.768, p < 0.001$).

6.3.4.3 *Post-Tests*

DISCRIMINATION OF INTERSECTIONS FROM PICTURES The analysis illustrates that the participants can discriminate these intersection pictures from other images (d′ = 0.8 and c = -0.1). Here, more than 50 % of the questions were answered correctly, while no bias could be detected.

ORDERING OF INTERSECTIONS On average, the Levenshtein distance is 14.4 (minimum = 11 ; maximum = 17). The maximum reachable Levenshtein distance for this sequence is 17. This average value of 14.4 gives evidence of an overall inability of the participants to correctly recall the arrangement of intersections they had seen along the route only from pictures of these intersections presented to them.

EXTERNALISATION OF LEARNT ROUTE On analysing the sketched routes regarding the correct sequences of turning actions along the trained route, all of the hand-drawn sketch maps were incorrect, and in the case of the given map, 10 out of 13 route drawings were incorrect. No influences of with any factors could be detected.

POINTING TASK Analysing the pointing test, no significant differences between the $G_{choremised}$ and the $G_{original}$ group or the factor recalled with photorealistic façades/with white façades could be detected. The overall pointing performance was low and resulted in an average pointing error (deviation) of over 30°.

6.3.5 *Discussion*

In this experiment, major differences in the wayfinding performance were identified between participants who were trained and tested in the schematised virtual world and those who were trained and tested in the non-schematised world. The participants of the group that were trained and tested in the choremised virtual world made significantly fewer errors than those of the other group. These findings support the hypothesis H1 I stated at the outset of the analyses.

On average, the participants of the choremised world group made 3 fewer errors than the participants of the other group. However, the former group was not significantly faster than the latter but, on average, outpaced them when performing the *route recall* task.

In this second experiment, which is based on a longer trained route with a far more complex challenging wayfinding task, it was found that schematisation enhances the participants' wayfinding performance. This result supports my assumption about the overt low-level challenge for the participants of the wayfinding task in the first experiment.

However, these findings show that the embedded *wayfinding choremes* only enhance wayfinding performance as to the error rate of participants of the schematised virtual world group. The hypothesis H2 thus cannot be confirmed, but the observations indicate a tendency toward a faster performance of this group as well. Additionally, a significant positive correlation is detected for the error rate and time span of the *route recall* phase.

These findings give evidence that the embedded *wayfinding choremes* facilitate selecting the correct branch at an intersection. Taken into account that there were significant differences only as to the error rate, this can be seen as an indicator for the quality enhancement of spatial representations through schematisation [Sholl, 2001]—as opposed to potential differences as to the time span, which would indicate an enhanced efficiency of the processes performed on the basis of this internal representation [Sholl, 2001].

Still, the pointing test shows no difference between the group trained in the choremised world and the group trained in the original world. If the internal spatial representation is affected by schematisation, a possible consequence may be that the built-up survey knowledge is also distorted as to the presented prototyped angle.

It might be expected that in this case, participants who experienced the virtual environment only with embedded *wayfinding choremes* would perform worst in the pointing task, owing to the schematised angular information. This is not the case, however, since all participants perform equally badly, independent of schematisation. The overall performance suggests that participants do not build up an internal spatial representation which might be employed to successfully perform a pointing task. An explanation for this observation would be that seeing and memorising a route only once does not suffice to perform a pointing test, or even, that participants generally show poor pointing performance in a virtual environment.

Along the same lines, only three participants managed to draw the trained route in correct sequence. All the other participants were unable to perform this task without errors in the externalisation post-test. These results indicate that the participants could not build up a sufficient internal representation to perform this survey task.

Further investigations are necessary, on the one hand, to analyse if a difference in the time span might be found with larger groups of participants involved, and on the other hand, to inspect more deeply the reasons for wayfinding performance enhancement through the embedding of *wayfinding choremes*.

To complete this analysis, no dependencies between visual appearance and schematisation could be detected. Participants who navigated in the choremised world delivered a better performance, independent of whether they were tested in a virtual city with photorealistic textured or white façades. As in experiment 1, no correlations can be detected by the FRS test between wayfinding performance and the employed orientation strategies or the self-assessment of wayfinding performance and the participation in a certain group.

Furthermore, in this experiment, no significant differences in the wayfinding performance of participants who were tested in a world with photorealistic façades and the group who was tested in a world with white façades could be found as to either error rate or time span. Both groups showed comparable wayfinding performance.

These findings can either be explained by the fact that, for this new virtual environment, a set of 126 different photorealistic façades was employed, so that the redundancy of façades information was decreased. On the other hand, the length of the predefined route was increased. The route in this case was more than 1 km longer and featured six more intersections to pass and remember.

The findings suggest that the presented façades information, due to the extension of the set, has lower redundancy and, therefore, no longer distracts the wayfinder during the recall phase. Still, it does not enhance wayfinding performance. Perhaps an even larger set of different façades pictures would give rise to differences between these groups.

These results pose a new research question on the quality of the visual appearance according to the complexity of the given wayfinding task and its virtual environment. Due to the focus of my present thesis I will not further investigate into this interesting question.

The results of the wayfinding performance of the participants of the photorealistic façades group and the group who was tested in a world with white façades as well as the ordering task during the post test phase illustrate that participants cannot remember the correct turning actions only from pictures of the intersections they have come across.

In the ordering post-test, none of the participants correctly arranged the intersections they had passed in the picture sequence. A participant who performed best in this test had a Levenshtein distance of 11, while the mean in this test was 14.4. This result indicates that the participants could neither recall or reconstruct the sequential ordering information with the pictures of intersections presented to them, nor could they employ the presented façades information as an anchor for correctly identifying the turning actions.

However, in the discrimination post-test the majority of participants were able to discriminate pictures of the intersections they had passed through photographs taken from the perspective of the respective incoming branch (d′ = 0.82).

Consequently, the façades information delivers sufficient information to discriminate familiar intersections.

The results of this experiment clearly illustrate that the embedded schematisation enhances wayfinding performance as to the error rate during the *route following from memory* task, independently of the visual appearance of the virtual environment. However, no significant differences could be made out as to the time span. This leads to the question if these results can be interpreted as an indicator of a one-way influence the schematisation exerts on the quality of the internal spatial representation—yet not on the mental processes based on it. Here, further empirical studies are necessary to prove this hypothesis.

6.4 the effects of schematisation in virtual environments

In this chapter, I presented a study to examine if the transferred schematisation technique *wayfinding choremes* has the proposed positive effects on the wayfinding performance. For this purpose, two experiments were designed to test the embedded *wayfinding choremes* in a *route following from memory* task.

The second experiment demonstrates that the integrated schematisation technique enhances wayfinding performance as to the error rate of the participants in a *route following from memory* task on the basis of a complex route.

Taken together, the results of both experiments suggest that the integrated *wayfinding choremes* have a positive influence on the wayfinding performance if the route is not memorable as a short sequence of turning actions.

A suitable explanation for this may be that, following the ideas of Klippel [2004], this schematisation technique enhances wayfinding performance either by supporting the organisation and structuring of the internal mental representation of route information or by supporting the recall and mapping of the built-up internal representation on the external world.

The results of this study indicate that the transferred schematisation technique enhances the matching between the internal mental representation and the external representation. The assumption was that this schematisation lowers the existing cognitive difficulty of the human agent with the external representation (see Chapter 5), which is supported by the results of this study.

This matching which is enhanced by schematisation also allows drawing conclusions about the internal structure of the mental representation. The *wayfinding choremes* are intended to reflect the conceptualisation of angular information during a *route following* task. Therefore, the conceptualisation brings out certain parts of the environment to ease the performance of a specific turning action [Klippel, 2004]. Consequently, the underlying mental structures or processes must correspond with the schematisation of the angular information [Klippel, 2004]. The qualitative nature of this schematisation is reflective of the internal mental representation. The results of this study indicate that people also use qualitative angular information during a *route following from memory* task in a virtual environment to remember the route. These findings are supported by a comparable conceptualisation of angular information found for both wayfinding tasks, i.e., *route following with maps* and *route following from memory*, with both external representations, i.e., maps and virtual environments (see Chapters 3 and 4). However, this study does not deliver any information about which (parts of) mental processes or which structures work better with qualitative information. Does this schematisation enhance the processes of building up the internal representation of a route, or the recall of this representation, or other reasoning processes on this internal structure?

The observation that, primarily, the differences in the error rate were significant indicates that the enhancement of this schematisation works on the structural level of the internal representation. However, further experiments are needed to verify this hypothesis.

To get a clearer picture of how the *wayfinding choremes* enhance the wayfinding performance I plan on carrying out further experiments which are left for future work (see 7.2.2).

One criticism against integrating this schematisation technique into a virtual environment is that the distortion of the angular information at the intersections can also distort the internal representation of the participant according to their survey knowledge. But inferring the results of the pointing task in experiment 2, no differences can be found between the two groups trained and tested in a schematised world or in a non-schematised world. Certainly, this may be due to each participant's short-term experience in the respective virtual environment. For an in-depth inspection, an experiment is needed in which the participants learn the layout of the virtual environment in several trials [e.g. Ruddle et al., 1997]. Nevertheless, the *wayfinding choremes* are not constructed to enhance the composition of survey knowledge and, following the results of the experiment 2, they do not downgrade it either.

Comparing the results to other studies on virtual environments which were aimed to enhance wayfinding performance (see Section 2.5.2), it has already been presented that underlying grids [Darken and Sibert, 1993] or environments created by the ideas of Lynch [1960][e.g. Ingram and Benford, 1995; Ingram et al., 1996; Ingram and Benford, 1996] can enhance wayfinding performance. Nevertheless, none of these studies indicate that the critical point lies on the angular configuration of the intersections and not on the streets.

Moreover, the other post-tests lead to the assumption that no explicit route memory is composed. In both experiments, none of the participants can recall the correct sequential order of the intersections from pictures of the particular intersections—although they can correctly distinguish them one by one. Also, only three out of 25 participants could externalise the learnt route as a sketch in experiment 2.

As an additional factor, I investigated the influences of the presented photorealistic façades on the wayfinding performance. In experiment 1, the participants tested in an environment with white façades were significantly faster and made fewer errors than the group tested with photorealistic façades. The same result was not found in experiment 2, in which the underlying route was longer, and where more façades information was provided. In experiment 2, no differences between the two groups were found.

A possible explanation is that the façades information is not used and required during the *route following from memory* task. Furthermore, in experiment 1, this information even decreased the wayfinding performance. This may be due to the small number of different photorealistic pictures and the fact that these pictures were presented redundantly in the virtual environment. In experiment 2, I increased the number of different façades pictures. This factor affected the wayfinding performance, so that both groups performed the task with a comparable error rate and in a comparable time span. Nevertheless, participants can discriminate the intersections they have passed along the route from intersections presented to them that they have never seen before.

In an additional experiment in the same virtual environment, Peters et al. [2010] concentrates on the question if people employ the same landmarks for writing a route direction. For this purpose, each participant navigates along the same two routes as in my above experiments and has to write down a route description for a fictitious navigator. Interestingly, in both cases, i.e., for the short route and for the long route, the majority of participants used landmarks to describe the route. In the case of the short route, the participants referred to four landmarks, and in the case of the long route, to nine on average. To conclude, the subjects of this study naturally used landmarks information in their written route directions and, in this case, utilised the façades information given by the photorealistic pictures.

However, the route descriptions have not been tested on quality issues yet. To analyse the quality of the described utilisation of façades information in an external representation, a follow-up experiment is needed.

These findings support the assumption that people do rate the façades information as a discriminable feature, i.e., an information supportive of wayfinding, but they do not anchor turning actions to this façades information.

For both experiments, no interaction effect between the factors choremised world/original world and tested with white façades/with photorealistic façades could be detected. Thus it can be deduced that the embedded *wayfinding choremes* enhance wayfinding performance for complex routes even if no façades information is available.

6.5 SUMMARY

In this chapter I presented a study concerning the question whether the transferred *wayfinding choreme* schematisation also enhances wayfinding performance in a virtual environment. Two experiments are presented in which the participants had to learn a predefined route. In both experiments, the wayfinding performance of two groups is compared: one group who navigated in a schematised world, and a second group who performed the task in a non-schematised world. The results of the second experiment—a follow-up experiment with a more complex route—illustrated that in the schematised world, participants made significantly fewer errors. These results support the initial hypothesis that the embedded *wayfinding choremes* enhance wayfinding performance during *route following from memory*. However, the second hypothesis was not confirmed in that no significant differences could be found between the groups for the duration of the route recall phase, which can be seen as an indicator that this schematisation enhances the structural qualities of the internal representation. Future experimental work is needed to investigate the question in what way this schematisation enhances the internal structures and processes. The study clearly illustrates that the transfer of schematisation principles works, and that schematisation is also beneficial in virtual environments. Concluding, this study can be seen as an indication that the transfer of *wayfinding choremes* was successful.

7 CONCLUSIONS AND OUTLOOK

This chapter concludes the present thesis with a review of the contributions announced in Chapter 1 and presents an outlook on future work—more precisely, on possible extensions of the theoretical work and additional future experiments.

7.1 CONTRIBUTION OF THIS THESIS

Nowadays, the variety of different types of external spatial representation is massively increasing. However, it is often ignored that certain spatial situations and wayfinding tasks require that a suitable type of representation be selected. This thesis does not only present transfer guidelines for schematisation techniques but also offers appropriate tools to analyse the informational requirements and presented information within a representation.

In this section I take a retrospective look at the contributions that were announced in Section 1.3 and discuss which claims of this thesis have proven justified.

The analysis of the information needs of wayfinding tasks as conducted in Chapters 3 and 4 on the example of *route following* provides a thorough inspection of information requirements according to both representation-theoretic aspects and psychological and cognitive properties. On the one hand, this analysis includes a functional decomposition analysis of wayfinding tasks according to their information requirements. This method delivers a concise inspection of the information needs of each sub-task as well as an examination of human conceptualisation of this information. On the other hand, this analysis links the representation-theoretic considerations and the psychological and cognitive aspects of external representations to the according wayfinding task, in order to match the information needs of a specific wayfinding task to the presented information of the external representation.

This analysis focuses on the wayfinders' informational needs and, based on representation-theoretic as well as cognitive considerations, presents clearly the interplay between a given wayfinding task and the assisting external representation. The linking of these considerations allows bridging the gap between human abilities and cognitive processes in performing wayfinding tasks and the requirements on an external representation to deliver a cognitively ergonomic assistance.

The analysis results in a systematic approach both inspecting the information requirements of certain wayfinding tasks and connecting these results to the information requirements on external representations. It also provides a thorough examination of human conceptualisation of information and its impact on the meta-knowledge employed to external representations, to bridge the communication gap and meet the information needs.

Based on this analysis, guidelines are developed for schematisation principles to transfer knowledge of schematisation techniques between different representation types. For transferring schematisation techniques, the guidelines comprise an analysis of the correspondences between the environment, the representation and the human agent according to a wayfinding task. This especially includes a sophisticated examination of the influences of schematisation to this system of correspondences. This analysis shows that schematisation techniques that, by easing cognitive processing, positively influence the correspondences between an external representation and the human agent are transferable if the applied conceptualisations can be compared.

The analysis of transferring guidelines is supported by an exemplary transfer of *wayfinding choremes* from a map representation to a virtual environment. This successful transfer results in enhancing wayfinding performance for *route following with maps* as well as for *route following from memory* in virtual environments.

Furthermore, the comprehensive inspection of environmental factors and mental processing of information for *route following*, in particular, angular information and its mental distortion by conceptualisation, illustrates the closing of the research circle from behavioural study to representational considerations to cognitive processes.

The in-depth investigations about aspects of the schematisation technique of *wayfinding choremes* allow drawing conclusions on the structure of the internal representation of route information. The results of the experimental work indicate that this qualitative visualisation of the schematised angular information enhances wayfinding performance in either of the external representations in question. The possibility of transferring schematisation techniques from one type of representation to another implies that the underlying mental representation and processes supported by this transfer must have strong similarities in the way they deal with certain informational aspects presented by the external representations. Here, further research is necessary to investigate into the cognitive details these findings are based on.

7.2 FUTURE WORK

In my thesis, I present guidelines and requirements to successfully transfer a schematisation technique from one external representation type to another. This work inspires a couple of enhancements on the introduced approaches as well as further applications in which the presented techniques may direct to new possibilities and enhancements.

7.2.1 *Transferable Schematisation Techniques*

This thesis can be seen as a starting point for designing generalisation guidelines for schematisation knowledge. The guidelines for transferring schematisation principles from one representational medium to another, as presented in this thesis, allow transferring knowledge about schematisation. The functional decomposition of wayfinding tasks, jointly with a representation-theoretic analysis of the representational media, allows a thorough inspection of the wayfinder's information needs as well as an examination of the way the essential information is presented by the respective external representations.

So far, I present a successful example of transferring *wayfinding choremes*, which were initially developed for map representation. This concept is transferred to a virtual environment. Hence, the *wayfinding choremes* must be embedded into this virtual environment. From study results it could clearly be deduced that this schematisation technique enhances wayfinding performance.

Within the scope of this thesis, I am limited to presenting this guideline using selected examples. Yet there exist many more interesting wayfinding tasks and types of external representations for further study and investigation into essential aspects.

For investigating and examining the introduced transfer approach, I need to use and integrate more tasks and representations.

7.2.2 *Future Experimental Work*

The study presented in Chapter 6 illustrates that the transferred schematisation technique of *wayfinding choremes* enhances wayfinding performance during a *route following from memory* task. The experiments also raised further research questions for future experimental work, however.

7.2.2.1 *Enhancement of Storage or Recall*

The presented case study shows that the transfer of *wayfinding choremes* to a virtual environment positively influences wayfinding performance. Although the results of this study illustrate the facilitating effect of *wayfinding choremes* on wayfinding performance, they do not provide a detailed answer to the question which processes or features of the internal representation are supported by the integrated *wayfinding choremes*. On decomposing the wayfinding task, the question was raised which components are supported by the schematisation. Klippel proposed that this schematisation technique enhances both the cognitive mapping process and the decision making processes [Klippel et al., 2005b]. These two subtasks, introduced in Chapter 3, contain many sub-subtasks. By dividing these subtasks by information processes, one can separate them into three categories: the storage of information into the internal representation, the recall of information from the internal representation, and the reasoning on the internal mental structure.

Through further experimental work, I plan to investigate which of these three subcomponents are supported by this schematisation technique. To this end, I plan on dividing the participants performing the *route following from memory* task into two groups, using an experimental design similar to the presented experiments in Chapter 6. The first group $G_{storage}$ will first be trained in a schematised world and then be tested in a non-schematised world. Hence, in this experimental design, the schematisation can only enhance wayfinding performance if the given schematisation supports cognitive components or processes involved with building up an internal representation of the route. The second group, on the other hand, will undergo an inverted design, meaning that the participants of this group G_{recall} will be trained in a non-schematised world first and then be tested in a schematised world. In this case, the schematisation should result in a better wayfinding performance if this schematisation supports cognitive components or processes that are in charge of recalling the necessary information from the internal representation. The wayfinding performance of either group in *route following from memory* will then be analysed and compared. This experiment may shed light on the question which subtask is supported by this schematisation.

As in the previous experiment the reasoning part is neglected, I plan to integrate think-aloud protocols [cf. Tenbrink and Wiener, 2007; Tenbrink, 2008] at the close of this experiment in order to investigate whether, or in what respect, the group reasoning processes differ. Furthermore, I aim to analyse wayfinding errors arising in either group in order to inspect if certain systematic errors occur.

Furthermore the results of this experiment with respects of error rate and time deliver more information whether the embedded schematisation supports the cognitive processes—would positively influence the time—or the quality of the internal representation—which is linked to the error rate.

7.2.2.2 *Direction Model Modifications*

The central point in the concept of *wayfinding choremes* is the conceptualisation of angular information at intersections in urban situations like a city street network. Using this schematisation technique, the turning branch at an intersection is replaced by a prototype of the according *wayfinding choreme*. There are seven *wayfinding choremes* based on a concept of direction. Concepts of direction are an ongoing research topic in AI as well as in spatial cognition [Klippel et al., 2004]. Direction can be seen as basic spatial relations, and many early direction models have facilitated homogenous partitions of space [Klippel et al., 2004].

The introduced schematisation technique of *wayfinding choremes* also uses a homogenous partition of space via an axes model with eight sectors of the same size as prototypical instantiations [Klippel, 2004]. These sectors define seven *wayfinding choremes* (see Section 2.4.4).

However, this homogenous direction model has been criticised by many researchers [e.g. Sadalla and Montello, 1998; Montello and Frank, 1996; Klippel et al., 2004; Klippel and Montello, 2007]. Different studies and theoretical assumptions illustrate that a need exists to modify the direction models.

Klippel et al. ran experiments to modify the direction model according to map representations [Klippel et al., 2004; Klippel and Montello, 2007]. They proposed a revised model that contains 6 sectors of different sizes, one axis and an unvented 'back' sector.

So far, for the representation of angular information in a virtual environment, no modified direction model exists. I aim to investigate in a future study how the direction model must be modified. For this purpose, I will present to the study participants short films of intersections at which specific turning actions are executed. The participants will then have to classify the presented turning action in terms of the seven *wayfinding choremes*: *veer left, left, sharp left, straight, sharp right, right, veer right*.

Furthermore, each participant will have to perform in a virtual environment certain turning actions like "go left" or "veer right" etc. at an intersection. Different types of intersections will be used in this experiment to examine which intersection configuration matches with which turning action.

This experiment can be seen as a starting point to investigate whether the different presentations of spatial information have an influence on the concept of direction and, consequently, to infer a need to modify the model of direction according to the presentation type.

7.2.2.3 *Transfer to Reality*

A long-term objective is to design suitable virtual environment applications as wayfinding assistance services for real world scenarios by using the presented transfer approach.

The success of the usability of this schematisation technique of *wayfinding choremes* for a training approach in a virtual environment for a real world scenario depends essentially on the results of 7.2.2.1. Should the *wayfinding choremes* support the storage of the correct turning action at a decision point, this approach may have a promising, positive effect on wayfinding performance. However, if the *wayfinding choremes* support the recall of the correct turning action, this schematisation technique is not suitable to train people in the schematised virtual environment.

So far, I have worked on transferring two-dimensional schematisation techniques to three-dimensional virtual environments in order to test if schematisation is a valuable tool for enhancing navigation performance. The presented study shows that people perform the *route following from memory* task with fewer errors in a schematised virtual city. However, all the experiments and individual performances were restricted to a virtual environment.

The next step will be to investigate whether people can transfer spatial knowledge from a schematised virtual environment to a real environment and if schematisation supports this transfer.

Transferring spatial knowledge delivered and learnt from a virtual environment is possible [e.g. Waller et al., 1998; Peruch et al., 2000; Wallet et al., 2009], and the acquired spatial knowledge actively learnt from a virtual environment is orientation-free [Sun et al., 2004].

Furthermore, according to representation-theoretic considerations, a virtual representation has a dual nature. According to the introduced context model (see Section 5.1.1), an external representation of spatial information via a virtual environment is a representation on the one hand, and an environment by itself on the other.

In the case of utilising a virtual environment to train people for a real-world scenario, this correspondence system changes. Imagine a navigation experiment whose participants have to perform a *route following from memory* task and are trained in a virtual environment—but are tested in a real world setting. Within this experimental setting, the correspondence system changes dramatically. During the training phase, the virtual environment has its dual nature as both representation and environment, but during the testing phase, no external representation is available—meaning that the participant has to solve the problem by recalling the route knowledge from memory.

In the follow-up study I will focus on the question if the schematisation technique offers the necessary qualities for a transfer from a virtual to a real environment. For this purpose, I aim to investigate if the integrated schematisation enhances the legibility of the environment on the one hand and the quality of the established spatial representation on the other hand.

7.2.3 *Seamless Navigation*

Seamless navigation is defined as "...a term which describes universal navigation systems, where transitions between different navigation modes and services are, more or less, seamless for the user. Switching seamlessly from passenger car navigation to pedestrian navigation and further indoor navigation is not a simple task. Integration of services is needed to cover all these situations." [Virtanen and Koskinen, 2004, p. 1].

Nowadays, the range of different modalities of presenting spatial information for wayfinding assistance is highly increasing. Currently, there exist a huge variety of different presentation types of spatial information for wayfinding assistance. This huge range contains, for example: traditional paper and digital maps, verbal or written instructions, pictorial information via satellite images or Google Street View, or virtual environments like Google Virtual Earth. There also exist mixed formats like augmented reality as well as maps with three-dimensional objects or car navigation systems with graphical and auditory output. However, most navigation assistance systems present spatial information in a single format, for example, as a map or in verbal instructions and do not offer the possibility to switch or choose between different modes of presentation.

Literature on the subject gives strong evidence for the advantages of presenting spatial information in different modes at the same time. An example that grounds these expectations is the theoretical model of cognitive collages from Tversky [1993], who stated in her paper that she did not believe in the mental map metaphor. In the opinion of Tversky, the mental map is more a mental collage. She points out that a maplike mental representation of space does not include the complexity and richness of environmental knowledge. Her mental collage metaphor reflects the variety of the mental representation which can contain not only information in a specific format like position information but also different sources and types of information. Furthermore, many experimental studies exist that compare different types of information against each other. An example of such studies is the comparison study on maps and verbal directions for wayfinding by Meilinger [2005]. In his study, the participants had to learn a route using a map, and using a written description. After learning, the persons were tested in walking along the route without any assistance. The results of this study were that for simple routes, written descriptions are efficient, and for complex routes, maps have their benefits. Another researcher who follows Tversky [1993]'s ideas of a mental collage is Hirtle [2000]. Hirtle argues that redundant information presented in a variety of media supports the wayfinder [Hirtle, 2000]. He introduced an online assistance service called Library Locator. This platform presents the spatial information to wayfinders for locating a certain library on a campus in three different representational formats: on a map, in a picture series, and in a written description.

My goal in the future will be to come up with an assistance system that covers more than one wayfinding task with multiple presentation formats adequate to the given tasks and the individual preferences. The first step on this way is to analyse what type of information presentation is suitable and preferred for a specific wayfinding task.

Having this long-time goal in mind, the first step is to search for the adequate representation of spatial information in a specific task.

For this purpose I can facilitate the work of Chapter 3 and 4, in which I first analyse the informational needs of a wayfinding task next to its subtasks, and then enquire into the question what kind of information the different types of spatial information presentation contain.

My work aims at delivering the information and ideas to create a wayfinding assistance system in the near future that does not only present spatial information for one specific wayfinding task in one particular type of external representation—but that rather provides a coherent and overall framework which subsumes all suitable representation approaches and, by integrating schematisation knowledge, selects the most suitable representation for an adequate wayfinding assistance for any wayfinding task.

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