Wayfinding Choremes

Conceptualizing Wayfinding and Route Direction Elements

Alexander Klippel

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Zusammenfassung

Die vorliegende Arbeit leistet einen Beitrag zur kognitiv adäquaten Charakterisierung von Routeninformation und deren Visualisierung. Ein zentrales Anliegen ist die Identifikation und Formalisierung primitiver Bausteine von Routen aus einer kognitionswissenschaftlichen, informatischen Perspektive. Die primitiven Bausteine werden hier als *Wegfindungschoreme* bezeichnet und sind definiert als mentale Konzeptualisierungen von primitiven funktionalen Wegfindungs- und Routeninstruktionselementen. Der Begriff C*horem* leitet sich aus der von Roger Brunet entwickelten chorematischen Modellbildung (*modelisation chorematique*) ab. Chorem ist ein Kunstwort aus dem Stamm des griechischen Begriffs für Raum, *chor-*, und dem Suffix *–em*, wodurch die Beziehung zur Sprache zum Ausdruck gebracht werden soll. Wegfindungschoreme sind abstrakte mentale Konzepte, die über Externalisierung zugänglich sind. Wichtige Formen der Externalisierung sind Verbalisierung und Graphikalisierung (Skizzen).

Eine wesentliche Erkenntnis dieser Arbeit ist die Unterscheidung zwischen funktionalen und strukturellen Bestandteilen von Routeninformation. Während bisherige Ansätze vielfach auf strukturellen Informationen aufbauen, d.h. sich mit der Konzeptualisierung von Objekten beschäftigen, zielt die Charakterisierung mittels Wegfindungschoremen auf funktionale Aspekte ab. In diesem Zusammenhang ist es wichtig zwischen Pfaden (engl. *paths*), also den Objekten entlang derer Wegfinden stattfindet, und Routen (engl. *routes*), den behavioralen Mustern beim Wegfinden, zu unterscheiden.

In dem behavioral-experimentellen Teil der Arbeit konnte Evidenz für die folgenden Aspekte von Wegfindungschoremen erbracht werden:

- Mentale Konzepte von Routenteilen beruhen auf behavioralen Mustern. Dies bedeuted, im Kontext von Wegfinden und der Kommunikation von Routeninformation sind funktionale Konzepte wichtiger als strukturelle.
- Wegfindungschoreme sind konzeptuelle räumliche Primitive von Routen. Sie können zu Routenelementen höherer Ordnung kombiniert werden.
- Kombinationsprinzipien werden beeinflusst von der Struktur und dem Vorhandensein zusätzlicher Routeninformation in Form von Landmarken.
- Es existieren prototypische graphische Instantiierungen von Wegfindungs-choremen.

Die ursprüngliche Intention von Brunet, mittels Choremen eine ‚Sprache' für räumliche Phänomene zu entwickeln, konnte für den Bereich von Routeninformation aus einer kognitionswissenschaftlichen Perspektive realisiert werden. Das Modell der Wegfindungschoreme, die als Terminale zu verstehen sind, umfasst dabei zwei zentrale Ansätze. Zum einen wird eine grammatische Notation verwendet, um Routeninformation auf der Basis von Wegfindungschoremen zu strukturieren und

Kombinationsregeln zu spezifizieren. Zum anderen bilden Wegfindungschoreme den Ausgangspunkt für einen kognitiv-konzeptuellen Vorgehen zur Kartenkonstruktion. Dieser kognitiv-konzeptuelle Ansatz ist komplementär zu bisherigen Vorschlägen, die als *bottom-up* charakterisiert werden können. Da er von mentalen Konzepten ausgeht, ist der Ansatz der Wegfindungschoreme als *top-down* zu sehen. Hintergrund dieser Vorgehensweise ist die Annahme, dass bei Übereinstimmung mentaler Konzepte und graphischer Repräsentationen eine kognitive adäquate Kommunikation möglich wird.

Abstract

This thesis contributes to the cognitively adequate characterization of routes and the visualization of route information. One central goal is the identification of primitive route elements from the perspective of cognitive science. These conceptual primitives are coined *wayfinding choremes*. They are defined as mental conceptualizations of primitive functional wayfinding and route direction elements. The term *choreme* is derived from a theory by Roger Brunet, chorematic modeling (*modelisation chorematique*). Choreme is a made-up word taken from the root of the Greek term for space, *chor-*, and the suffix *–eme*. By this combination Brunet indicates his goal: the creation of a language for space.

Wayfinding choremes are abstract mental concepts that are accessible by externalizations. For this thesis two kinds of externalizations are pertinent: verbalization and graphicalization (sketch maps).

One major achievement of this thesis is the distinction between structural and functional elements of route information. Most approaches, especially those concerned with the visualization of route information, focus on structural aspects, i.e. they are concerned with the conceptualization of objects. In contrast, the wayfinding choreme theory aims at a functional characterization of route information, i.e. it focuses on actions that demarcate only parts of a structure. In this context a distinction is enforced between paths, linear objects in the environment, and routes, linear behavioral patterns.

In the behavioral-experimental part of this thesis evidence for the following aspects of wayfinding choremes was found:

- Mental conceptualizations of route parts are based on behavioral patterns. This means that in the context of wayfinding and the communication of route information functional rather than structural concepts predominate.
- Wayfinding choremes are conceptual spatial primitives of routes. They can be combined to route elements of higher order.
- The chunking principles of wayfinding choremes are influenced by the structure into which a route is embedded and the existence of additional route information such as landmarks.
- There are prototypical graphical instantiations of wayfinding choremes.

The original intention of Brunet to develop a language for spatial phenomena is realized in the present work for the domain of route information from a cognitive scientific perspective. The model of wayfinding choremes, which can be understood as terminals, comprises two central parts. First, a grammatical notation is used to organize route information on the basis of wayfinding choremes that allow for the specification of chunking principles. Second, the wayfinding choremes are employed to construct maps. As wayfinding choremes originate in abstract mental concepts this approach is termed cognitive conceptual. In contrast to other approaches that can be termed bottom-up, the

wayfinding choreme approach is top-down. The rationale behind this procedure is that it can be assumed that a correspondence between internal and external representations has positive effects on map-wayfinder interaction.

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Conventions

Linguistic examples are italicized

turn right at the intersection

Mental conceptualizations are written as small capitals

TURN RIGHT AT THE INTERSECTION

Nonterminal categories of the wayfinding choreme route grammar (WCRG) are written in angle brackets

<DecisionPoint>, <STC>

Terminal categories are the wayfinding choremes (wc); they are further specified by an index that details the turning concepts and optionally route information, such as routemarks.

wc_s or $wc^{R+;hr}$

Finite sequences of terminals are written without commas or brackets

$wc_s wc_s wc_s$

production rules (definitions) are written as

::=

Optionality is indicated by

[ ]

Repetition is indicated by

{ }

Definition-separator-symbol

|

If an exact number of items is required it is done by an explicit rule

<XY> ::= $wc_s wc_s$

"Speak of anything spatial, and there was, is, or will be a mapmaker seeking to make it more understandable through a mosaic of points, symbols, lines, headings, and coloring—that is, through a map."
—*The Mapmakers*, by John Noble Wilford, 2000

1 Introduction

Wayfinding and the communication of route information constitute fundamental activities in our daily life. Considering the core elements involved, we quickly find out that *decision points*, for example, at intersections, play the most important role. However, what is the difference between thinking of an intersection per se and thinking of an intersection at which I perform a sharp right turn? The intersection is a part of our physical environment. The sharp right turn at the intersection is an *action* that is performed within this physical environment. The action demarcates parts of the intersection from a *functional* perspective. In this thesis, I introduce the concept of ***wayfinding choremes*** that I define as:

Mental conceptualizations[1] of primitive functional wayfinding and route direction elements (in short, route elements).

Wayfinding choremes serve as elementary models of goal directed spatial behavior. Given their functional nature, they reflect procedural knowledge, i.e. knowledge about how to interact with the world. In this sense wayfinding choremes are schemata and do not as such concern categorical knowledge about physical spatial objects. I proceed by giving an interdisciplinary motivation for research on wayfinding choremes. This is in order to render the term wayfinding choremes more precise, to specify their role in visual communication, and to account for the characterization of route information.

The motivation (section 1.1) for the theory of wayfinding choremes arises from the question: What characterizes cognitively adequate *aspectualization* (Freksa & Barkowsky, 1996; Berendt, Barkowsky, Freksa, and Kelter, 1998)? The benefits of aspectualization will be explained and grouped into four categories: perceptual, cognitive, computational, and technical. The scope of this thesis is given by categorizing route directions and by making the following distinctions: between *common map interpretation* and *expert map interpretation*, and between different environments. Against this background, the goals and hypotheses of this thesis are laid

[1] Fonseca et al. (2002) use the term *mental conceptualization* since *conceptualization* is not only used in cognitive science but in general, everyday usage as well. If not further specified I use the term conceptualization in the meaning of mental conceptualization.

down in section 1.2. Section 1.3 details the approach and the scientific background. Section 1.4 gives an overview of the organization of the thesis.

1.1 Motivation

Wayfinding and route directions have developed into central research areas in cognitive science. What makes their investigation so appealing is that they uniquely combine elements of human spatial cognition: They take into account characteristics of spatial environments, they 'naturally' involve the interaction with representations of spatial knowledge in external media, and they reveal perceptual and cognitive processes necessary to interact with spatial environments, external media, or both. Wayfinding is defined by Golledge (1999b, p. 6) as:

> "[...] the process of determining and following a *path* or *route* between an origin and a destination. It is a purposive, directed, and motivated activity. It may be *observed* as a *trace* of sensorimotor actions through an environment. The trace is called the *route*. The route results from implementing a *travel plan*, which is an a priori activity that defines the sequence of segments and turn angles that comprise the path to be followed. The travel plan encapsulates the chosen strategy for path selection."

The study of wayfinding, comparable to the study of language use, has become a *window to cognition*, revealing cognitive core principles (Mark & Gould, 1995; Montello, to appear). Most importantly, wayfinding is rooted in space and space is regarded as essential for cognition (Lakoff & Johnson, 1980; Freksa & Habel, 1990). Likewise, route directions offer a perspective on cognitive processes that naturally combines spatial and cognitive aspects, i.e. the conceptualization of spatial environments from the perspective of actions that take place in these environments (e.g., Couclelis, 1996). Of the many facets of wayfinding and route directions, the following ones are pertinent for the cognitive conceptual approach advocated in the current work, and for wayfinding choremes as conceptual spatial primitives of wayfinding and route directions:

- Stressing the *functional* aspects of wayfinding and route directions. By the distinction between the level of the physical reality (referred to as *structure*[2]) and actions that demarcate and use parts of physical structures (functional perspective), an important step is made toward cognitive adequacy, both from

[2] The primary reading of structure in this thesis (especially in contrast to *function*) is related to the first definition of structure found in WordNet (structure): "[...] construction – (a thing constructed; a complex construction or entity [...])". With structure I refer to the physical layout of street networks. In this sense, the use of structure in this thesis is ambiguous; it denotes linear physical entities in the spatial environment. These linear physical entities in turn add an additional means to structure our environment.

the perspective of cognitive modeling and cognitive ergonomics (cf. Strube, 1992).

- Concretizing the mental conceptualization of turning concepts at decision points.
- Providing a functional characterization of route information on this basis.
- Identifying conceptual representations that underlie both pictorial and verbal route directions.
- Enhancing the visual communication of functional route information.

Technological developments open new perspectives on the production of maps. The number of maps, especially those created for special purposes such as wayfinding, has tremendously increased. In contrast, the quality of maps has not improved to the same degree; many questions arise with respect to the new methods of depicting and providing spatial information.

As special-purpose maps represent only information that is needed to solve a given problem—in contrast to general-purpose maps depicting information for solving various problems—they can benefit from *aspectualization* (Freksa & Barkowsky, 1996; Herskovits, 1996; Tversky, 1996; Freksa, 1999). Roughly, aspectualization can be defined as selecting aspects from rich information sources. This comprises not only the selection of objects that are relevant for a given task, but additionally the specification of those properties and relations that hold between objects from a representation-theoretic perspective, for example, qualitative spatial relations (see section 2.3). Aspectualization means deliberately simplifying information to achieve cognitive adequacy. It goes beyond the level of abstraction that is reached and aimed at by classical cartographic generalization[3].

In the following sections, I first characterize important concepts of map complexity that constitute the basis for characterizing aspectualization from the perspective of cognitive and perceptual adequacy. I then give an overview of the benefits of aspectualization as they can be found in areas such as perception, cognition, or technical system design. As such, they are—implicitly and explicitly—influential research topics in cognitive science, geography, psychology, informatics, and cartography. The benefits of aspectualization provide the motivation for this work, i.e. identifying cognitively adequate principles of aspectualization.

1.1.1 World Complexity and Map Complexity

Representation theory (Palmer, 1978; cf. also Furbach, Dirlich, and Freksa, 1985; Mandler, 1988a) differentiates between *objects* and *relations* between objects. Additionally, one has to think of relations that hold between *parts of objects*. The complexity of an object increases when the relations between its parts become more

[3] In this reading, aspectualization corresponds to schematization in the terminology by Herskovits (1998, p. 149): "Systematic selection, idealization, approximation, and conceptualization are facets of schematization, a process that reduces a real physical scene, with all its richness of detail, to a very sparse and sketchy semantic content." Aspectualization accentuates the point of actively choosing pertinent 'aspects'.

complex. The working definition of complexity employed here is that more details or more relations comprise higher complexity[4]. Approaches in Artificial Intelligence (AI) take the 'internal' complexity of objects into consideration in order to deal with the complexity of the relations among objects. For example, the difference between the two region connection calculi (RCC 5 and RCC 8) (e.g., Randell, Cui & Cohn, 1992; Gotts, 1994; see section 2.3.2.1) lies in the ontological status of the boundaries of the objects that increases the number of relations between two objects.

A similar issue arises in the context of wayfinding: What constitutes, for example, the complexity of an intersection? Is it the intersection as such or is it the relation between its parts? The point of view that the complexity is determined by the relations between the parts of an intersection corresponds to the functional perspective taken in this thesis. This is because the action performed at an intersection is central for the complexity.

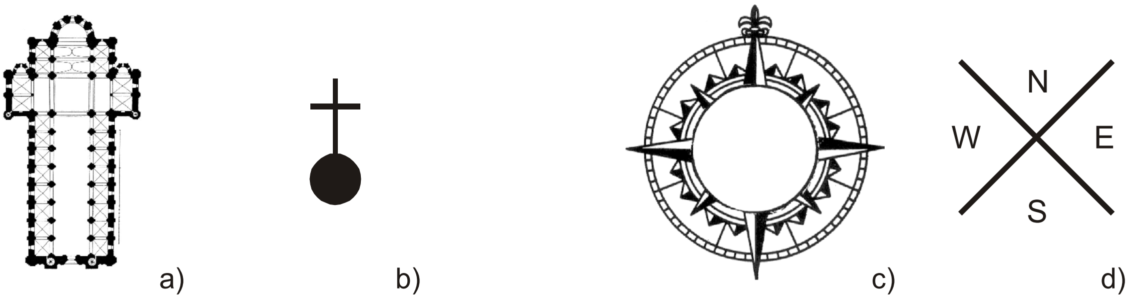

Figure 1. The complexity of objects versus the complexity of relations. a) shows a floor plan of a church whereas b) is a simple symbol. c) stands exemplarily for the detailed relations that can be read off a compass whereas d) shows qualitatively modeled cardinal directions.

A further prerequisite for defining aspectualization and its benefits, and for subsequently taking the approach of spatial primitives, is to concretize *map complexity*. An examination of the relevant literature (e.g., Arnheim, 1976; Monmonier, 1974; Bollmann, 1981; Petchenik, 1983; Tufte, 1990, 1997; Keates, 1996) suggests the following distinctions:

- semantics versus syntax and
- visual complexity versus cognitive complexity.

Even though these distinctions can be made seldom in a pure sense, they serve to structure the field.

Semantics and syntax. In the tradition of semiotics a trilateral relationship is generally agreed on, for example, between the sign-vehicle, the referent, and the interpretant (cf. MacEachren, 1995; Nöth, 2000). With respect to sign-vehicles, semantics denotes the relation of a sign-vehicle to what it actually stands for. Syntax on the other hand

[4] Obviously, this simple definition disregards the effects that organization can have on complexity. This organization is also referred to as *structure* (e.g., Lockhead & Pomerantz, 1991) that can be instantiated, for example, by reoccurring pattern, shape, or color (see also footnote 2).

analyses combinatorial and integrative possibilities of sign-vehicles. Syntax is sometimes understood as an analysis of the inner structure of a sign-vehicle independently of its transferred meaning (cf. Eco, 1977; see Figure 1).

In the case of maps, syntax and semantics are tightly interwoven, as the depiction of much content often requires the use of many sign-vehicles. Besides, the more sign-vehicles one uses the more relations are depicted, deliberately or not. This constitutes one of the major benefits of depicting information graphically. The medium as such provides information 'on the fly'. For instance, two points depicted on a map are spatially related to one another even though the spatial relation between them may not be the primary goal of that map. This oftentimes advantageous property also involves the possibility of misinterpretation since it is nearly impossible—or at least requires great sensibility—to neglect the qualities of the medium. In the consequence, graphical depictions can convey a degree of accuracy that is not intended. They are generally not suited for depicting *qualitative* information. The representational medium is a continuum and does not support the representation of a small number of discrete equivalent classes of spatial locational information. This latter characteristic leads to the question, how to communicate information that legitimately can be read off a map.

In spite of this, the degree of syntactic complexity can be defined for single sign-vehicles: Churches might be represented by a standardized sign such as a black dot with a little cross on it, or they may be depicted by their floor plan (see Figure 1). Generally speaking, the same content can be depicted using different sign systems. This becomes evident when comparing atlases edited by different publishers (cf. Dierke, 2002; Falk, 2003).

Semantics originally denotes the meaning of a sign-vehicle which leaves open the aspect of the relations between sign-vehicles in a map. To overcome this deficit MacEachren (1995) discusses the approach of Morris (1938) to differentiate between syntax and *syntactics* (i.e. the term for syntax in the semiotic tradition). Here syntactics only accounts for the relations among sign-vehicles in a map with respect to, for example, the logic of a map legend. Bollmann (1981) uses syntax-pragmatics complexity to account for the relations between sign-vehicles with respect to their relative position and their distribution and the meaning that is communicated by these characteristics.

Visual complexity versus cognitive complexity. Closely related to the discussion of syntax and semantics is the distinction between visual and cognitive complexity. From the viewpoint of visual complexity maps that are full of *visual clutter* (cf. Phillips, 1979, 1981) hinder information extraction. From a cognitive point of view maps that depict a great number of relations or complicated relations are more complex than those that show only a few or simple relations. The two critical questions are: How easily can I extract the information (visual complexity) and how much information do I have to deal with to solve a given problem (cognitive complexity)? These two concepts—visual and cognitive complexity—are tightly interwoven and are hardly separable. Figure 2 illustrates a simple example of different visual complexities. In the left part of Figure 2, locations of objects are connected via straight lines that are visually easy to perceive. In the right part, the same objects are connected via curved lines.

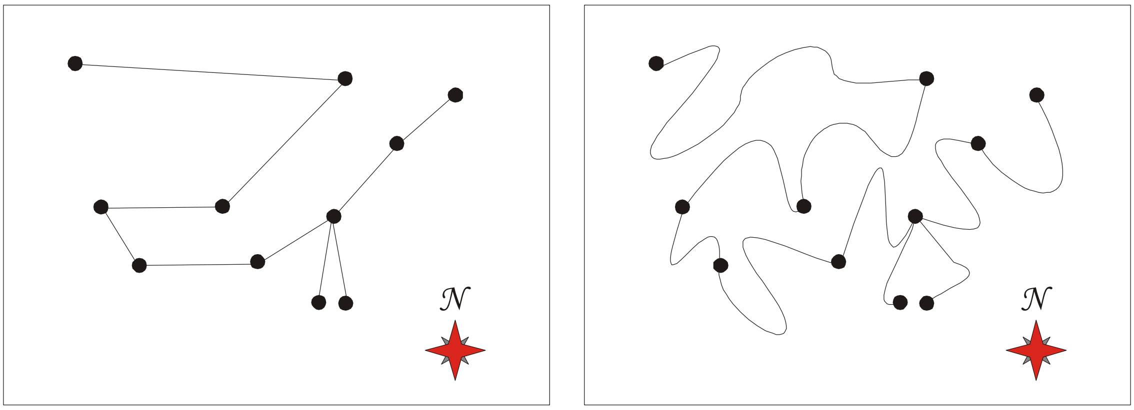

Figure 2. Different visual map complexities.

1.1.2 Aspectualization

> "The geographic world surrounding us is extremely complex. When we want to master a given problem in this world, we need to single out particular aspects of current interest from this multifaceted formation. So at any given time we are only interested in [a] few objects, and concerning these objects again we are regarding only particular properties and/or relations. The capability of isolating the relevant aspects and relating them to one another, results in a unique intellectual efficiency. This efficiency, however, is necessary for successfully operating in the world." (Freksa & Barkowsky, 1996, p. 109)

The question of aspectualization is not a matter of 'whether' but rather of 'how'. Many research efforts deal with the definition of aspectualization processes. Every scientific field has its own approaches for processes that allow for reducing the informational content or for emphasizing relevant aspects. Depending on the emphasis of each approach we find terms such as:

- abstraction,
- generalization,
- schematization, or
- modeling.

According to this proposition and without detailing the differences behind those terms an overview of research concerned with the complexity of visual graphic representations from the perspective of information processing theory is given. This section provides foundations for depicting spatial information in an aspectualized way, for example, by a wayfinding choreme map. Tversky (2003) identified benefits of aspectualization; I have regrouped them and added further aspects:

- visual-perceptual,
- cognitive,
- computational, and
- technical.

1.1.2.1 Visual-Perceptual Advantages of Aspectualization

This section mainly considers cartographic literature (for an overview of psychological research cf. Palmer, 1999; Goldstein, 2001). Until the 1970s most experimental research conducted on maps in the field of cartography dealt with the perception of individual map symbols or limited comparisons among symbols (cf. Petchenik, 1975). Some research was cognitive in a way but did not explicitly aim at revealing and considering cognitive processes. There were only a few accounts that took into consideration the greater picture of information processing and research was mostly restricted to highly specific research questions (e.g., Arnberger, 1982; Dent, 1975; for an overview cf. Montello, 2002). The reason for this can be seen in the lack of suitable methods to elicit cognitive processes.

Even though the concept of complexity is not well defined in the cartographic literature, there are various investigations concerned with the visual-perceptual complexity of maps. In these investigations different methodologies such as eye fixation studies, tachistoscopic measurements, or subjective judgments were employed. This research aimed at defining the effects of different degrees of visual-perceptual complexity on the process of cartographic communication.

While greater detail may add realism to a visual display, it does not necessarily affect functional variables (i.e. the ability to make judgments based on the information). For example, Kaplan, Kaplan, and Deardorff (1974) demonstrated that subjects could base judgments on the information presented in coarse architectural models. Consequently, they argued that simplification of the display has a number of benefits, from increasing generality to reducing the information processing demand. In the Kaplan et al. (1974) study, high- or low-detail models of housing developments were presented to subjects in a between-groups design. The high-detail model had facade and landscaping details such as windows and contour lines. Subjects rated the housing development models in terms of functional aspects (e.g., how satisfactory the houses would be with respect to privacy). When subjects viewed pictures of the actual housing development on which the models were based, participants in both high- and low-detail conditions reported that the model that they had seen was an adequate representation of the actual development. From these results it can be concluded that the coarse model was as useful as the more detailed one in making these kinds of judgments.

Dobson (1980) showed in an experiment in which he employed tachistoscopic methods, that with increasing complexity of the stimulus—in this case: density of signs—the assimilation of information decreases. In their investigations Castner and Eastman (1984, 1985) state relationships between eye fixation data and the complexity of the stimulus. On this basis they classified fixations in the following way: Type-1 fixations have a duration of less than 300 ms; they indicate information that is easily graspable. Type-2 fixations last between 400 ms and 550 ms; fixations of this type indicate more complex information processing. Type-3 fixations last longer than 600 ms; they are not directly related to the visual stimulus and indicate higher level cognitive processes (Castner & Eastman, 1985).

Taylor and Hopkin (1975) argue that 'overloading' a map is the biggest drawback in map design. Consequently, Thorndyke (1981) promotes that maps should have a simple design, for example, by using dynamic graphics within computer systems that depict only the requested information. This reduces the amount of information that needs to be processed by viewing one map; although it may add a temporal aspect if more than one map is needed.

An abstract instruction manual is developed by Castner (1996). He discusses the differentiation between subject information and basic information and how they have to be applied in the map design process. He offers a simple procedure based on a 2x4 table to ensure that the map is not overloaded with information. The rows are separated into subject information and base information, the columns are ‘point’, ‘line’, ‘area’, and ‘letter’. "[...] filling it [a table] in as one develops the design of a map may help (or perhaps force) the designer to identify the visual tack necessary for the design to work [...]" (Castner, 1996, p. 7). It is not necessary to depict symbols on every level. An optimal map takes a place in between offered information and complexity.

Phillips and his collaborators (e.g., Phillips, 1979; Phillips & Noyes, 1977, 1982) researched on the topic of visual clutter. They performed studies to elaborate the effects of different typographic systems on the efficiency of map reading. They, too, claim that visual clutter is one of the most urgent problems in map communication. From a somewhat more general perspective on visual displays Tufte (1990, 1997) has provided many examples that underpin the need for visually clear and focused depiction of information with visual displays.

To sum up, the discussed findings from the primarily cartographic literature support the proposition that the display of information should be as simple as possible. The discussion so far laid the focus on the visual-perceptual aspects. That is, how easily can information be extracted from a representation. The next section will shed light on cognitive and conceptual considerations.

1.1.2.2 Cognitive and Conceptual Considerations

From a cognitive point of view, aspectualization is necessary to adapt to a complex environment. I will discuss four topics that underpin this assumption:

- the general necessity of aspectualization,
- the limited capacities of working memory,
- the ease of integration of information, and
- the speed of decision making.

Aspectualization is necessary to deal with the abundance of information. The world offers an incredible amount of information in every second we interact with it. The unfocussed, simultaneous processing of all information available would lead to a system breakdown. A stimulus may be perceptually (e.g., visually) simple but still be complex from a cognitive perspective. Clark (1989) described the problem from an evolutionary information processing point of view and termed it *The 007 Principle*: An organism can only afford to know what it "needs to know". Any organism that stores too much information is at an adaptive disadvantage because extra information requires extra processing. In a potentially hostile world, survival can depend on quick decisions; too much information can easily slow down decision making (see below). Organisms that store only what is necessary can process that information far more efficiently[5].

The study of language, as a *window to cognition*, reflects this position as well. To say it in Herskovits' words: "[T]here is a fundamental or canonical view of the world, which in everyday life is taken as the world as it is. But language does not directly reflect that view. Idealizations, approximations, conceptualizations, mediate between this canonical view and language." (Herskovits 1986, p. 2). She uses *schematization* as a superordinate category and states that selection, idealization, approximation, and conceptualization are facets of schematization. The main characteristic of schematization is that it is a process which enables us to deal with the richness of detail that we encounter in interaction with "real physical environments", as it results in a reduction to a "very sparse and sketchy semantic content". There are many examples that underpin this process. Consider, for example, a sentence like "the village is on the road to London" (Herskovits, 1998). By this example Herskovits makes clear that the reduction occurring in schematization involves the application of abstract spatial relations to simple geometric objects, i.e. points, lines, surfaces, or blobs. This reading of schematization is akin to aspectualization (see footnote 3).

Limited capacities of working memory. Cognitive psychologists differentiate parts of our memory. They assign them different functions grounded in the observation that we process information in interactions and that we learn and store information, i.e. the distinction of *short term memory* and *long term memory*. The basic idea that our memory is limited in its information processing capacities is associated with the work of Miller (1956) who experimented with the number of elements that participants were able to store in their short term memory during a restricted learning period. He came up with the often quoted if misinterpreted result that seven plus/minus two pieces of information can be easily recollected. The important effect he found is that the overall number of pieces of information can be increased by forming *chunks* of information, for example, combining four numbers to one: 1 9 9 1 to 1991. The further development of these findings resulted in what today is called *working memory* (Byrne, 1996), which is modeled extensively, for example, in the work of Baddeley (e.g., 1986).

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[5] The problem is to know a priori: what is necessary.

Sadalla, Burroughs, and Staplin (1980), Downs and his collaborators (e.g., Downs, Liben, and Daggs, 1988), and Allen and his collaborators (e.g., Allen & Kirasic, 1985; see also section 4.1.2) transferred these results to the interaction with spatial environments, for example, during wayfinding. Wayfinding through complex or cluttered parts of the environment necessitates the organization of complex parts into smaller and/or less complex parts.

Integration of information. Aspectualization reduces the effort of integrating different information sources (e.g., Tversky, 2003). This aspect is not isolated from the points already mentioned, for example, the limited capacities of working memory, or the necessity to cope with information overload. It is easy to comprehend that aspectualized information can be integrated more effortlessly than information on a finer level of granularity (cf. Hobbs, 1985).

Whereas this position is obvious from an information processing perspective it also raises the question of what happens when we deal with multiple information sources. Should all information sources involved be aspectualized? In an experiment Berendt, Rauh, and Barkowsky (1998) showed how aspectualized maps (subway maps) influence reasoning strategies. Extending this line of thought we could ask, how do people manage to apply information from an aspectualized information source to the real world, i.e. rich and detailed physical scenes. Navigation in a subway network, as it takes place in a restricted spatial environment, allows for a higher degree of aspectualization than navigation in less restricted networks, for example, city street networks. In the latter case, more information may be necessary. Harvey (1991) pointed out that for cross country runners nothing leads to greater insecurity than features found in the environment that are not marked in the map or, worse, shown in the wrong position. To which degree this is a problem for schematic maps is an open question.

Speed of decision making. The last point I want to make here is that too much information slows decision making (cf. Kaplan et al., 1974; Chown, 1999). If I have to consider only two choices, for example, to decide whether I should take the left or the right branch of an intersection, the task is easier compared to decisions at star shaped intersections. What has to be clear is that the information necessary to make the decision has to be represented somehow. If, for example, the information that A is connected to B is relevant, lets say, to traverse the subway network of Hamburg, this information has to be depicted. Probably the easiest way to do this is to include a connecting line; theoretically however, a color coding of the stations, for example, showing the same color for those that are directly connected, would fulfill the same objective.

1.1.2.3 Computational Perspective

From a computational perspective, especially of AI, there are several reasons that add to the importance of defining suitable aspectualization processes and seeking for conceptual primitive relations and objects (cf. Freksa, 1991). While it is possible to abstract from single occurrences and still aim at representing great detail, I briefly point out here what can be termed *high level abstraction*:

Compact data format. Aspectualization enables compact data formats. It is obvious that with lesser elements to represent the overall amount of information that has to be stored decreases.

Computational efficiency. Aspectualization improves the efficiency of computations and in some cases it makes them possible in the first place (cf. Chown, 1999). This is especially reflected in the aim to define inference and reasoning processes within frameworks of sparser geometries.

Representation by sparser geometries, for example, ordering information. Ordering information, as one example, is extensively used to formalize qualitative information and to characterize human reasoning processes (Schlieder, 1991; Röhrig, 1994; Eschenbach, Habel, Kulik, and Leßmöllmann, 1998; Kulik, 2002). Ordering information is also used as a general "tool" to characterize qualitative knowledge formally. Besides ordering information, topology plays a major role in the field of qualitative spatial reasoning (cf. Egenhofer & Herring, 1991; Hernández, 1994).

Ontologies. Abstraction leads to the definition of concepts. Ontologies—the hierarchical structuring of knowledge about things by sub-categorization according to their essential (or at least relevant and/or cognitive) qualities—are then used to organize the obtained concepts. Besides many problems with ontologies they are necessary for modern information systems. Their most important aspects are that they structure the knowledge about a given field and thus allow for exchanging this information.

Human Computer Interaction (HCI). The benefits of aspectualization for human computer interaction (HCI) are also discussed in other sections, for example, conceptual / cognitive (see section 1.1.2.2) and visual-perceptual considerations (see section 1.1.2.1). They are also closely linked to technical considerations (see section below) for aforementioned reasons. "Since humans usually prefer to communicate in qualitative rather than in quantitative categories, qualitative spatial representations are of great importance for user interfaces of systems that involve spatial tasks." (Musto et al., 2000, p. 115)

1.1.2.4 Technical Considerations

Especially in the light of new information technologies and their constraints, visualization can and has to be adapted. While this encompasses the benefits of data provided on the fly at a designated location, it also calls for dealing with the shortcomings of modern visual displays, i.e. their comparably bad resolution which decreases readability and enforces aspectualization processes to guarantee that information can be read off the display. In the cartographic literature and for cartographic depictions, this has been discussed only recently. Yet, the properties of display visualizations have been dealt with in various approaches (e.g., Brown, 1993; Spiess, 1996; Ditz, 1997; Neudeck & Brunner, 2001; Brunner, 2002).

The driving forces behind this development are twofold. The first one is the rapidly evolving market of navigation assistance. In this area proposals from computer graphics and informatics are most influential (e.g., Wahlster, Baus, Kray, and Krüger, 2001; Chittaro, 2003; Malaka & Zipf, 2000; Zipf, 2003) besides some more recent approaches in cartography (e.g., Gartner, Uhlirz, Pammer, and Radoczky, 2003; DGfK, 2002). The second one is the possibility to provide cartographic information via the internet (e.g., Burdack, Ueberschär, and Schweikart, 2003; Gartner, to appear). Many principles for displaying information can be shared by these two areas of application, even though as a rule of a thumb we can assume that *the smaller the display, the more aspectualization is required*.

In conclusion, from all this work we see how important it is to define suitable means to aspectualize information and that various fields of research already provide detailed approaches.

1.2 Scope, Goals, and Hypotheses

1.2.1 Scope

For the delimitation of the scope of this thesis, the following specifications are needed:

- kinds of route directions,
- different kinds of environments, and
- a distinction between common map interpretation and expert map interpretation.

Route directions occur in many forms and can be characterized according to several questions in cognitive science (Klein, 1979, 1982; Habel, 1988; Couclelis, 1996; Denis, 1997; Maaß, 1993; Maaß, Wazinski, Herzog, 1993; Lovelace, Hegarty, and Montello, 1999; Klippel, Tappe, and Habel, 2003). From the perspective of communication media, we can differentiate between *verbal* and *graphic* route directions. From the perspective of the temporal relation between route directions and corresponding actions, a distinction can be made between *accompanying* route directions and route directions given *in advance*. Regarding the communicative setting, route directions can be provided in a *monologue* or in a *dialogue*. From a cognitive conceptual point of view, it is relevant to characterize the information source, for example, whether a route direction provider has access to a *veridical* map, or whether she relies on her *memory*.

The present work offers a characterization for route directions that are given accompanying or in advance to the actual travel in graphic format. Nevertheless, relations to verbal route directions are established throughout this thesis. Conveying route directions is in form of a monologue and does not take into account dialogue systems (e.g., Wahlster, Reithinger, and Blocher, 2002). The experimental setting in chapter 4, study 2 (conceptual chunking of route direction elements), focuses on the conceptualization of route information based on veridical spatial information.

Wayfinding and route directions are related to different spatial environments. It is beyond the scope of this work to give characterizations of all possible settings. It is an open question to which degree the mental conceptualizations of route direction elements depend on the characteristics of a given spatial environment. From the diverse possibilities—open spaces, network spaces, indoor, outdoor, on, above, or under the surface of the earth—I restrict myself to wayfinding and the communication of route directions in city street networks, i.e. outdoor network spaces on the earth. How the results of this thesis may extend to other environments is discussed in the outlook (see section 6.3.1).

I want to make a brief comment on *common map interpretation* and *expert map interpretation*. I use common map interpretation as the term for the commonsense (*naive* in the reading of Mark & Egenhofer, 1995) interaction with maps. This kind of map interaction bears currently the best application for spatial cognition research. The key question is how knowledge about cognitive processes and mental representation allows for constructing maps that are *cognitively adequate*. As this thesis is basic research, cognitive adequacy is understood in the present context to comprise both readings (cf. Strube, 1992): to ease cognitive processes while interacting with a map and to reflect cognitive processes. In contrast, I understand expert map interpretation as analyzing maps scientifically. Experts, for example geographers, use information provided by a map to draw conclusions by applying additional, often very specific, knowledge sources. Imagine, for example, a weather map showing isolines of air pressure. Only by applying additional knowledge is it possible to infer the movement of air masses and to make predictions on weather development (cf. Lobeck, 1993). In this investigation, I am concerned with common map interpretation.

1.2.2 Goals and Hypotheses

The goal of this thesis is to develop a theory of wayfinding choremes, which details conceptual spatial primitives employed in wayfinding and route directions. The theory combines research from a multidisciplinary background. This includes the specification of a cognitive conceptual approach to map construction as the general framework as well as the identification of cognitive processes that lead to conceptual spatial primitives and that organize their combination. The present work also aims at a characterization of route information. To this end, a grammatical notation is applied. More specifically, the following question will be answered:

- What is the minimum set of conceptual spatial primitives that is required to characterize wayfinding and route directions?
- Which requirements define conceptual spatial primitives for visual communication?

- Which assumptions from qualitative spatial reasoning have to be applied?

The main hypothesis is:

> A limited set of wayfinding choremes is applicable to characterize route information and aid wayfinding and the communication of route directions. The wayfinding choremes can be specified for external representational media. As such, they are the building blocks for cognitively adequate map construction.

More specifically:

- The distinction between structure and function is essential for this investigation. The focus on functional aspects allows for a cognitively adequate characterization of route information.
- Wayfinding choremes are the terminals of the ***W**ayfinding **C**horeme **R**oute **G**rammar* (WCRG). They are functional in that they characterize conceptualizations of actions in street networks. Routes can be characterized based on wayfinding choremes.
- Employing wayfinding choremes in wayfinding assistance improves the cognitive adequacy of visualized route information.

1.3 Approach and Scientific Background

The approach to the work at hand can only be multidisciplinary. This kind of research has proven to be fruitful to develop theories for complex cognitive processes such as wayfinding and communicating route directions. It may require a sacrifice of in-depth analyses in order to reveal interconnections and to achieve full explanation of phenomena. This thesis compromises between the two extremes. It combines methods from cognitive psychology, geography, and cartography as it examines existing aspectualization principles and focuses on the representation of spatial information cartographically. It also sets up a framework within informatics, especially AI, as results from the area of qualitative spatial reasoning are evaluated and taken as a basis for the theory of wayfinding choremes. This work is also a contribution to the field of cognitive science as it will reveal basic conceptualization processes. The psychological methods applied include the analysis of verbal data, the collection of memory data, and the interpretation of sketch map drawings. The experiments are basic research on cognitive processes rather than usability studies to test the functionality of existing technical systems.

All the aforementioned methodologies and results refine the theory of wayfinding choremes. They are employed to formally describe the wayfinding choreme route grammar. The theory of wayfinding choremes then guides the use of wayfinding choremes in route direction assistance systems. This research circle (see Figure 3) has become an accepted methodology for interdisciplinary approaches, as it integrates research tools from different scientific fields under a superordinate research question. To sum up, in this thesis the following approaches are undertaken to better understand wayfinding choremes:

- analyses of conceptual spatial primitives,
- specification of the cognitive conceptual approach to map construction,
- definition of basic elements of paths and routes,
- distinction between structure and function,
- empirical analysis of conceptual spatial primitives, their combination, and their interaction with other environmental features in behavioral experiments,
- specification of the wayfinding choreme route grammar,
- integration of wayfinding choremes into graphic wayfinding assistance systems,
- identification of new research directions.

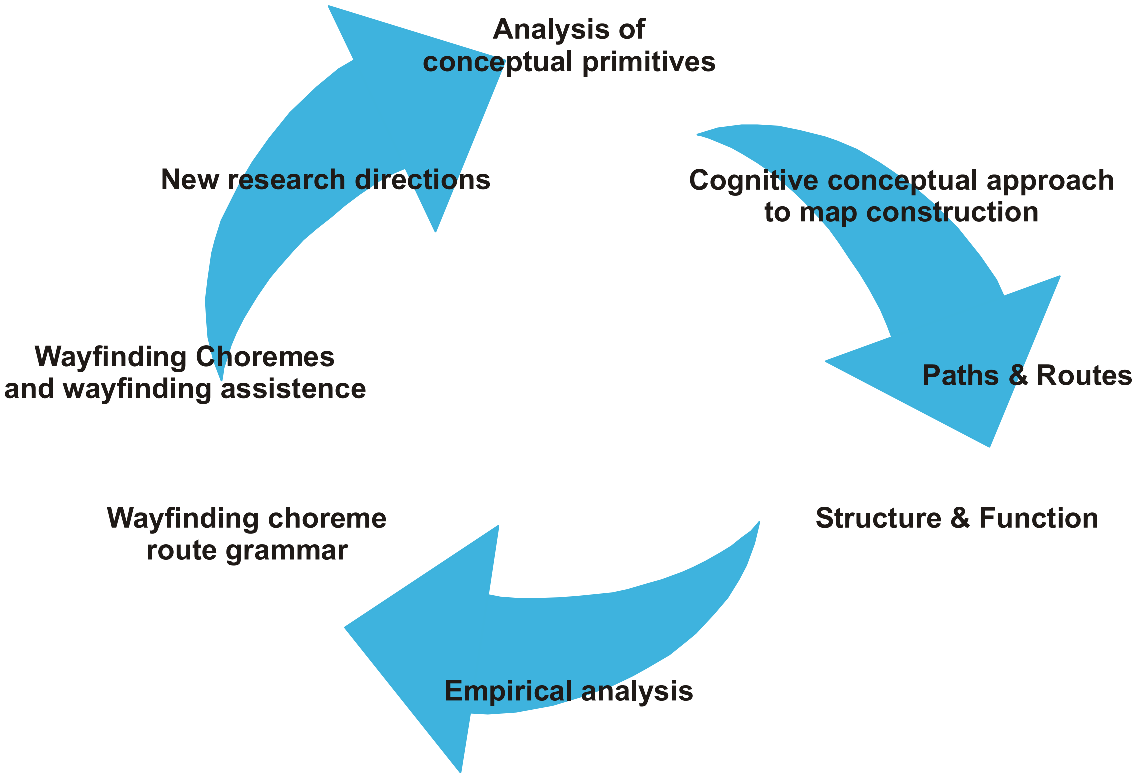

Figure 3. Research cycle for the wayfinding choreme theory.

1.4 Organization of the Thesis

Chapter 1 laid out the prerequisites and the motivation for this thesis. It opened with the definition of wayfinding choremes. This definition comprises already the topics that will guide the reader throughout this work. First, I deal with mental conceptualizations; second, I stress a functional perspective; third, the scope of this work is wayfinding and the communication of route information. Moreover, some terminological distinctions were detailed. Most pertinent is the explication of aspectualization that I use in the sense of singling out particular aspects and within these aspects only particular properties and/or relations are relevant. In this reading aspectualization is more concrete than abstraction and more specific than schematization. The benefits of aspectualization have been detailed and related to factors of map complexity. The scientific approach of this thesis is best characterized as a research cycle. According to the multidisciplinary claim from which the wayfinding choreme theory originates, methods from various disciplines are employed in this work.

Chapter 2 presents a synopsis of the extensive research on conceptual spatial primitives from the perspective of wayfinding choremes. Section 2.1 discusses the distinction between qualitative and quantitative approaches. Section 2.2 gives an overview on cognitively motivated research on conceptual spatial primitives. As many sciences nowadays are concerned with cognitive processes, I provide a within topic discussion and a focus on pertinent approaches. From this perspective, wayfinding and route directions (section 2.4) are discussed with two foci: the *RouteGraph theory* (Werner, Krieg-Brückner, and Herrmann, 2000) and the *direction toolkit approach* by Tversky and Lee (1998, 1999).

Chapter 3 has two purposes. First, to elaborate the cognitive grounding of the theory of wayfinding choremes. To this end, I define a cognitive conceptual approach to map construction, in which I set out the general possibility to start map construction not by the collection of accurate surveying data but to consider abstract mental concepts (conceptual spatial primitives) of spatial situations as the building blocks of maps (section 3.1). Second, it is necessary to define and to develop the relevant concepts more specifically to establish a suitable terminology. Consequently, I detail the distinction between paths and routes (section 3.3) leading to two sequels:

- the formulation of a basic grammar for routes (section 3.4.2) and
- the differentiation between structural and functional aspects of route information (section 3.5).

Chapter 4 details behavioral experiments for further insight into this account. In section 4.1 current research is discussed that investigates the representation and conceptualization of turning information at decision points, the chunking of basic route elements, and the role of landmarks in wayfinding and route directions. As the literature does not provide sufficient insight into some pertinent questions, three additional experiments were carried out to investigate:

- The conceptualization of direction (turning) information at decision points and their graphical externalization (study 1, section 4.3.1).
- The combination of wayfinding choremes to **H**igher **O**rder **R**oute (**D**irection) **E**lements (HORDE)[6] by means of chunking (study 2, section 4.3.2).
- The importance of placing landmarks at decision points with a direction change and some further chunking principles (study 3, section 4.3.3).

Based on these prerequisites I detail the wayfinding choremes route grammar in chapter 5. The underlying models of qualitative spatial reasoning and the set of wayfinding choremes are discussed in section 5.1.1. The chapter proceeds by providing rules for the combination of wayfinding choremes according to the three chunking principles identified in experiment 2: *numerical*, *structure*, and *landmark chunking*. Section 5.3 details the processing of routes characterized by wayfinding choremes by term rewriting. In the second part of chapter 5 (section 5.4), I describe the application of the wayfinding choreme approach to graphical user interfaces for accompanying and in advance route directions.

Chapter 6 concludes this thesis and gives an outlook on ongoing and future research. Section 6.1 summarizes this thesis. Results and major findings are discussed in section 6.2. The extension of the wayfinding choreme theory, planned and future behavioral experiments, and the relations to current research are provided in section 6.3.

[6] Within the Acronym HORDE, 'higher order' is meant in an ontological sense, which means that it is an intermediate level concept. 'Higher order' is not meant in a mathematical sense.

"The apparent simplicity of an ordinary sketch map is deceptive; in fact, even the simplest map is a remarkably complicated instrument for understanding and communicating about the environment."
—*The Nature of Maps*, by A.H. Robinson & B.P. Petchenik, 1976

2 Approaches to Conceptual Spatial Primitives

In this chapter, I provide an overview of research on conceptual spatial primitives as one primary kind of concepts underlying effective aspectualization. It is beyond the scope and the possibilities of this thesis to exhaust every theory that has been developed to individualize conceptual spatial primitives. The treatment centers on those approaches that are most influential for the development of the wayfinding choreme theory[7]. In section 2.1, I preliminarily discuss the distinction between qualitative and quantitative approaches. Section 2.2 gives a survey of cognitively motivated work on conceptual spatial primitives. Besides briefly illustrating contributions from cognitive psychology, I mostly restrict myself to geography and cartography. Building on the vast amount of research carried out to reveal cognitive organizational principles, I detail in section 2.3 approaches from Artificial Intelligence that resulted in formal models of spatial reasoning. The focus on direction models follows the requirements of this thesis. Wayfinding and route directions are discussed in section 2.4. I devote specific attention to the RouteGraph theory by Werner et al. (2000) and the direction toolkit approach by Tversky and Lee (1998, 1999). The RouteGraph theory is work in progress that offers a cognitively motivated formalism for the representation of route knowledge. The direction toolkit approach is akin to the wayfinding choreme theory in the endeavor to characterize conceptual spatial primitives. Its shortcomings led to the design of study 1 (see section 4.3.1). The different approaches to conceptual spatial primitives and their relation to wayfinding choremes are explicated in chapter 3 (see especially Figure 19).

[7] The focus of the treatment of conceptual spatial primitives is on cognitive aspects relevant for wayfinding and communication of route information rather than on visual-perceptual aspects (e.g. Biedermann, 1987; Gibson, 1979; Marr, 1982).

2.1 Quantitative versus Qualitative Approaches

The terms *primitive* and *conceptual spatial primitive*, respectively, can be interpreted from different points of view. Besides differentiating between objects and relations (see section 1.1.1) two kinds of approaches are pursued (cf. Hernández, 1994): First, approaches that seek to identify 'smallest' entities from which more complex entities can be built. Second, approaches that aim at characterizing entities and relations on an intermediate conceptual level, which can be combined to more complex entities and can also be specified further if necessary. In the first case, no specific names (concepts) are assigned to the basic entities. The aim is a homogenously precise representation and each given magnitude is allocated to an individual number. This approach has been termed *quantitative*. Hernández (1994) has summarized its basic assumptions:

- There is an infinitesimally exact world "out there"; the more detail a representation contains the better.
- Computers are essentially number processors, therefore, a numerical coordinate representation is the most appropriate.

In the second group of approaches, the conceptual spatial primitives defined are generally labeled and their number is restricted according to a given context. The focus is on aspects that are relevant for solving a particular problem. Such approaches are termed *qualitative* (e.g., Hayes, 1978; de Kleer & Brown, 1984; Freksa, 1991). In the last decade great progress has been made in formalizing qualitative primitives that are regarded as being close to mental concepts of space. Research on qualitative spatial reasoning has origins from various disciplines, for example, from geography (Mark & Egenhofer, 1995; Frank & Raubal, 1999; Egenhofer, Glasgow, Gunther, Herring, and Peuquet, 1999) and cognitive science / AI research (e.g., McDermott & Davis, 1984; Freksa & Habel, 1990; Freksa, Habel, and Wender, 1998; Freksa, Brauer, Habel, and Wender, 2000).

The drawbacks of the quantitative approach lead directly to the benefits of the qualitative approach. Most topics have already been discussed in section 1.1.2 (aspectualization) and need not be repeated here. Additional arguments for approaching knowledge representation qualitatively are (Freksa, 1991):

- invariance under certain transformations,
- independence from specific values and scale, and
- the expressiveness of qualitative constraints.

2.2 Cognitive Conceptual Approaches

2.2.1 Schema and Frame Theories

Aristotle (trans. 1941) noted that structuring mechanisms are indispensable for human beings to 'survive' the flood of information entering the senses (see section 1.1.2). Whereas this early theorizing was concerned primarily with the Ontology of objects in the world, the present work focuses on *procedural knowledge*. From the experimental and theoretical work of a number of cognitive scientists especially in the 1970s, the idea gained ground that *schemata* act as an interface between sensory input and long-term memory representations. At that point, there was neither a consistent research direction nor a consistent terminology. The knowledge structures in question were termed, among others, *frames*, *schemata*, *beta structures*, or *scripts*. From all the different conceptions *schemata*, *scripts*, and *frames* became more elaborated theories.

According to Rumelhart (1984) the basic idea of schema theory goes back to the work of Kant. To make this point clear he quotes the Oxford English Dictionary: "In Kant: any one of certain forms of rules of 'productive imagination' through which the understanding is able to apply its 'categories' to the manifold of sense-perception in the process of realizing knowledge or experience." (Rumelhart, 1984, p.162). Through the work of Bartlett (1932) and Piaget (e.g., 1963) they became modern research topics in the last century.

Neisser (1976), as one of the most influential schema theorists, defined *schemata* as mental constructs, functioning as mediators to perception. He proposed the *perception cycle* (see Figure 4) that states that information we perceive can only be organized according to a given schema we possess. Its dynamic characteristics in turn allow for the adaptation to more specific situations. Neisser's theory bridges the gap between bottom-up approaches that primarily seek structures in the environment (e.g., Gibson, 1979) and theories that are primarily top-down oriented, i.e. concept-driven. A schema selects specific aspects of a given situation or object while other pieces of information are neglected. According to this proposition, behavior is directed towards the intake of new information which can modify the schema, and so on.

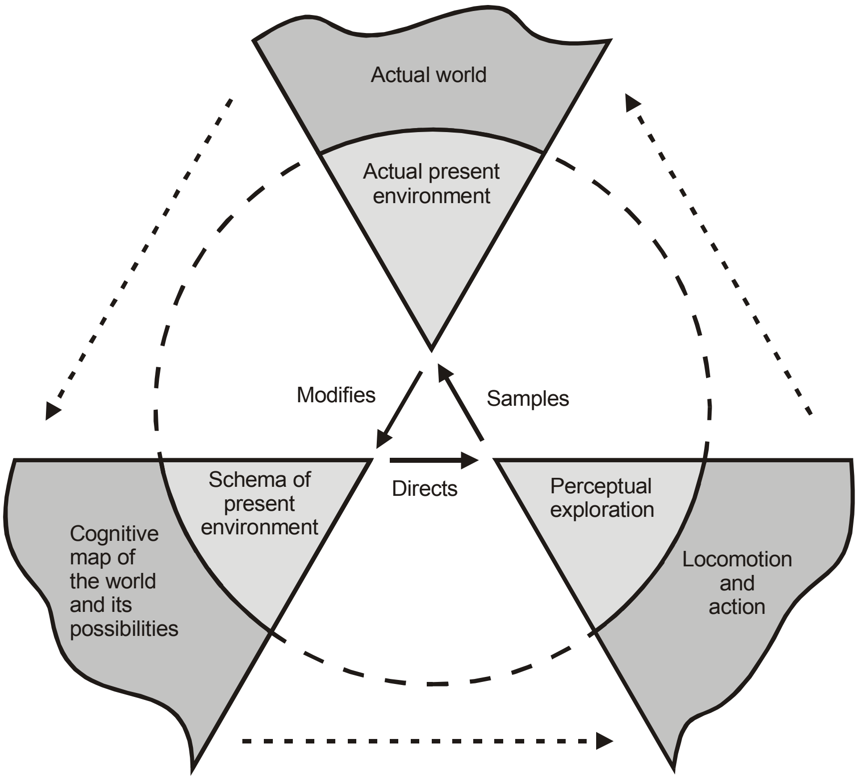

Figure 4. Neisser's perception cycle (Neisser, 1976).

The organization of knowledge in schemata is assumed to facilitate information processing and thus enable us to solve particular problems more efficiently. The common ground for all schema theories is that the knowledge is packed into units: "A schema [...] is a data structure for representing the generic concepts stored in memory." (Rumelhart, 1984, p. 163).

Starting from philosophy and cognitive psychology schemata and schema theories have found entrance into nearly all disciplines. In cartography, for example, Eastman (1985) has discussed their characteristics, i.e. their hierarchical, embedded nature. It is important to note that schemata are not only used to structure and to store declarative knowledge but are also applied to sequences and actions, i.e. to organize procedural knowledge.

Especially the work by Lakoff and Johnson (1980; Johnson, 1987; Lakoff, 1987) on *image schemata*[8] has gained much attention in research concerned with geographically oriented space theories. Image schemata are defined as recurring imaginative patterns that enable us to comprehend and structure experience while moving through and interacting with the environment (Johnson, 1987). Even though their work is not universally accepted its popularity can be attributed to two aspects: First, the image schema theory is not an entirely new approach (cf. Clark, 1973; Downs & Stea, 1973; Moore & Golledge, 1976; Shepard, 1987; Golledge, 1993), but it summarizes approaches that work on explaining the influence of spatial environmental

[8] See also Mandler (e.g., 1992).

aspects on cognition without converging into a single theory. Second, Johnson and Lakoff stress the aspect of *imageability*, a concept that already has been introduced by Lynch (1960) (see section 2.2.2). Compared to more abstract theories the direct relation to visual and other sensual experiences makes their theory appealing especially to those scientific fields that are concerned with the visualization and communication of spatial information. MacEachren (1995), for example, relates findings on image schemata to questions of map design and cognitive aspects of cartography.

The specific characteristics of image schemata—declarative as well as procedural knowledge, explainability, relation to visual perception—have led researchers to apply them to wayfinding (e.g., Raubal, Egenhofer, Pfoser, and Tryfona, 1997; Frank & Raubal, 1999). Examples for image schemata relevant for wayfinding are: PATH, SURFACE, or LINK. These accounts support the proposition that wayfinding and route directions are key concepts of spatial cognition and they explain why wayfinding and route directions have become a field of research in themselves.

2.2.2 Kevin Lynch: The Image of the City

With his pioneering work, Kevin Lynch (1960) introduced a new viewpoint to architecture. Instead of looking at cities as such, Lynch made an effort to explain cities as they are perceived and structured by their inhabitants. He proposed the concept of *imageability* that characterizes the way people create mental pictures of their environments. Lynch restricted himself to physical, perceptible objects. The key idea of his approach is that the images formed consist of a **limited number** of recurring elements, which may be understood as conceptual spatial primitives. These primitives appear in different forms which, however, possess the same inherent properties; they are the building blocks of every image that people employ when they structure their city environment. He also showed that these elements may be of more general application (see section 2.2.1). Lynch differentiates between five basic elements: *paths*, *edges*, *districts*, *nodes*, and *landmarks* (see Figure 5). His perspective on these elements is provided in the following:

- *Paths*. Paths constitute the basis for what is widely discussed as route knowledge. For Lynch, paths are the most predominant elements used for organizing a city environment. They connect places and other environmental elements are arranged along them. Examples for paths are streets, walkways, transit lines, canals, and railroads. They are physical objects in the environment (see section 3.3).
- *Edges*. Edges are linear boundaries between areas. Edges either are perceived as division lines between areas of different characteristics, like, for example the city and a rural area, or, they are physical obstacles forcing a detour, such as walls, dykes, or ditches.
- *Districts*. Districts are the only areal components Lynch introduces. Districts are medium sized areas and a distinction can be made between what is inside a

district and what is outside. They are held together by common features that their elements share.

- *Nodes*. Nodes are more than simply intersections of roads. Nodes are important strategic places. They comprise junctions, places of breaks in transportation, crossings or convergences of paths, shifts from one structure to another. They also can be street-corner hangouts or enclosed squares deriving prominence from a concentration of important features.
- *Landmarks*. Landmarks are outstanding objects that gain their significance through physical or social concepts. For Lynch, the difference to nodes is that landmarks are 'from-the-outside objects', meaning that the observer does not enter into them. Both categories belong to the group of point-like reference objects. Examples of landmarks are buildings, signs, stores, or mountains. Landmarks can take various forms regarding their visibility, their location and their meaning, for example, a tower that can be seen from various points in a city versus a store distinguishing a certain street corner. Even mobile objects, such as the sun, can be landmarks in Lynch's terminology.

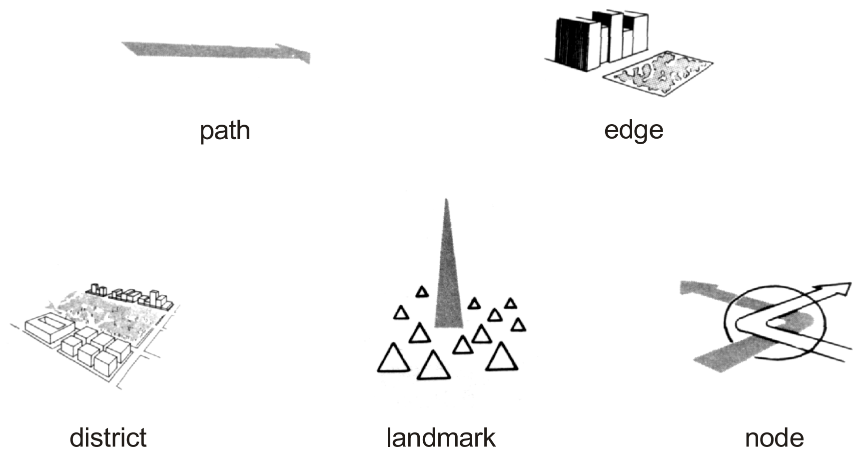

Figure 5. A depiction of Lynch's (1960) basic elements of a city.

Lynch's work inspired manifold research projects. For example, further classifications of landmarks (e.g., Appleyard, 1969, 1970; Raubal & Winter, 2002; see section 5.1.2.3), the integration of information needs of pedestrians into modern navigation systems (Corona & Winter, 2001), and the extension of his ontology to virtual environments (e.g., Darken & Sibert, 1996; Dieberger & Frank, 1998).

2.2.3 Reginald Golledge: Spatial Primitives

Whereas the perspective of geography on space was highly descriptive in its beginnings, it has become more analytic in the second half of the last century. More relevant for the work at hand is the fact that geography has broadened its interests from the focus on the world we live in to the world 'inside human heads' as well. Actually, *mental conceptualization* has become a key issue in geographical investigations documented by research meetings (cf. Mark & Frank, 1991) and research initiatives (cf. Goodchild, Egenhofer, Kemp, Mark, and Sheppard, 1999). The overarching aim of these endeavors is to enhance modern information systems and make them more natural and user-friendly.

An influential cognitively oriented approach to define primitive spatial concepts is taken by Golledge (1991, 1992, 1993, 1995) who identifies basic components of spatial knowledge, which he eventually terms *spatial primitives*. Whereas Lynch (1960) focused on perceivable physical objects, Golledge specifies relations. They are grouped into *first-order spatial primitives* and *derived concepts*. For Golledge, these categories have cognitive equivalents, and they are independent of a particular environment and of a given scale. He claims that an awareness of spatial primitives will positively influence research on GIS interfaces. He (1995) identifies as first order primitives:

- *Identity*. Identity is the most basic attribute. It individualizes occurrences in our environment and allows for differentiating between them. Identifying an occurrence provides the basis for recognizing and evaluating it.
- *Location*. Location provides the necessary information of the place where an occurrence exists. Naturally for geography, this is—besides identity—the most important spatial primitive.
- *Magnitude*. Magnitude tackles the complicated question of how much of an occurrence exists at a specific location.
- *Time*. Time characterizes the time interval in which an occurrence exists.

From the first order primitive 'location' the following concepts can be derived:

- *Distance.*
- *Angle and direction.*
- *Sequence and order.*
- *Connection and linkage.*

Wayfinding choremes are more detailed conceptual spatial primitives than Golledge's components as they are defined specifically for the domain of wayfinding and route directions. This enables their direct application in human-computer-interaction (see section 5.4.

2.2.4 Roger Brunet: Chorematic Modeling

An approach that bridges the gap between geography and cartography explicitly, but is not strictly cognitively motivated, is *chorematic modeling* by Roger Brunet (1980, 1987, 1993). The intention behind this method is to identify spatial structures, systems and subsystems by employing *applied regional analysis*[9]. In an extensive theoretical

[9] Applied regional analysis is a subfield of geography.

examination Brunet laid the foundation for his theory and operationalized the structures to such an extent that it became possible to ascribe names to them. The theoretical approach of "New Geography" (e.g., Haggett, 1965) serves as a central aspect for his theory. Following Wirth (1979, p. 84) four topics are central for "New Geography":

- a tendency for theorizing (‘Theoretisierung’) and abstraction,
- emphasizing the general (‘das Allgemeine’) and rule dependencies (‘Regelhaftigkeit / Gesetzmäßigkeiten’),
- the use of quantitative procedures that lead to formalization and modeling, and
- prognoses derived from the aforementioned proceedings.

Especially the first two points correspond to the approach taken here. There are several aspects of Brunet’s theory relevant for communicating spatial information and for work on conceptual spatial primitives with a corresponding graphic realization. It bears similarities to work in cognitive science even though the relations are not explicitly mentioned[10]. Brunet’s basic assumptions are, first, that by elementary models, as depicted in his table of choremes Figure 6, all spatial phenomena can be described. And, second, that by a combination of choremes the essentials of spatial organization can be represented. "[...] even though this may be shocking and appears to be an 'oversimplification', but after all, science rests on simple things." (Brunet, 1993, pp. 112-113).

Brunet suggest the name *choreme* for these elementary models and denotes their graphical counterparts as "strong forms" with respect to their Gestalt, i.e. their visual appearance (Brunet, 1987). The lexical root of the term *choreme* is derived from the Greek work for space (*choros*). The suffix '*-eme*' is used to indicate an analogy to linguistics and semiology. Choremes are used to depict spatial knowledge in a map. Brunet does not claim that choremes are the smallest possible entities. This becomes obvious when he states that "the only ultimate element is the individual [the choreme], and the individual is known to be tremendously complex." (Brunet 1993, p. 113). With this statement he is in agreement with Golledge (e.g., 1992) who subdivides reality into occurrences but probably will not object to the assumption that every single occurrence can be broken down into smaller elements.

Following Bertin (1974) and the classical distinction of cartographic primitives, three aspects characterize representations in the plane, for example, in a map: *point*, *line*, and *area* (or region)[11]. In Brunet's classification (1987) these elements constitute

[10] Compare, for example, work on image schemata (e.g., Johnson, 1987; see section 2.2.1) . Image schemata bear by their names and by their very idea great similarity to the approach taken by Brunet: center-peripherie (same terminology), mailage (container), attraction, contact, and so on. To my knowledge there is no work that explicitly relates these two approaches.

[11] This is a cartographic distinction, which is on an abstract level in congruence with classifications in other disciplines like in mathematics and computer science. Nevertheless, these elements are not meant to be their ideal abstractions, i.e. that a point is dimensionless and a line has just one dimension. More appropriate terms would be point-like, linear, and areal. A river, for example, is in most cases a linear object. The correspondences, however, in a database could be indeed lines or areas.

the first three columns of his table of choremes (see Figure 6). The forth column is labelled *net* ('reseau'). The elements in the 'net row' are not as independent as the first three and can be regarded as their synthesis in horizontal direction.

With his choreme table, Brunet gives the first indication for a graphical modeling of relations that exist in a denoted area. A region has to be analyzed under an abstract point of view to obtain the essential structures in it. To achieve this goal an 'exact' geometrical realization is neglected. The resulting organizational elements of an area can be represented by a limited number of graphical units, i.e. the graphic representations of the choremes. Brunet states that there is a limited number of mechanisms that lead to perceivable (cognitive) spatial structures.

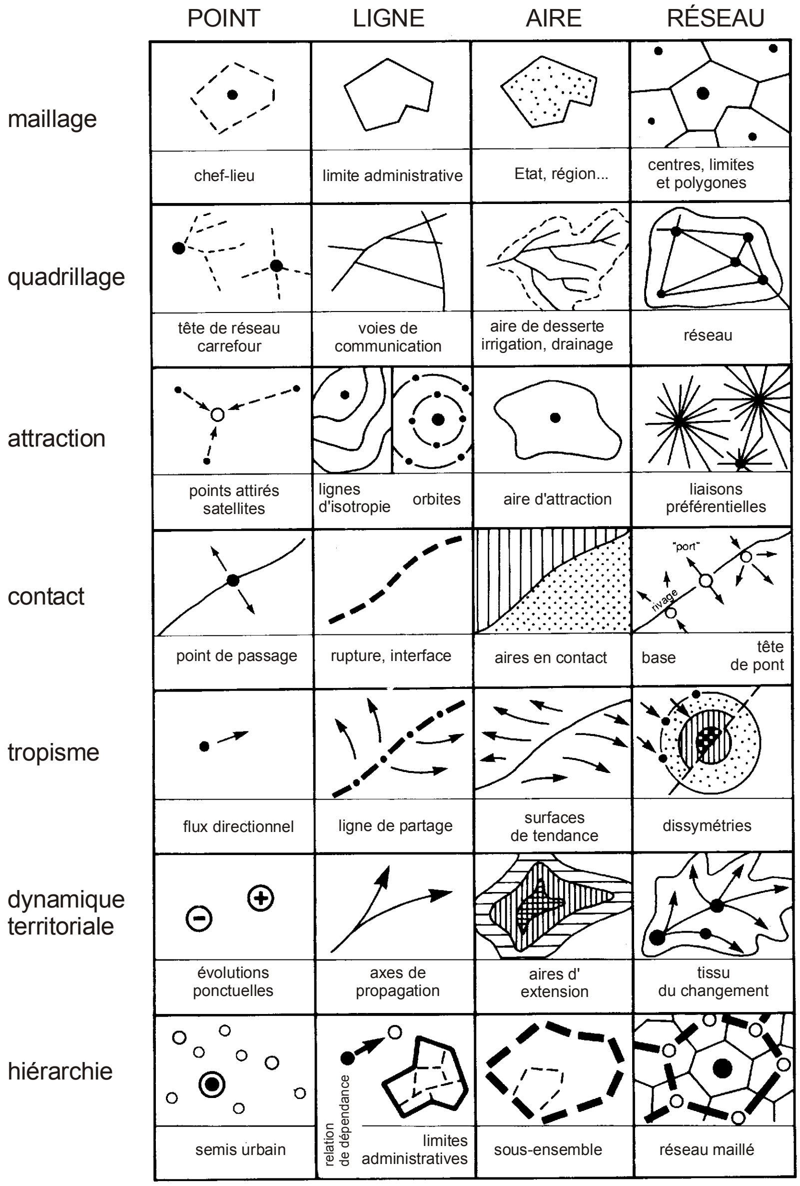

Figure 6. Brunet's table of choremes (1987, p. 191).

Brunet (1987) does not assume that the choreme table is complete; rather he emphasizes the general idea of a limited number of models. This point is stressed by authors who have modified the choreme table (e.g., Cheylan, Deffontaines, Lardon, and Théry, 1990) or have adapted it to a specific area of application, like for its use in school (Fontabona, 1994).

Every cartographic representation is an abstraction of the external world. In the case of chorematic maps, we obtain a further abstraction that has a long tradition of critical discussion within cartography. With respect to chorematic modeling Ormeling (1992) uses the term "meta-cartography".

2.2.5 Summary: Cognitive Conceptual Primitives

The purpose of this section was to summarize previous work on cognitive conceptual primitives pertinent to this thesis. Schema and frame theories provide a general basis for approaches on how information is organized into distinguishable units. These theories have gained new attention by the work on image schemata that subsumes a lot of earlier research. From the viewpoint of spatial cognition, the work by Lynch (1960) was the first that offered an ontological approach and identified the constituents of mental maps. Golledge (e.g., 1995) has to be credited for his more general attempt to define the primitives of relational spatial knowledge. To my knowledge, Brunet (e.g., 1987) has not received extensive attention outside France which may be attributed to language difficulties. Yet, he is the first geographer who relates abstract conceptual models and map design. He does not explicitly state connections to cognitive science, nonetheless, his choremes show great similarity to concepts in spatial cognition research.

The conceptual spatial primitives discussed so far do not suffice for wayfinding and route directions. Image schemata remain on an abstract level; the concept *path*, for example, is not specified further regarding its components or specific spatial information. It is important to note that Lynch examined the cognitive maps of people of a city in general and not from the perspective of a specific task such as giving route directions. His work focused some beginning ideas on how a city and the spatial environment can be structured from a more cognitive point of view, but of course has to be—and already is—revised for some more task specific areas. Finally, direction is not a first order primitive for Golledge, but when we focus on wayfinding and route directions, it is.

2.3 Formal Models of Conceptual Spatial Primitives

Since the 1980s, research on spatial knowledge, especially on qualitative spatial reasoning (QSR), has gained considerable interest in Artificial Intelligence (e.g., McDermott & Davis, 1984). Even though the term *cognitive spatial primitive* is rarely explicitly used, the approaches can be seen under this perspective for two reasons: First, most of the approaches make use of a limited number of equivalence classes or primitive concepts. Second, these models are claimed to be cognitively adequate in the following sense: They are supposed to be valid from the perspective of cognitive modeling as well as from the perspective of improving cognitive processing. I give a brief introduction to QSR before I turn to the two most pertinent areas for this thesis, position information (section 2.3.2) and direction information (section 2.3.3).

2.3.1 Qualitative Spatial Reasoning

Cohn (1997) refers to Weld and de Kleer (1990) when he postulates that the principal goal of qualitative reasoning (QR) is to represent our everyday commonsense knowledge about the physical world. A second focus, in his opinion, lies on the underlying abstractions used by engineers and scientists when they create quantitative models. A great deal of research on QR took place; qualitative *spatial* reasoning (QSR) has developed later. Its importance is documented, for example, by Habel and Freksa (1990). Actually, it is often pointed out as an astonishing fact that in their beginnings the qualitative reasoning community, especially qualitative physics, focused primarily on processes and only later turned their attention to basic aspects of space and time (Hernández, 1994; Vieu, 1997). The main goal of QSR is to provide calculi that rely on spatial entities of higher order. These entities, or conceptual spatial primitives, have to be formalized for implementation on a machine without quantitative techniques. Qualitative approaches apply to natural language understanding, computer graphics, computer vision, or cognitive robotics (Cohn, Magee, Galata, Hogg, and Hazarika, 2003; Moratz, Nebel, and Freksa, 2003). The key question in QSR is which conceptual spatial primitives are used in a calculus. The approaches can be characterized not only by the kind of spatial knowledge they model but also by the number of conceptual spatial primitives they use.

One of the most influential accounts is the calculus for temporal (and later on linear spatial) reasoning by Allen (1983) and his work on a logic for time and action (1984, 1991). His calculus (1983) is based on 13 relations that can hold between two time intervals. For the context of the work at hand note that the intervals are considered as temporal primitives rather than as composed of points in time.

2.3.2 Position in 2D

2.3.2.1 Topology

Topology is regarded as the most fundamental form of qualitative description of position in a planar structure (Egenhofer & Mark, 1995; Barkowsky, 2002). It studies the characteristics of geometrical objects independently of an underlying coordinate system, that is, disregarding angles or distances. It is informally characterized as *rubber sheet geometry*. Topology treats those properties that are invariant under topological transformations (translation, rotation, scaling, and shearing).

Different levels of granularity determine the number of basic relations assumed in a topological calculus. These basic relations are the primitive spatial concepts of the formalization. For example, in the region connection calculus (RCC) introduced by Randell, Cui, and Cohn (1992) and further elaborated in various papers (e.g., Cohn & Gotts, 1996; Gotts, 1994), the main difference is the ontological status of the boundaries of a region. This results in the distinction of 5 basic relations (RCC 5) or 8 basic relations (RCC 8). Another example is the proposal of intersection models for topological relations between sets by Egenhofer and Franzosa (1991) and Egenhofer and Herring (1990). They first introduced a 4-intersection model for topological relations which they extended into a 9-intersection model. The difference is that in the 9-intersection model the complements of two objects in question are modeled (in addition to interior and boundary in the 4-intersection model).

Topological relations characterize qualitative distance relations between two regions and are based on point sets (e.g., Egenhofer, 1989). Figure 7 depicts the eight basic relations with which these distances can be characterized using the labeling introduced by Randell et al. (1992). The "interior" of such a region is the region area minus the boundary curve:

- DC(X, Y): X is disconnected from Y. The regions are disjoint.
- EC(X, Y): X is externally connected with Y. The regions are not disjoint but the interiors are.
- PO(X, Y): X partially overlaps Y. The interiors of the two regions intersect, but none is a subset of the other.
- TPP(X, Y): X is a tangential proper part of Y. Region X is a subset of region Y, but not a subset of its interior.
- NTPP(X, Y): X is a nontangential proper part of Y. Region X is contained in the interior of region Y.
- TPPI(X, Y): X is an inverse tangential proper part of Y. Y is a subset of X, but not a subset of its interior.
- NTPPI(X, Y): X is an inverse nontangential proper part of Y. Y is contained in the interior of region X.
- EQ(X, Y): X equals Y. The two regions are identical.

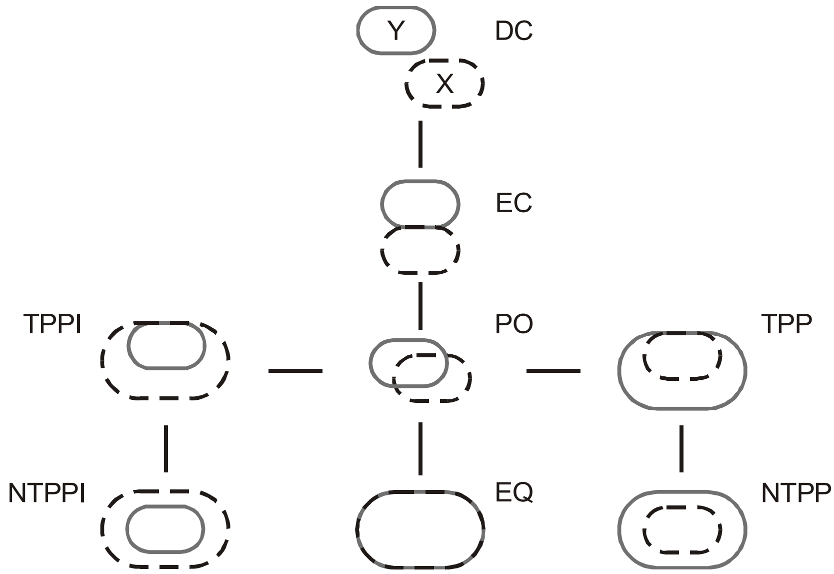

Figure 7. Visualization of the eight basic topological relations specified, for example, in the RCC 8 calculus (cf. Randell et al., 1992).

2.3.2.2 Arrangement / Ordering Information

There are two related kinds of ordering information in the plane. The first has been studied extensively by Schlieder (1990, 1993, 1995) who termed it *panorama* or *arrangement*. This kind of ordering information characterizes the order in which point-like objects are seen in a panorama from the selected viewpoint. Figure 8 illustrates a panorama for a point *S*. Capital letters denote lines directed to reference points, lower case letters stand for their complements. A panorama defined by Schlieder (1993) consists of consecutive reference points, for example *AcdB* or *CDbA*. It thereby defines a (counter) clockwise circular order for the point in question, *S* (cf. also Röhrig, 1994).

The second kind of ordering information is detailed for linear objects that are located in a plane, for example, subway networks.[12] The framework of ordering information, as for example defined by Kulik and Eschenbach (1999), gives a formal account of the spatial relations of betweenness (cf. also Eschenbach et al., 1998). For linear ordering information the geometric structure consists of three types of entities and two primitive relations. "The entities are points [...], curves [...], and oriented curves [...]. The primitive relations are the binary relation of incidence [...] and the ternary relation of precedence with respect to oriented curves [...]." (Kulik & Eschenbach, 1999, p. 3). We see that the characterization by ordering information is very sparse and that it relies on a very small number of basic relations. Here again, it is important to determine for which entities the formalism should hold.

[12] Ordering information on linear structures can also be used to reason about points in the plane and extended objects. For cardinal directions, this has been shown in Kulik & Klippel (1999).

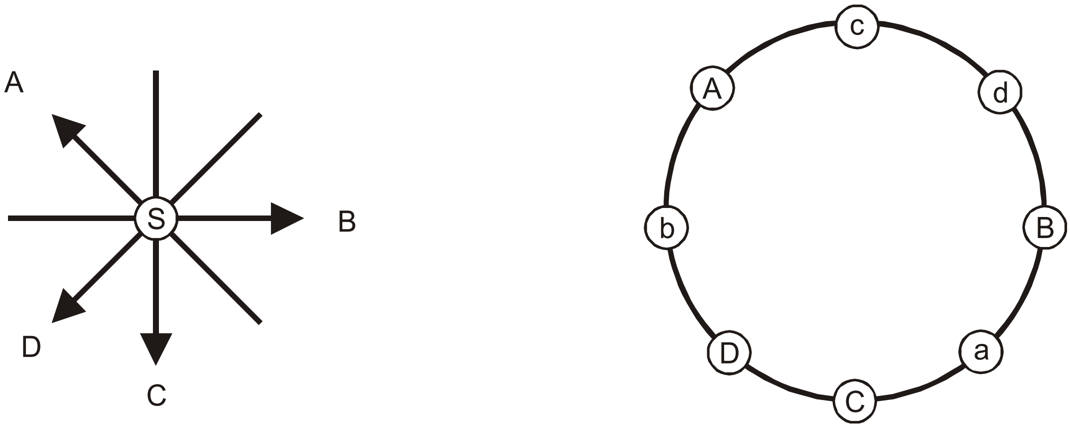

Figure 8. A position relative to reference points in a plane and its depiction by a panorama (Schlieder, 1993).

2.3.3 Direction / Orientation

Directions (orientations) are viewed as basic relations (Habel, Herweg, and Pribbenow, 1995)[13]. Depending on the level of granularity in a model, different numbers of equivalent classes of directions are taken into account. I exemplify the granularity shift and the resulting basic relations by calculi for cardinal directions, i.e. North, South, East, and West. These models are not restricted to cardinal directions because reference systems—intrinsic, relative, or absolute—share basic components and are transferable into one another (cf. Levinson, 1996; Eschenbach, 1999).

2.3.3.1 Cardinal Directions by Projections

With respect to cardinal directions, the most basic distinction that can be made is between North / South and East / West (see Figure 9). This distinction can be modeled by partitioning a planar structure by a straight line. A straight line separates two half planes that are labeled: North / South or West / East, respectively. Thereby we obtain four directions that are pair-wise opposite. This approach is called *cardinal directions defined by projections* by Frank (1992). For the geographic space, the meridians and the parallels of latitude accomplish this partitioning. The composition of basic relations (North, South, East, West) allows for the modeling of more complex relations, for example, Northwest, which is a conjunction of North and West.

[13] This stands in contrast to Golledge (e.g., 1995), where direction but not specific directions are primitive concepts.

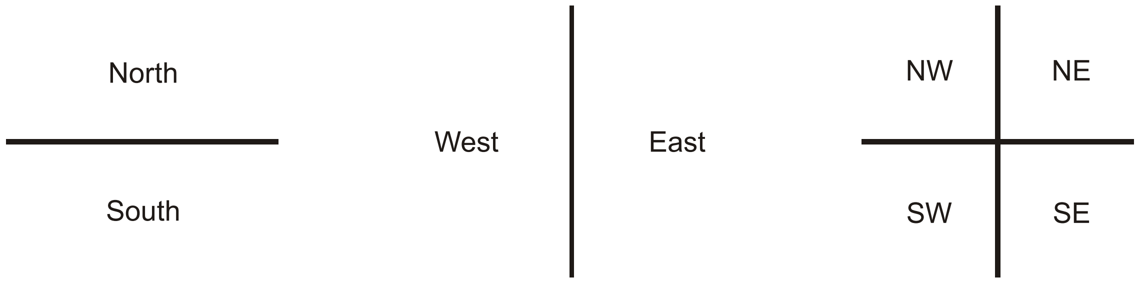

Figure 9. Cardinal directions defined by projections.

Basic relations, or, to be more precise, the pair-wise distinction of cardinal relations North / South and East / West can be extended, for instance, by adding a neutral area (see Figure 10). The concept works for both pairs of relations and offers additional possibilities for modeling more than four directions. Based on these distinctions various calculi are discussed in the literature that, for example, use additionally relations defined by the axes (e.g., Ligozat, 1998).

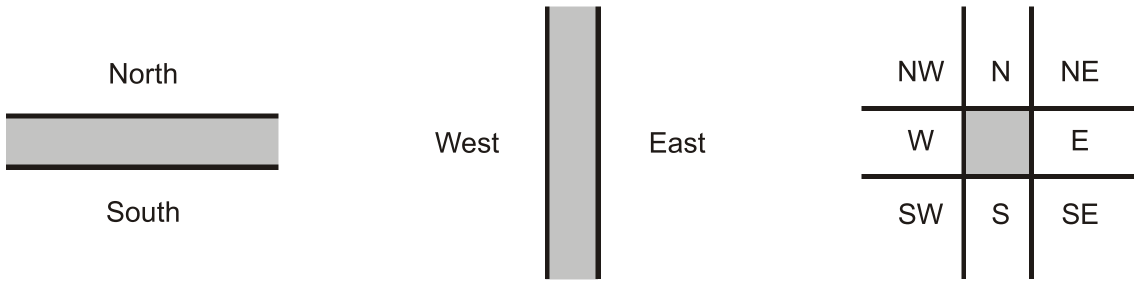

Figure 10. Cardinal direction models with neutral area (gray parts).

2.3.3.2 Cardinal Directions as Sectors

The modeling of *cardinal directions as sectors* is an alternative to the modeling of cardinal directions by half planes. In many ways, it is the most prototypical concept (Frank, 1992). This holds especially, when we model cardinal directions between two point-like objects. The most frequently used granularities are the *4-sector model* and the *8-sector model* (see Figure 11). If necessary, these models can be divided further by homogenously bisecting the degree of the angle between the axes, i.e. 90° for the 4-sector model, 45° for the 8-sector model, 22.5° for the 16-sector model. Other models, for example, with differently sized sectors are computationally more demanding and are rather uncommon (Montello & Frank, 1996; see section 4.1.1). These models are not only valid for cardinal directions but also for relations with respect to objects in which case the cardinal direction can be replaced by direction concepts of an egocentric reference system, for example, front, back, left, and right in the case of a 4-sector model (cf. Hernández, 1994).

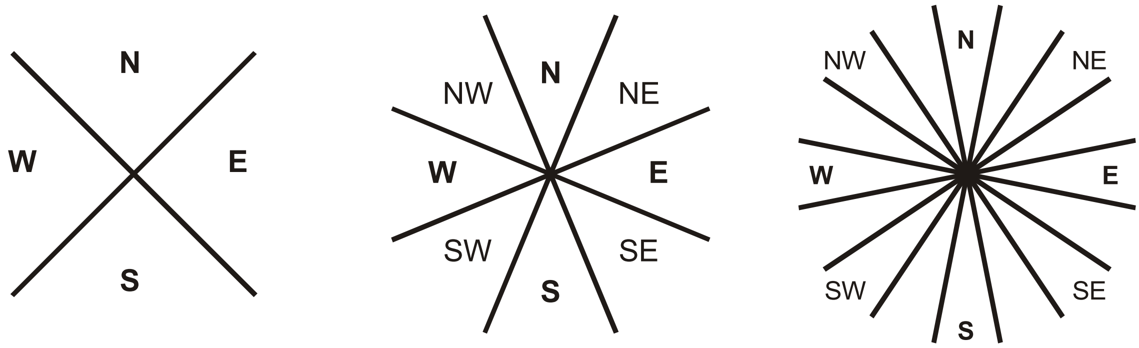

Figure 11. Sector models for cardinal directions.

2.3.3.3 Freksa's 'Doppelkreuz' Calculus

Another foundational approach individualizing qualitative directions is the *double cross calculus* by Freksa (1992) with further specification by Freksa and Zimmermann (1992)[14]. Freksa uses 15 basic relations to obtain a cognitively plausible specification of directions for reasoning tasks such as wayfinding. His approach includes the possibility for 'exact' directions that may correspond to qualitative mental orientation concepts, as well. Freksa's model starts with a reference axis instantiated and oriented by the intrinsic reference system of an agent (the origin (O) in Figure 12), i.e. the front/back distinction. Additionally, he specifies two reference axes that are perpendicular to the first one. These additional axes intersect the reference axis at the position of the agent, for example, the starting point of a planned movement, and at some point in front of it, for example, the assumed endpoint of a movement (the destination (D) in Figure 12) (Freksa & Zimmermann, 1992). The model yields 15 qualitative relations for a given point with respect to the mounted reference system: the co-location with origin or destination, a location on the axis in between origin and destination, a location on one of the other 6 axes, or in one of the 6 sectors (see Figure 12).

[14] In their 1992 work, Freksa and Zimmermann named their approach, i.e. the specification of the calculus's basic structure, *orientation grid*.

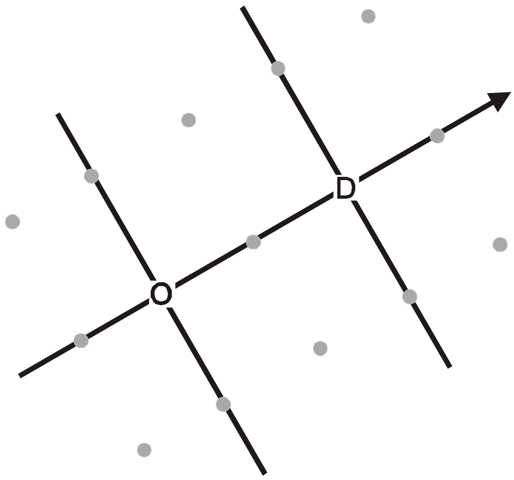

Figure 12. The double cross calculus (Freksa, 1992; Freksa & Zimmermann, 1992). Origin (O) of a movement, possible destination (D), plus 13 derived locations.

It is interesting to note, that the relations specified in the double cross calculus have only a partial correspondence to natural language expressions. Naming relations as concepts is done for parts of the system but not for the complete system. One has to refer to an additional reference object, i.e. the destination (D) to assign linguistic concepts.[15]

2.3.4 Summary

These examples show that most approaches of QSR can be viewed from the perspective of searching for the 'right' conceptual spatial primitives. Having said this, it is also obvious that at this point only a small selection of approaches is discussed (cf. Cohn & Hazarika, 2001). The conceptual spatial primitives employed are not necessarily cognitive spatial primitives (cf. Montello & Frank, 1996). They often take into account beneficial solutions from a computational point of view. They do not always aim at modeling exactly cognitive processes as these may not be the best solutions to build a running system. Therefore, it is an open question whether these systems work very well. Qualitative relations of direction have recently been used in wayfinding models and map schematization (e.g., Raubal & Worboys, 1999; Casakin, Barkowsky, Klippel, and Freksa, 2000). They will be employed for the formal characterization of wayfinding choremes in chapter 5.

[15] This is an illustration of the fact that not every spatial relation has to have a corresponding concept that is expressed in natural language. This facet of conceptual spatial primitives is discussed further in the outlook, as it is not the focus of the present work.

2.4 Wayfinding and Route Directions

In the following sections, I summarize a selection of results on wayfinding and route directions pertinent to the work at hand. Section 2.4.1 starts with a survey of research on wayfinding and route directions. In the subsequent sections, two approaches are discussed in greater detail as they provide good examples for the state of the art in two disciplines, and are essential for the clarification of the wayfinding choreme model: cognitively oriented informatics (the RouteGraph theory) and cognitive psychology (direction toolkits). In section 2.4.2 the RouteGraph theory (Werner et al., 2000) is detailed. The RouteGraph theory details an abstract formalism for the specification of navigational knowledge. Section 2.4.3 presents the verbal and pictorial toolkits proposed by Tversky and Lee (1998, 1999). Tversky and Lee take a high-level approach to wayfinding and route directions. This means, they develop a model of idealized route directions and seek to provide a finite set of 'building blocks' for their construction. The building blocks are conceptual spatial primitives such as 'intersection', which are claimed to constitute a conceptual 'toolkit' for the construction of both verbal and graphical route directions. The general idea corresponds to the wayfinding choreme approach. Nevertheless, Tversky and Lee's toolkit approach needs modifications. This is shown in chapter 4.

The wayfinding choreme theory is basic research on mental conceptualization processes. The results are applicable to modern wayfinding assistance systems and will be discussed in chapters 5 and 6. As this thesis does not focus on a technical solution, the recently enormously growing work on navigation assistance and wearable computing is only integrated insofar as it adds to the approach taken here (e.g., Chittaro, 2003).

2.4.1 Approaches to Wayfinding and Route Directions

Wayfinding has gained much interest in various disciplines, for example, geography, psychology, and artificial intelligence (cf. Arthur & Passini, 1992; Golledge, 1999a; Hunt & Waller, 1999; Wahlster et al., 2001; Raubal, 2002; Montello, in press). The design of efficient wayfinding aids depends on a good understanding of the wayfinding process itself (e.g., Passini, 1992). A basic approach to wayfinding processes is given by Downs and Stea (1977), who differentiate the following four sub-tasks: 1. Orientation, i.e. determining one's position in an environment, 2. Choosing the route, i.e. planning one's route to the destination, 3. Keeping on the right track, 4. Discovering the destination. This model is still valid even though it has been modified with respect to different aspects of wayfinding (e.g., Allen, 1999). To have a distinct model of wayfinding becomes even more important in the light of new information technologies as it is now possible to aid the wayfinder directly at different stages during the wayfinding process. Modern mobile wayfinding assistance supports different sup-processes of wayfinding (e.g., Baus, Butz, Krüger, and Lohse, 2001; Baus, Kray, Krüger, and Wahlster, 2001). For successfully aiding wayfinding processes, it is not only important to know the constituents of a wayfinding process but also to include design aspects of the graphic interface. Models for graphic wayfinding support especially with maps have emerged (e.g., Darkes & Lenox, 1999; Baus, Butz, et al., 2001; Jackson, 1998; Shepard & Adams, 1971;).

Recently the depiction of spatial information by schematic representations has gained particular interest as these forms of representations are considered similar to peoples conceptions of space (Tversky & Lee, 1999) and as such are regarded as cognitively adequate information sources in the wayfinding process (e.g., Agrawala & Stolte, 2000, 2001). Again, this topic is addressed by several disciplines. Starting off with Grice (1975) who formulated general principles of effective communication, Habel (1988) and Denis, Pazzaglia, Cornoldi, and Bertolo (1999) specified components of good route directions from a cognitive science point of view. There are various detailed models on the entire process of giving and receiving route directions (e.g., Klein, 1979; Wunderlich & Reinelt, 1982; Habel, 1988; Carstensen, 1991; Couclelis, 1996; Allen, 1997; Denis et al., 1999) and increasing literature on wayfinding (e.g., Golledge, 1999a).

Montello identifies wayfinding as one part of navigation together with locomotion. Whereas locomotion focuses on the movement of the body, wayfinding is the more cognitive oriented task of planning that movement: "When we wayfind, we solve behavioral problems involving explicit planning and decision-making—problems such as choosing routes to take, moving toward distal landmarks, creating shortcuts, and scheduling trips and trip sequences." (Montello, to appear)[16].

Schweizer, Katz, and Janzen (2000) make the distinction between *route directions* and *route descriptions*. Route directions are task-oriented verbal or graphical specifications of the actions that have to be carried out in order to reach a destination from a specific origin. In contrast, route descriptions may serve the function to select one of several available routes. The emphasis is on features of the (spatial) environment like whether there are scenic sites, good shopping opportunities, or dwellings of celebrities. The latter aspects are irrelevant for my approach. In this sense, route descriptions rather correspond to the definition of *R-path* as given in section 3.3.

Aiding the movement of artificial agents in spatial environments requires the formal specification of route knowledge and environmental information. Consequently, the field of cognitive robotics contributes crucial insights on the nature of route knowledge and environmental information. Most prominent is the TOUR model by Kuipers (1978) that Raubal (2001) designates the starting point of computational theories of wayfinding. From the manifold approaches in this field (e.g., McDermott & Davis, 1984; Krieg-Brückner, Röfer, Carmesin, and Müller, 1998; Moratz, Nebel, and Freksa, 2003) the next section details the RouteGraph theory (Werner et al., 2000) that

[16] There are alternative perspectives on the terminological differentiation, for example, Sharkawy and McCormic (1995) who use wayfinding as superordinate concept and claim orientation (where am I?) and navigation (where am I going, and how do I get there?) its subprocesses.

originates in spatial cognition research (Freksa, Habel, and Wender, 1998; Freksa, Habel, Brauer, and Wender, 2000).

2.4.2 The RouteGraph Theory

The RouteGraph theory (Werner, et al., 2000) is an abstract formalism to express the key concepts of route based navigation; these group around *places* and *route segments* and are specified in great detail to formally represent complex navigation knowledge. The RouteGraph theory builds on interdisciplinary research on wayfinding and navigation (e.g., Lynch, 1960; Siegel & White, 1975; Habel, 1988; Gillner & Mallot, 1998; Herrmann, Buhl, and Schweizer, 1995) and is not restricted to one species (e.g., Wehner & Menzel, 1990; Etienne, Maurer, Georgakopoulus, and Griffin, 1999; Wiltschko & Wiltschko, 1999). The main assumptions behind this general approach are that on an abstract level the tasks of planning routes and of executing the correct actions along the way are the same for most species and for artificial agents such as robots (e.g., Trullier, Wiener, Bertholz, and Meyer, 1997; Krieg-Brückner, 1998). The similarity and existence of only a few universal navigation strategies (concepts) on an abstract level is claimed, for example by Allen (1999). The RouteGraph is kept abstract to allow for the integration of different needs arising from the different abilities of various agents. The RouteGraph theory instantiates a common platform to express or derive all necessary concepts.

In the outline of their model Werner and his collaborators sketch a potential formalism in which they abstractly formalize the constituents of their model. The model, again, is not meant to be directly implemented or suitable for a specific agent, for a specific domain, or for only one discipline. The RouteGraph is an approach to characterizes route knowledge. RouteGraphs are described in the formalization language CASL (e.g., Astesiano, Bidoit, Krieg-Brückner, Kirchner, Mosses, Sannella, and Tarlecki, 2003). I summarize the basic concepts of the model discussed in Werner et al. (2000) (see also section 3.3).

Route – A *route* is a mental entity that specifies the knowledge an agent has to posses to navigate successfully in spatial environments. Therefore, a route is close to what Siegel and White (1975) defined as *route knowledge*. It is the concatenation of directed *route segments* from one *place* to another. As an example of a route Werner et al. (2000) mention the commuter train line S6 from Munich to Tutzing. More precisely, they should refer to it as the knowledge about the commuter train line. They state that routes can be cyclic. This does not imply that the knowledge is cyclic but that the traveller knows that a cycle is required. The physical reality is not part of their ontology (see section 3.3).

Place – A *place* is a tactical decision point where one has to make decisions about the continuation, i.e. choosing the next *route segment*. Places are the *source* and the *target* of route segments. A very broad definition of what a place can be includes the neuronal activity of rats when they recognize a place they have been to (O'Keefe & Nadel, 1978). Places are defined as physical locations with respect to allocentric reference systems. Two places can be the same or they can be different dependent on the situation, for example the direction of traveling. Places can also be identified by activities alone without mentioning the physical environment.

Path along a route – A *path* along a route is the dynamic usage of a route or a part of it. As a route is a mental entity, it is not to be confused with a physical entity that actually can be used. A path is meant to characterize the actual movement an agent performs (this becomes clear by their reference to Eschenbach, Tschander, Habel, and Kulik, 2000).

Route Segment – Two places (source and target) have a *route segment* between them, i.e. source and target are the endpoints of a route segment. The source and the target are connected by a *course*. Additionally, *entry* and *exit* of the route segment specify the concrete start and end of the course. This means that a route segment has 5 components: source, target, course, entry, and exit.

Course – A *course* is a component of route segments. A course is direction sensititve and specifies navigational decisions, for example, 'walk through door'.

Entry and exit of a route segment – *Entry* and *exit* are defined by the places and the route. They specify route segments, i.e. what to do in order to enter and exit a route segment. Although they are specified by the route, they are modeled as belonging to the route segments. It is important to note that they do not have to be specified, i.e. in the formalization they are not necessarily assigned a value.

Kinds of route segments – Different *kinds of route segments* can be distinguished. Tasks and different navigational tactics are influenced by the means of travel and the environment. The kind of a route segment has to be consistent with the bounding places. Additionally the information associated with each component of a route segment has to belong to the same kind. Examples for kinds of route segments are: CommuterTrainLine, ShipRoute, FootPassage, CityRoad, HighWay (cf. Krieg-Brückner, 1998).

Reference system and position – Each place comes with its own *reference system* (again, place is meant to be the knowledge of some physical object which might be referred to as place as well). Most basic is the direction in which one approaches a place. The reference position is a well defined position with an additional bearing within a place. For example, in front of the city hall. The same physical location can have various reference systems that are associated with it. They are dependent on the respective route. As long as the reference systems of one place are not integrated, the 'same' place is treated as being different.

RouteGraph – The integration of routes into a *RouteGraph*. The representation of places and route segments corresponds to the mathematical notion of a directed graph with a set of nodes (places) and edges (pair of source and target in route segment). The union of routes into a RouteGraph corresponds to the union of nodes and edges into a graph (see Figure 13).

Place integration – the integration of places each with its own reference system and reference position is one of the most demanding tasks within the RouteGraph theory.

Layers and transfers – *Layers* are defined as different kinds of routes or even different kinds of RouteGraphs. Each layer represents a RouteGraph of one kind. *Transfers* are used for abstraction hierarchies and the 'transfers' between different layers. A transfer is a special route segment that is not required to have the same kind of source and target. Consequently, it allows for the modeling of multimodal transportation. A transfer can consist of a whole route or even of a RouteGraph. A transfer is directed and has either a one to one or a one to many connection relation.

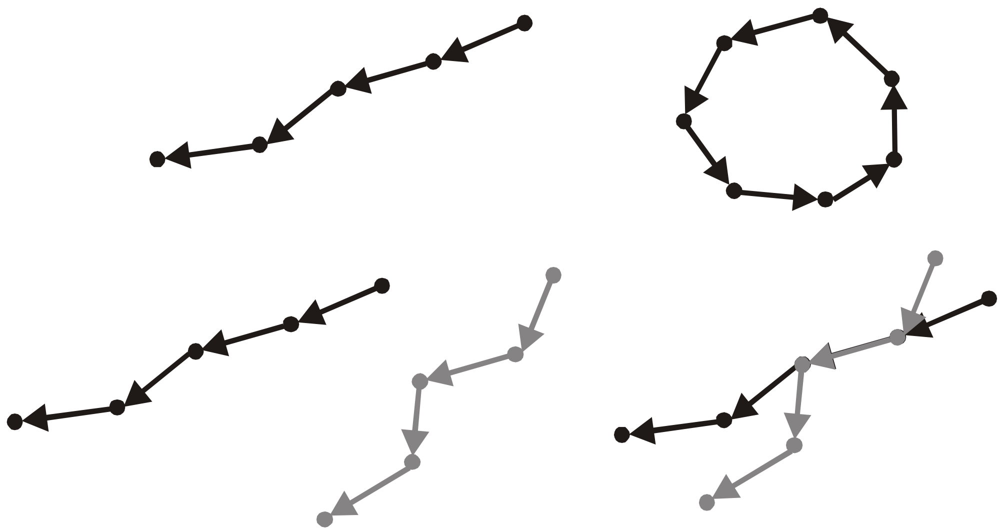

Figure 13. Integration of routes into RouteGraphs (Werner et al., 2000).

In its present state, the RouteGraph theory has a much broader application and scope than wayfinding choremes. It can be characterized as an abstract data type (Roggenbach, pers. comm.[17]). One important difference between the two models is the focus on route knowledge in the RouteGraph theory and the emphasis on mental conceptualizations adopted in the work at hand. Yet, the RouteGraph theory bears possibilities to formalize wayfinding choremes. It would be necessary to define additional concepts that allow for the concatenation of two route segments that are connected via a place. Additionally, the reference system at a place together with entry and exit values have to be adapted. By this procedure the original concepts of the wayfinding choremes can not as easily be addressed as in the specification used in chapter 5. It will be discussed in the outlook since the combination of the two approaches might bridge artificial and natural agent interaction (see 6.3.8). The terminological distinctions are further discussed in section 3.3.

2.4.3 Direction Toolkits by Tversky and Lee

Communicating route directions by graphical means is a younger field of research and is intensively studied by analyzing sketch maps (Tversky, 1995; Tappe & Habel, 1998; Tversky, Zacks, Lee, and Heiser, 2000). Especially the work by Tversky and Lee (1998,

[17] 17.06.2003

1999) and Tversky et al. (2000) resulted in a collection of conceptual spatial primitives for route directions, both graphical and verbal (see Figure 14). Based on their first study (1998) they tested the appropriateness of these toolkits to construct verbal and graphical route directions in follow-up experiments (Tversky & Lee, 1999). One of their main claims is that the structure of verbal and graphical route directions is based on the same conceptual structure, i.e. the same abstract mental concepts underlie both forms of external representations.

In Tversky and Lee (1998) the data is collected by stopping by-passers on the Stanford University campus and asking them for route directions—either graphical or verbal—to an off-campus restaurant. The authors coded the data according to Denis' (1994) categories and, additionally, marked supplementary spatial information such as cardinal direction, arrows, distances, extra landmarks, and extra landmark descriptions.

The structural similarity of both, verbal and graphical route directions, led Tversky and Lee (1999) to examine possibilities of translating depictions to verbal directions and vice versa. For this follow-up task, they used the results of their first study and derived a *pictorial toolkit* and a *verbal toolkit*, respectively. In the new study participants received different route finding problems and one of the two toolkits. The participants were also encouraged to complete the toolkit whenever they felt the need for it. The elements of the pictorial toolkit were graphical, whereas the elements of the verbal toolkit were verb phrases. One key question in their experiment was whether the toolkits were at the right level of granularity. Another was whether the participants judged the provided elements sufficient to construct verbal route directions and graphic route directions. The experimental design allowed for answering this question by either validating the toolkits or by specifying additional elements (Tversky & Lee, 1999). The pictorial toolkit (see Figure 14) contained three types of perpendicular intersections—X-, T-, and L-shaped—, two types of paths, i.e. curved and straight, and two types of arrows, bent and straight. Additionally, landmarks were presented either as rectangles or circles.

The results of this experiment suggest that the participants generally regarded the toolkits as sufficient. Some of them, however, adjusted the angles of the intersections and in exceptional cases the route segments were changed. Further elements were specified for exit ramps, overpasses, street signs, and traffic lights. The landmarks were changed, too; yet they did not necessarily become more iconic. Some participants adopted a strategy to annotate graphic route directions with descriptive linguistic information.

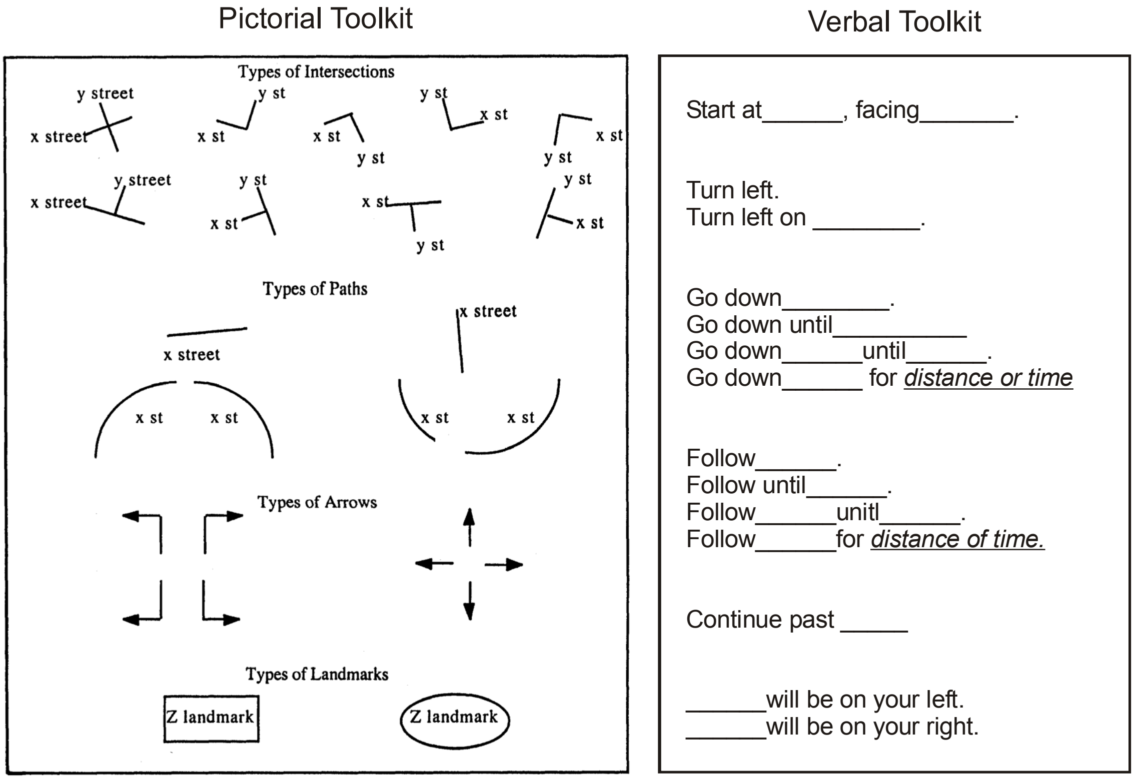

Figure 14. The pictorial toolkit and the verbal toolkit by Tversky and Lee (1999, modified).

"The existence of parallel depictions and descriptions for a domain, such as routes, suggests a common conceptual structures underlying both. The conceptual structure consists of something analogous to semantics, a set of primitives with meanings, and something analogous to syntax, a way to combine meaningful primitives to construct a meaningful whole." (Tversky & Lee, 1999, p. 63). In subsequent work (Tversky et al., 2000) the toolkits were reduced to core elements of route directions resulting in a subset of the original toolkits.

2.5 Summary

The purpose of this chapter was to give a survey of work on conceptual spatial primitives and how they relate to wayfinding and route directions. The focus of this chapter was on three areas of interest: First, conceptual spatial primitives were discussed as a profile through many disciplines, primarily cognitive psychology and geography. Whereas cognitive psychology provides a general basis for the characterization of processes that organize information into basic units, cognitive geographic research provides knowledge on some more spatial characteristics. Additionally, chorematic modeling (Brunet, 1986) has been discussed, as it starts map construction with conceptual models, an approach that this thesis will render more specific for route information.

Work in Artificial intelligence has provided several formalisms for the characterization of reasoning processes and knowledge representation. It is essential to note that these approaches aim at the identification of conceptual spatial primitives that are used as equivalence classes. This means that the richness of spatial information is reduced (aspectualized) by assigning 'similar' relations to one equivalence class; this class is treated homogenously. This process leads to but a few classes, in which the available information is highly condensed.

The last sections of this chapter dealt more explicitly with approaches on wayfinding and route directions. As it is well beyond the scope of this thesis to provide an exhaustive review, the focus has been on two prominent approaches: the RouteGraph theory (Werner et al., 2000) and the toolkit approach by Tversky and Lee (1998, 1999). These approaches have been chosen as they stand in close relation to the wayfinding choreme theory and they both originate from high-level work in cognition.

Nevertheless, as has become clear in the last sections, there are differences in the objectives compared to the wayfinding choreme approach. First, the range of the application for the wayfinding choreme model is grounded in mental conceptualizations disregarding requirements that arise from formalizing route knowledge for autonomous robots. The level of granularity assumed is therefore coarser to reflect mental conceptual primitives and not necessities arising from locomotion. The RouteGraph theory has a clear engineering aim, namely to enable artificial agents to move within the environment.

Second, the graphic toolkit developed by Tversky and Lee is centered on spatial objects and their internal structure. In contrast, I have defined wayfinding choremes as mental conceptualizations of primitive functional route direction and wayfinding elements. Such functionally determined conceptual spatial primitives bear the advantage of allowing for a limited amount of variation whereas the physical appearances of intersections might change considerably. This becomes obvious by surveying European city centers.

'Well, do you happen to know where a proper path is?' 'This is a short cut.' 'Between two places where you're not lost, d'you mean?' 'I keep *tellin'* you, I ain't lost! I'm . . . directionally challenged.'
—*Lords and Ladies*, by Terry Pratchett, 1992

3 The Cognitive Basis of Wayfinding Choremes

This chapter relates the findings elaborated in chapter 1 and chapter 2 to questions of map making and route characterization. To this end, I define what I call the *cognitive conceptual approach* (section 3.1). This perspective is illustrated by discussing levels of abstraction and working out the trilateral relationship between *world*, *map*, and *wayfinder*. On this foundation, I render the term wayfinding choremes more precise (section 3.2). To characterize routes based on wayfinding choremes, it is necessary to analyze route components in greater detail, especially to distinguish spatial structures from spatial behaviors that take place in spatial structures. Consequently, the chapter proceeds by analyzing path (structure) and route (behavior) characteristics resulting in a wayfinding terminology and a definition of basic elements (section 3.3). Establishing the basic set of route direction elements is the first step in defining the wayfinding choreme route grammar (section 3.4). The chapter concludes by stressing the importance of a functional perspective (section 3.5).

3.1 Cognitive - Conceptual Approach to Map Construction

In this section I differentiate between two general approaches to map making, one that I term *cognitive conceptual approach* (CCA) and the more generally used *data-driven approach* (DDA). Alternatively, the CCA can be termed the *top-down approach* and the DDA the *bottom-up approach*. The DDA starts with rich representations of spatial environments and derives representations that are more schematic by systematic abstraction, for example, by cartographic generalization. In contrast, the CCA is characterized by taking abstract mental concepts—in the current case of wayfinding and route directions these are wayfinding choremes—as a starting point, and approaches richer representations by concretizing, combining, and contextualizing them. These two general approaches intertwine with the dichotomy *map design* and *map construction*. After motivating these terminological distinctions and analyzing their special features, I define the wayfinding choreme theory as a *cognitive conceptual approach to map construction.*

Terminologically, I differentiate between *map design* and *map construction*. Map design as defined for example by Dent (1996), is the ‘normal’ approach to map making. It includes all steps necessary to create maps in a classical sense, i.e. choosing the right projection, selecting the relevant data, and, most importantly, choosing appropriate visualization techniques. In contrast, I define map construction as research on constitutional elements of maps, i.e. what are the building blocks of cartographic depictions. Map construction focuses on basic entities and their (spatial) relations, and less on their visual appearance on screen or on paper. As a superordinate concept for both terms, I use *map making*.

> **Map design** – Making maps according to general cartographic principles, i.e. collecting and organizing spatial data, choosing the right projection, and especially visualizing the data.
>
> **Map construction** – Research on the constitutional elements of maps. Classically, these elements are points, lines, and areas (from a cartographic perspective). More recently, interesting contributions are coming from the fields of cognitive science and ontologies. In the definition used here, it also subsumes the spatial relations between or within objects.
>
> **Map making** – The superordinate term comprising both map design and map construction.

Map design normally starts with collecting data on spatial environments in a defined manner—either by surveying or by deriving information from secondary sources, for instance, from aerial photographs (Robinson, Morrison, Muehrcke, Kimerling, and Guptil, 1995). Consequently, spatially accurate—in the sense of complete, rich, and correct—representations and surveys constitute the starting point for deriving less accurate depictions; the converse is not possible[18]. This approach, here called DDA, is intertwined with the research area of *cartographic generalization*, i.e., roughly speaking, the thematic and graphic simplification of cartographic expressions (e.g., Weibel, 1997). As cartographic generalization is not the central topic of the work at hand the following simplification of possible levels of abstraction may suffice as an illustration (see Figure 15).

[18] E.g., generalizing an underground map from a topographic map is possible, but the converse is not.

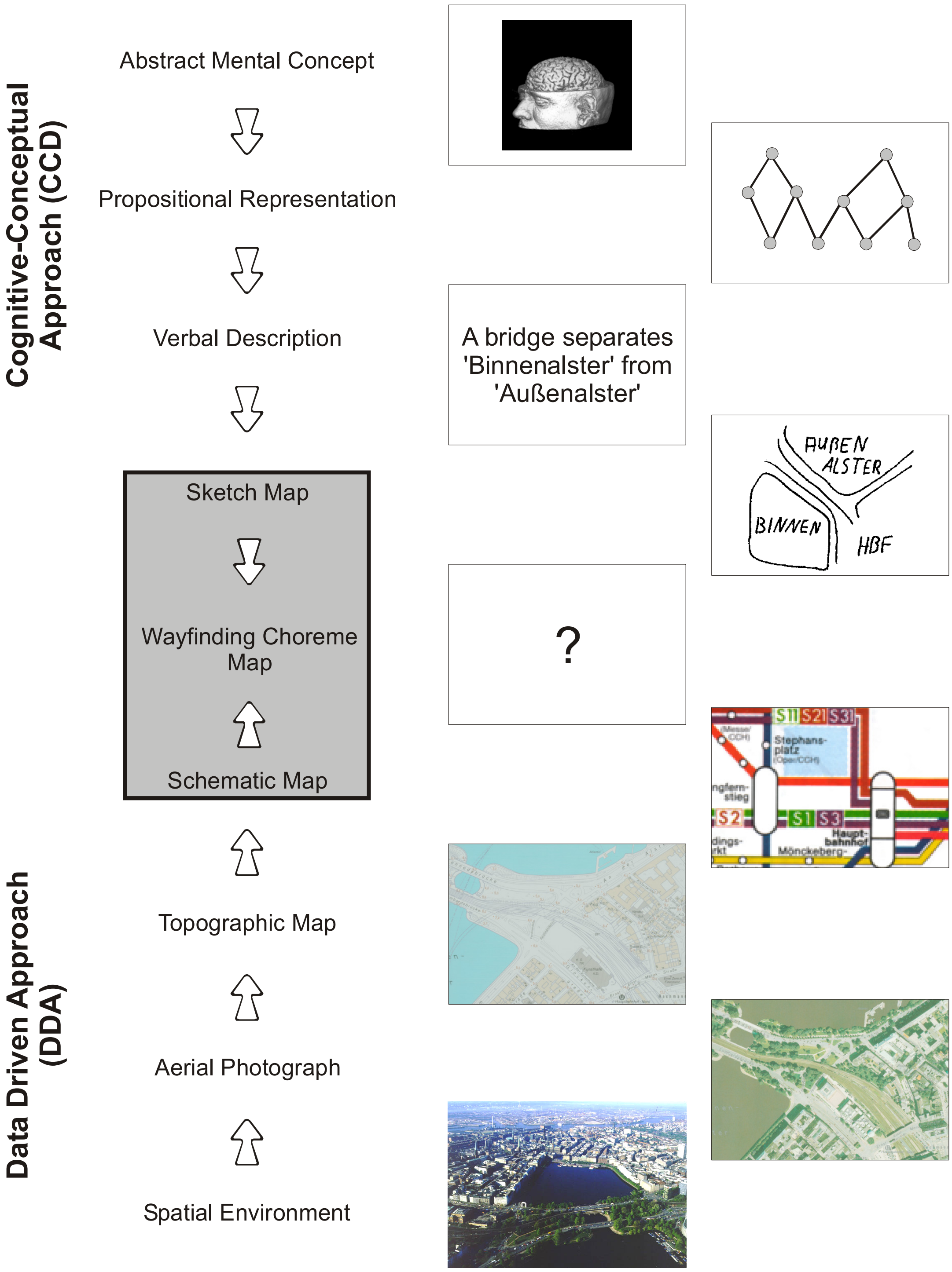

Figure 15. The levels of abstraction underlying top-down and bottom-up approaches to map making (cf. Freksa, 1999; MacEachren, 1994; Bryant et al., 1995; Wastl, 2000). The gray area denotes map-like representations in close relation to principles of cognitive organization (maps: Deutsche Grundkarte & Luftbildkarte St. Georg, Freie und Hansestadt Hamburg, Amt für Geoinformation und Vermessung; brain image: http://neuroimage.usc.edu/ 02.02.2003; aerial photograph: www.hamburg.de, 12.08.2002).

The starting point for the DDA is a rich spatial environment[19]. One conceivable step of abstraction is an aerial photograph taken in orthogonal fashion. Here, we are already at the stage of an external, planar, and bounded representational medium with the same medial representation characteristics and constraints as maps, but without the corresponding symbolism. From this representation topographic maps are derived[20]. Topographic maps can be termed *primary representations* as they fulfill measurable criteria concerning the accuracy of spatial information and the completeness of the data. They are standardized to a high degree (e.g., Grünreich, 1990; ATKIS; SDTS). Starting with large-scale maps, small-scale maps are derivable by means of generalization (e.g., Brassel & Weibel, 1988; Buttenfield & McMaster, 1991). Various approaches have been undertaken to automate this process but full automatization is unlikely to be achieved (e.g., Beard, 1991; Meng, 2003). Spatial information changes in the process of generalization, it is getting sparser. According to the purpose of the map and/or due to the greater amount of information that has to fit less *map space* some aspects are emphasized while others are de-emphasized. With less space available symbolization plays a greater role, i.e. objects formerly depicted by their ground plan are now represented by symbols. The means to handle this transition are the classical cartographic generalization rules: elimination, aggregation, collapse, typification, exaggeration, selection, classification, simplification, conflict resolution (displacement), refinement, and symbolization (e.g., Dent, 1996; ESRI, 1996).

Beyond the scope of the cartographic tenet, i.e. to give the map-reader a precise image of the environment (Dorling & Fairbairn, 1997)[21], we make maps that are termed *special purpose*, *task-specific*, or *schematic* (e.g., Freksa, 1999; Tversky, 2000; Gartner, to appear). A schematic representation focuses only on a relevant set of spatial aspects, and provides design freedom that enables the representation of highly focused, context-adapted information. Especially work on schematic maps (e.g., Berendt, Barkowsky et al., 1998; Cabello, de Berg, van Dijk, van Kreveld, and Strijk, 2001), where *concepts of design* are applied (for example, in European subway maps using only straight lines) gives rise to a different view on map making. MacEachren states: "As we move toward the graphic end of the continuum, […], there is an increasing number of abstraction decisions left to the analyst/map designer." (MacEachren 1994, p. 39). It follows that the relation between topographic and schematic maps can be characterized as a one to many relation; from the same topographic depiction—or the underlying data set—an inexhaustible set of schematic maps can be derived (see Figure 16).

[19] A photograph is already a representation of a spatial environment (see Figure 15) but may suffice for illustration in this context.

[20] I neglect the possibility of characterizing the levels of abstraction in an ‘abstract’ manner regarding the data bases, i.e. the data that results from surveying, or the preprocessed data, for example, the ATKIS Catalogue. By no means I want to indicate that this is the only or most important way of abstraction.

[21] This view is changing, especially with the development of new presentation techniques and in some research areas like GeoDesign (e.g., Kunzmann, 1993).

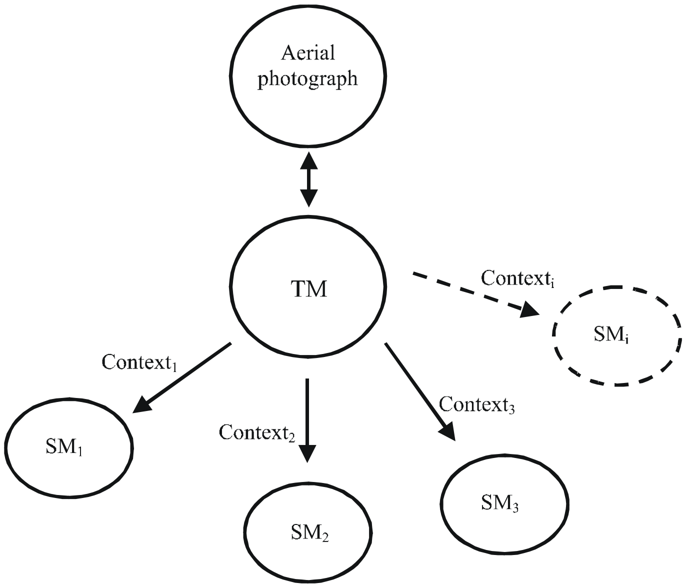

Figure 16. The relation (one to many) between a topographic map (TM) and schematic maps (SM).

This is the DDA perspective to map making, which I associate with map design. The DDA starts with the richest source of information and reduces and focuses this information further and further. This approach leads to a systematic reduction in accuracy, in possible inferences, and in the number of depicted entities. On the other hand, we gain design freedom, for example, to apply design concepts, to focus on specific aspects, and most of the time to increase readability[22].

In contrast to the DDA to map making, the CCA starts with abstract spatial information, abstract mental concepts in Figure 15 (cf. section 2.2.4). Abstract mental concepts (cf. approaches on naive physics (de Kleer & Brown, 1984), naive geography (Mark & Egenhofer, 1995), or QSR) are accessible to us, for example, by analyzing natural language expressions, sketch maps, and by applying various other psychological methods (Habel & Tappe, 1999; Knauff, Rauh, and Renz, 1997; Tappe, Klippel, and Habel, 2001). A first conceivable step towards externalizing and concretizing abstract mental concepts is their verbalization. One important aspect to remember is that linguistic expressions, in contrast to pictorial representations, are underspecified. This means that there is a gap between an expression such as *turn right* in a verbal description and the depiction of an intersection at which one has to turn right. Visualizing spatial information requires choosing **one** depiction, which is rendered specific (given concrete spatial coordinates) in its externalization on a two-dimensional, spatio-temporally fixed representation medium (e.g., Habel, 1998). In contrast, linguistic expressions are underspecified in that their interpretation is per se contextually adaptable to a greater extent than the interpretation of pictorial

[22] Tversky (2000) would oppose this point of view. In her reply to Uttal (2000) she strongly argues that maps reflect people's mental conceptualizations of their spatial environments. This rather holds for older, i.e. historic, maps and for schematic maps.

representations. The semantic content of a term such as *turn right* only captures the general concept of change of direction according to one's main body axis. The application of this concept to a specific spatial configuration leaves room for interpretation. Interestingly, approaching conceptual schematic representations this way leads also to a one to many relation, in that one abstract, underspecified spatial knowledge structure bears the possibility of various graphical representations.

> **Abstract mental concepts** – Are defined as underspecified, and above all task-specific, knowledge structures, necessary for solving spatial problems, such as wayfinding. An abstract mental concept is neither equal to a natural language expression nor to a specific mental image.

Wayfinding choremes are abstract mental concepts in this sense for the domain of wayfinding and route directions. An example from the wayfinding domain may illustrate this definition: To reach a destination from a given origin, the most basic spatial fact one has to make sure of is that these two locations are connected, for example, by a concatenation of path segments (see section 3.3; see also section 2.2.1 on image schemata).

Verbalization and graphicalization are two forms of externalizing abstract mental concepts at the first levels of preciseness (see Figure 15). The transition from natural language spatial expressions to sketch maps involves compliance to further medial constraints. As indicated by the gray area in which schematic maps, wayfinding choreme maps, and sketch maps are placed in Figure 15, these forms of representation share properties and are external, planar, and bounded representations that reflect—to varying degrees—mental spatial concepts.

It was only since the 1970s, however, that awareness swept through cartographic research that higher-level cognitive processes of map readers are significant to the map-user-interaction (Robinson & Petchenik, 1976; Blades & Spencer, 1986; Peuquet, 1988; Montello, 2002). Even for schematic maps that are close to sketch maps, it is claimed and is indeed common practice (e.g., Elroi 1988a, 1988b; Cabello et al., 2001) that they are derived in a DDA fashion, although guided by cognitive concepts "[…] schematic maps differ from sketch maps in that they are derived from topographic maps […]" (Freksa, Moratz, and Barkowsky, 2000, p. 105).

Thus, one goal of the work at hand is to take the next step and apply abstract mental concepts 'directly' to a map construction process, not by schematizing rich spatial representations stepwise (e.g., the stepwise abstraction of shape simplification algorithm, see Latecki & Lakämper, 2000; Barkowsky, Latecki, and Richter, 2000). To demarcate maps resulting from a cognitive conceptual approach I will refer to them as *wayfinding choreme maps*.

Schematic map – Maps made by a DDA. They intentionally simplify spatial information more than it is aspired by cartographic design principles.[23]

Wayfinding choreme map – Maps made by a CCA. Mental conceptualizations of primitive functional route direction and wayfinding elements are applied to construct these maps; they are comparable to (formalized) sketch maps.

As mentioned earlier, the levels of abstraction are simplifications of the diverse processes and forms of representations that are in between very rich and highly abstract instantiations. Figure 15, however, underrepresents one important aspect, i.e. that abstract mental concepts are grounded in experience with rich spatial environments (e.g., Clark, 1973; Shepard, 1987; Lakoff & Johnson, 1980; see also section 2.2.1). They result from processes and survival mechanisms described—with respect to the work at hand—in chapter 1. Figure 15 depicts abstract mental concepts and detailed representations of spatial environments at opposite ends of the levels of abstraction. This problem is acknowledged by depicting the relation between the CCA and the DDA to map making in Figure 17. It is important to note that both approaches have their origin in rich spatial environments but that the steps they take are different. While the DDA yields at first a representation of the environment that is as precise as possible and derives other less precise representations from this representation, the CCA starts with mental conceptualizations, i.e. highly processed abstracted information, and has to adapt these abstract concepts to constraints of representational media.

The possibility cannot be excluded that programs such as *shape simplification algorithms* can create maps that look similar or identical to wayfinding choreme maps. Nevertheless, the CCA is concept-driven even though some aspects may overlap with the DDA, for example, maintaining topological information or specific kinds of ordering relations.

[23] Every map is schematic in the sense that details of the environment are depicted in a simplified form. I use schematic in the meaning employed in cognitive science (e.g. Herskovits, 1998; see section 1.1.2) that stresses the fact that there is an intention for the schematization applied. According to section 1.1.2 (aspectualization) the term *aspect map* seems to be more appropriate. I do not use aspect map here as its definition goes beyond what is visually present: "[...] a formal description of a map that allows to distinguish between intended or representational pieces of information and information that can be read off the map due to the pictorial property of over-representation" (Barkowsky & Freksa, 1997, p. 355).

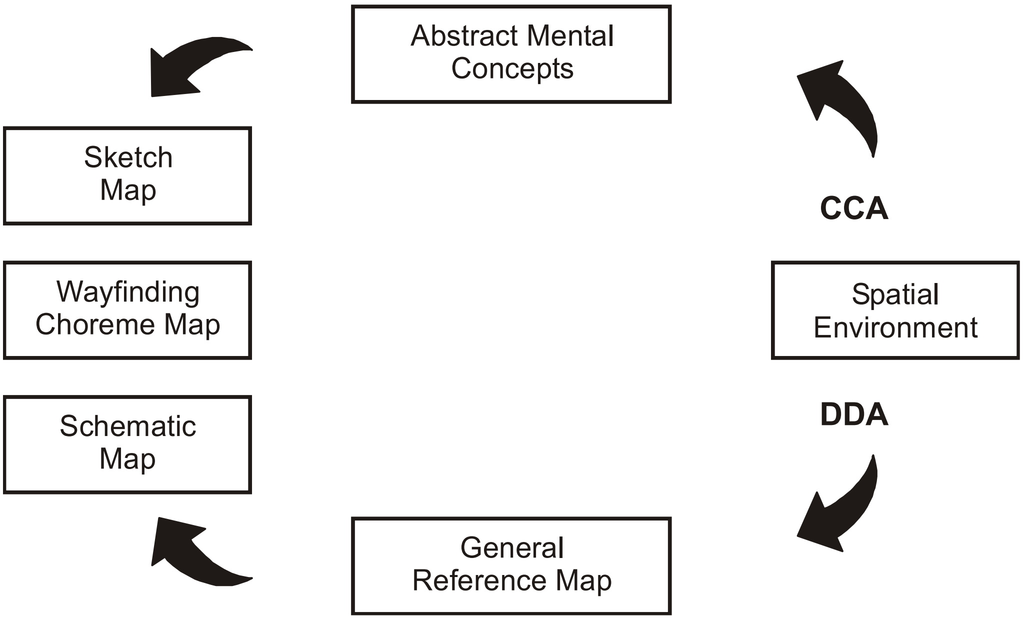

Figure 17. The cognitive conceptual approach (CCA, top-down) to map construction versus the data-driven approach (DDA, bottom-up).

3.2 Interaction Triangle

To further elaborate the interaction between world, map, and wayfinder, and the grounding of the cognitive conceptual approach to map construction, I introduce an *interaction triangle* (see Figure 18). In the following, I discuss the idea of conceptual spatial primitives as a basis for wayfinding choremes.

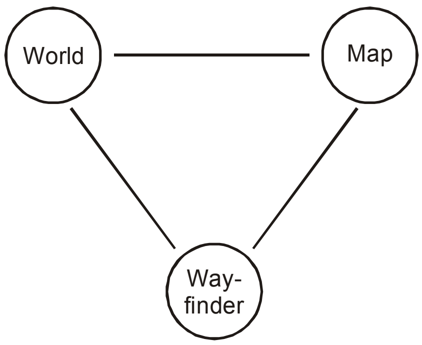

Figure 18. The interaction between world, map, and wayfinder.

In the present work the term wayfinding choremes is systematically ambiguous. On the one hand, it denotes mental conceptualizations of primitive functional wayfinding and route direction elements. On the other hand, it stands for the externalization of mental conceptual primitives of wayfinding and route direction elements. When instantiated in a representational medium, externalizations occur in two forms: graphically and verbally[24]. The focus of the present work is on *graphic conceptual primitives* (graphicalization). The following terminological distinction is motivated by Chomsky (1986). In his theory on language and grammar, Chomsky distinguished I-language and E-language. 'I' stands for internal and denotes an abstract part that underlies the observable behavioral aspects of language. 'E' stands for external and means these observable behaviors. Correspondingly, I refer to mental conceptual primitives, i.e. abstract mental concepts of basic route direction elements, as *I–wayfinding choremes*. In contrast, the (graphic) externalizations of I–wayfinding choremes are termed *E–wayfinding choremes* (see Figure 19).

I–wayfinding choreme – The mental conceptualization of primitive functional wayfinding and route direction elements.

E–wayfinding choreme – The externalization of mental conceptualizations of primitive functional wayfinding and route direction elements, i.e. the externalization of an I-wayfinding choreme.

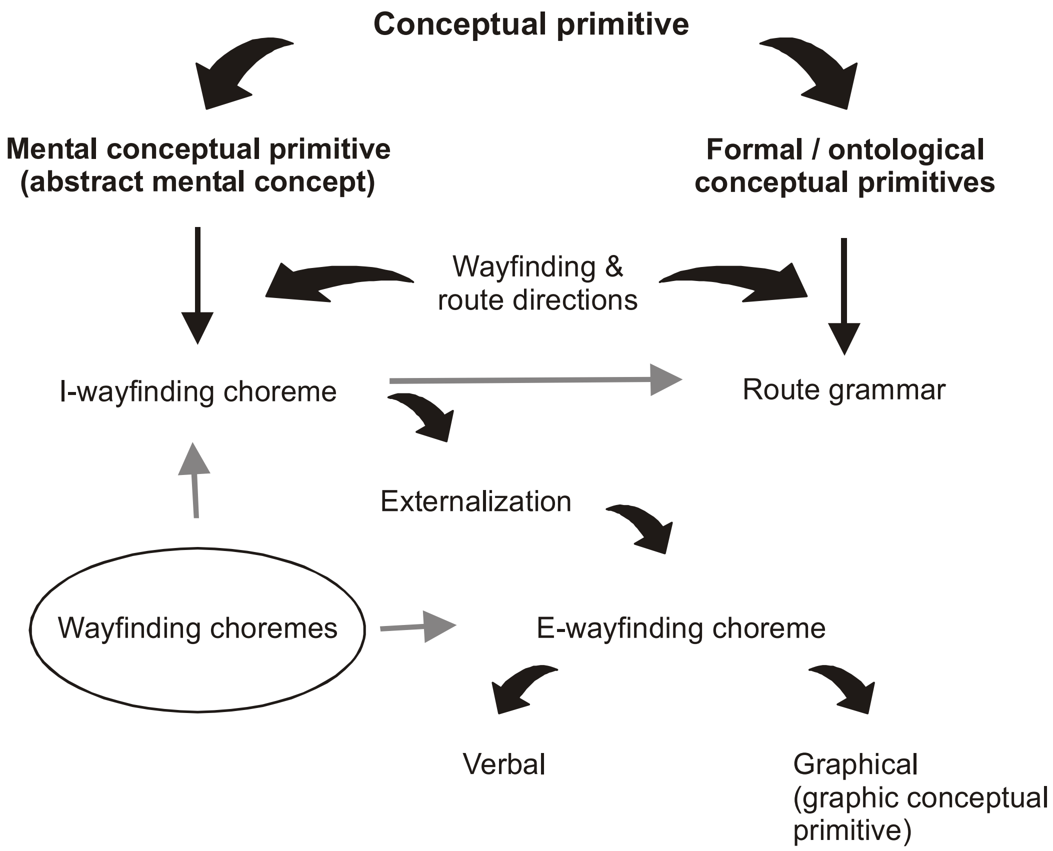

Figure 19. Relation between conceptual primitives and wayfinding choremes.

[24]A motorical action or a sign language gesture could be regarded as an externalization, too. This line of thought is not pursued in the work at hand. For an overview of externalizations used in experimental settings see Liben (1982).

As shown in chapter 2, it is generally agreed that cognitive processes and reasoning on spatial relations are mediated by *structuring processes.* The interaction between the world and the wayfinder, the map and the wayfinder, but also between the world and the map are indirect. 'Indirect' in the present context expresses the idea that structuring processes are the basis for the interactions between the referent (the world) and the representation (the map). If a cognizing individual (a wayfinder) is involved, the term structuring process is changed to *conceptual structuring process* (CSP). Based on this trilateral relationship, depicted in the interaction triangle (see Figure 18), I detail the mutual relations between the three components to reveal their characteristics for the work at hand.

Structuring processes act on the information flow from rich to sparser domains, i.e. from the world to the map, from the map to the wayfinder, and from the wayfinder to the map[25]. After discussing 'the edges' of the interaction triangle, their trilateral relation can be examined, as this represents the basis for cognitively adequate map construction (MacEachren, 1995).

> **(Conceptual) structuring processes –** The general term for (cognitive) processes that handle the organization of information about environments.

3.2.1 Conceptual Structuring Processes

Map – world relation. Maps enable access to information not known to us or to places at which we are not present or that are too large to be perceived directly. Yet, they are no direct windows to the world, i.e. the mapping relation is not 1:1 (e.g., Eco, 1994); rather they are "[...] a highly processed representation of selected aspects of it [the world]." (MacEachren, 1995, p.190). This requires structuring processes in between the world and the map that reduce and organize the innumerable pieces of information in the world to pieces of information that can be depicted in a map. Structuring processes important for map making are grouped into three main areas:

- map projections,
- object categorization and selection, and
- object depiction.

A map projection is a mapping from a spherical surface to a planar medium. This comprises the reduction in dimension from the surface of a three-dimensional sphere to a two-dimensional plane. All projections distort at least one of the following qualities: angles, distances, or areas. On a map, the *principal scale*—denoted as a fraction like 1:10,000 in the margin of a map—is only preserved at certain points or along certain lines, i.e. the *points or lines of zero distortion*. Particular scales at certain points vary throughout a map according to position and direction. The following features characterize map projections: *property* denotes which kind of information is generally

[25] For a more detailed analysis, cf. e.g., Neisser (1976).

preserved, *class* is the superordinate term for the shape of the projection plane (e.g., cylindrical), and *aspect* denotes the position of the projection plane (e.g., Maling, 1992; Robinson et al., 1995).

While map projections handle general constraints of the representational medium, the selection of information on the world is organized by various ‘catalogues’ in which objects are characterized that potentially could appear on a map. Examples of these catalogues for basic topographic map objects are the German ATKIS (Amtliches Topographisch-Kartographisches Informationssystem) and the SDTS (Spatial Data Transfer Standard). ATKIS, for example, is composed of modules. The Basis-DLM (Digitales Landschafts-Model, digital environmental model) describes topographic objects in the environment and the relief of the earth’s surface. Objects are assigned to object types and are characterized by their geographic location, their geometric type, and other attributes. Which object types exist and how objects have to be depicted defines the ATKIS object catalogue (ATKIS Objektartenkatalog). Besides these catalogues there are various other cartographic conventions applicable to the depiction of geographic objects, for example, the graphic variables by Bertin (1974) (see also, Keates, 1996; Slocum, 1999; Dent, 1996).

Most object catalogues are not cognitively motivated as they aim at modeling the world in a precise manner to provide the basis for all kinds of calculations and depictions. For example, the concept ‘intersection’ is not an explicit part of the ATKIS object catalogue while it definitely plays a crucial role in mental conceptualizations of routes and route directions.

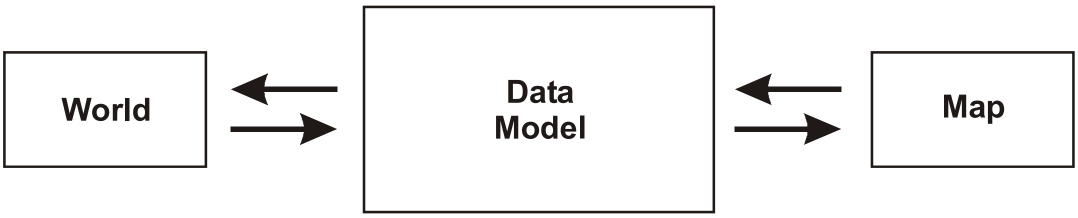

Figure 20. Map – world relation.

World – wayfinder interaction. In the introduction, I argued for aspectualization as an important, if not vital, aspect of our interaction with the world. The world is accessible to us via our senses but is too complex to be processed in its entirety. As a result, conceptual structuring processes (CSPs) are compulsory. Assuming CSPs is congruent with the common postulate in cognitive science that sensual information from peripheral systems is translated into an abstract representation format[26]. In this way, the ‘translatability’ between different input and output systems of the knowledge processing system is guaranteed. The specific format is subject to discussion and no agreement has been reached, yet. Consensus has been achieved on the assumption that the respective format partially depends on the task (cf. the imagery-debate and resolution of the

[26] For a different view compare the work of Barsalou and his collaborators (e.g., Barsalou, 1999; Barsalou, Solomon, and Wu, 1999; Barsalou et al., 2003). They argue against an amodal format and claim that the perceptual input channel plays a major role (cf. also Freksa, Barkowsky, and Klippel, 1999).

imagery debate, e.g., Paivio, 1971; Block, 1981; Kosslyn, 1994). As discussed in sections 1.1.2 and 2.2.1, terms used to describe CSPs and their results are aspectualization, conceptualization, schematization, frame, schemata, mental models, or concepts. The general term chosen here, *conceptual structuring processes*, denotes that active processes organize the information. This terminology corresponds to the information processing perspective of cognitive science (e.g., Stillings, Weisler, Chase, Feinstein, Garfield, and Rissland, 1995).

The human information processing system acts on various levels. The most basic distinction can be made between low-level and high-level processes. All levels contribute actively to the reduction and structuring of information. CSPs are high-level processes and are pertinent to the work at hand. Hence, conceptual refers to conscious processes or, if not directly accessible to conscious thought, to those processes that can be expressed by one of our output systems.

As mentioned above, it is broadly agreed that a common format results from CSPs into which the information input from different perceptual and sensory channels such as auditory, haptic, or visual input is rendered (see Figure 21). One supporter of this perspective is Jackendoff (e.g., 1996, 1997). Jackendoff (1997) uses *conceptual structure* as a term for a system of mental representations, in which reasoning, planning, and the forming of intentions take place. His *Intermediate-Level Theory* claims that somewhere between sensation and cognition lies a level of representations that is conscious, while low-level and high-level processes are not available to consciousness. Conceptual structure is not part of language per se. He also argues that conceptual structure must be linked and is in fact **the** link to all sensory modalities, i.e. auditory, haptic, etc. He also states that conceptual structure is not available to consciousness although expressible, for example, via consciously formed linguistic expressions. Figure 21 illustrates this relationship especially for visual input. While viewing an intersection in the world our visual system constructs a representation of the shape of the intersection. At the same time, the visual system drives the conceptual system—through appropriate interfaces—to retrieve the concept of an intersection. Jackendoff proposes that a concept is a combination of its conceptual and its spatial representation. Importantly he states that "[...] our understanding of what we see is a consequence not only of visual images but also of the conceptual organization connected to those images." (Jackendoff, 1997, p.191). It may be the case that this assumption is even more important for the conceptualization of actions such as *turn right at the next intersection*.

Conceptual structure is a current instantiation of world knowledge acquired during ontogenetic and socialization processes. In a given context, a specific conceptual structure is instantiated. To make this point clearer some authors use the term *current conceptual representation* (Habel, Tappe, and Guhe, to appear; von Stutterheim, 1999; Jackendoff, 1983). In the domain of route directions, Klippel et al. (2003) use the term *current spatial representation*.

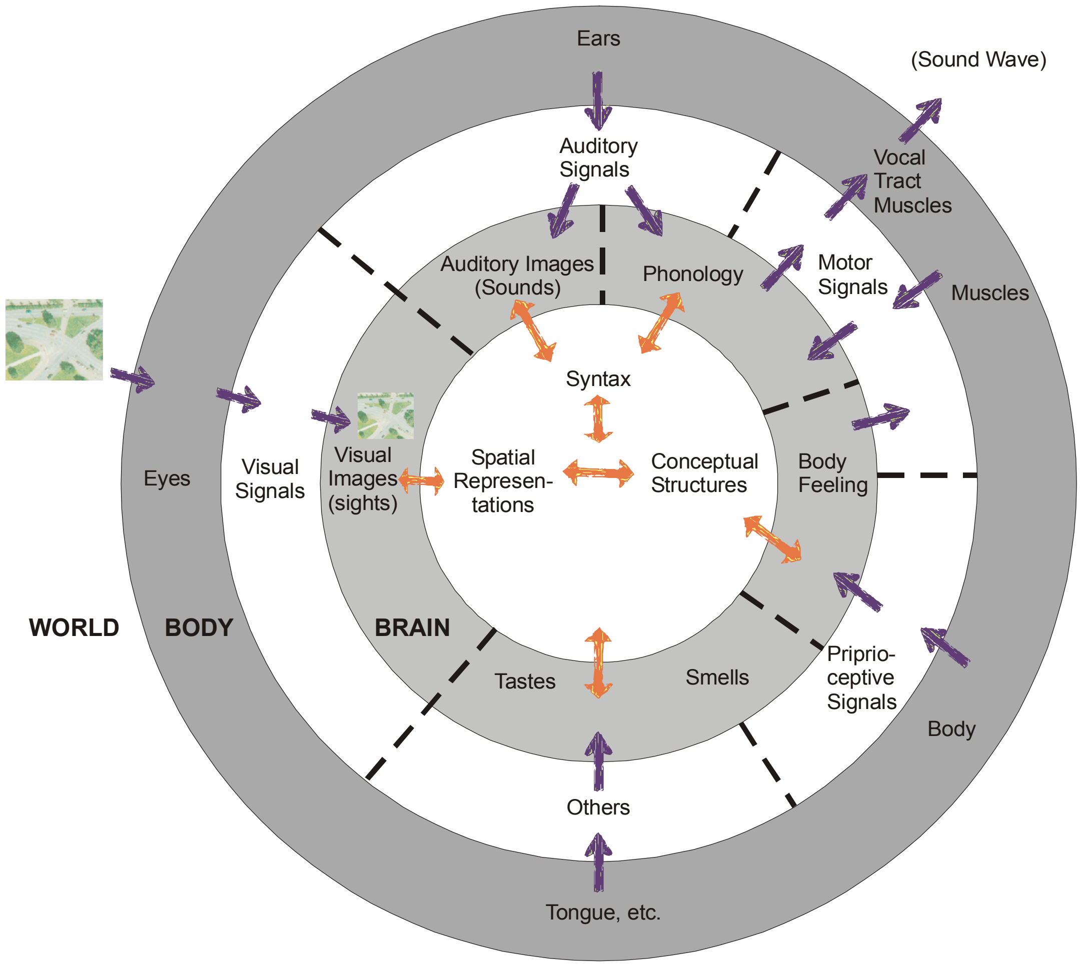

Figure 21. Information processing according to the Intermediate-Level Theory (modified from Jackendoff, 1997).

Results of conceptual structuring processes are called abstract mental concepts, and in the context of the work at hand I-wayfinding choremes.

Map – wayfinder interaction. It is important to distinguish between a scientific approach to map – wayfinder interaction (map interpretation) and a common sense perspective (common map interpretation, see section 1.2.1). With the dawn of experimental cartography (Eckert, 1921/1925; Robinson, 1952), the shift from perceptual research in cartography to more cognitively oriented approaches (e.g., Petchenik, 1975; Medyckyj-Scott & Board, 1991; Montello, 2002), and the application of cognitive science research to aspects of map making (e.g., MacEachren, 1995), the question of conceptual structuring processes as a field of research for map making evolved. Work by Liben and Downs (e.g., 1989, 1992) and Blades (1991) shows that we start to understand maps as representations of our environments between the age of 3 and 6. Accordingly, we can assume that partially the same CSPs apply to wayfinder – map interactions as they do to wayfinder – world interaction. We have to be aware of the fact, however, that we deal with a different scale while interacting with a map, i.e.

we are in pictorial space (Montello, 1993). We have a different perspective on the map (bird's eye perspective) than we have on the environment (field perspective). Additionally, we can turn maps to align the representation with what it represents. During wayfinding the task is getting more complex as we do not only have to read the information off the map but also have to match this information with our actual surroundings. This fact argues for aspectualization as we can use all three sources of knowledge in this interaction: the world, the map, and the wayfinder. For example, Raubal and Worboys (1999) cited a statement by Norman (1988) that people do not necessarily need to have complete knowledge of a spatial situation in order to behave effectively. In their model of wayfinding, Raubal and Worboys suppose that knowledge is distributed, i.e. it is partially intrinsic to the wayfinder, but also partially in the world and in the constraints of the world.

MacEachren (1995) proposed the question of individualizing abstract mental concepts (similar to his idea of map schemata) underlying map – wayfinder interaction as a future line of research. He supposes that the exploration of map schemata "[...] offers a way to bring together ideas about perception of map symbols, cognitive processing of map-derived information, and the roles of knowledge, experience, practice, and training on the part of the map readers." (p. 193). His work strongly builds on ideas of Lakoff (1987) with the main assumption that we acquire fundamental principles through interaction with our environment and that these principles in turn are the basis for the conceptualization of new information from the environment or from its representations (cf. also, e.g., Piaget, 1963, 1970; Clark, 1973; Shepard, 1987; Mandler, 1988b, 1992).

MacEachren (1995) discusses the various schemata necessary for reading a map and distinguishes between general and specific map schemata. As general schemata he discusses, for example, container, linear order, up-down, and part-whole schemata. He also points out that these schemata depend on cognitive development: children and adults posses them to different degrees. In spite of this, MacEachren (1995) proposes that "[...] humans possess a general map schema [...]." (p. 198).

As one example of a specific map schema MacEachren describes the *hypsometric map schema*. Different general schemata constitute the hypsometric map schema: up-down, source-path-goal, linear order, light-dark, and center-periphery. For this schema MacEachren (1995) states that "[...] it makes fairly direct use of several of the kinesthetic image schemata that Lakoff identified as preconceptual embodied schemata, and it does so with only modest metaphorical extension of these concepts" (p. 201). He concludes that if map designers choose appropriate schemata, the interpretation of maps becomes easier and more effective.

In the sense of the classification proposed by MacEachren the work at hand deals with specific map schemata: spatial schemata for route directions with a focus on the relevant spatial information. The wayfinding choremes defined in this work go beyond image schemata in the sense that they are more specific. This means that conceptualizations are examined that are essential to wayfinding and route directions.

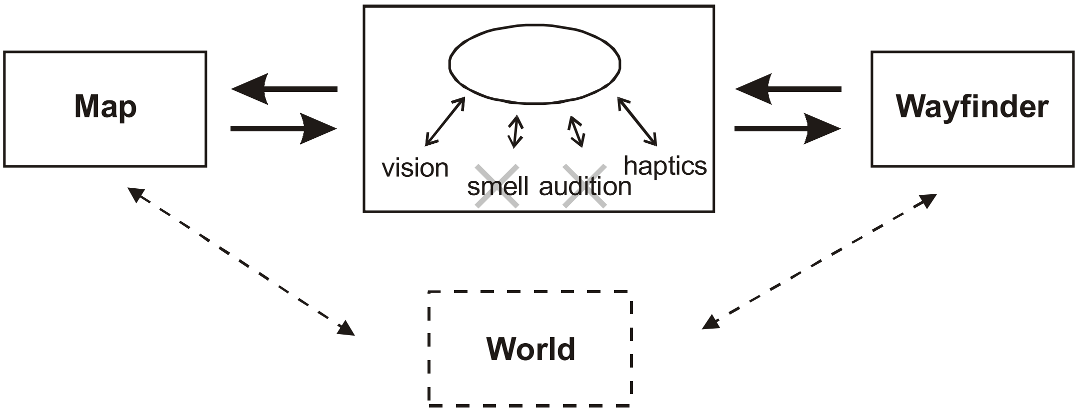

Figure 22. Map – wayfinder interaction.

Recent studies (e.g., Montello, Waller, Hegarty, and Richardson, in press) suggest that the real world is by no means always the best way to acquire spatial knowledge. The question that arises here is whether the abstract mental concepts we acquire from representations differ from those we acquire in direct interaction with the environment. Consequently, we can pose the question of whether we 'only' adopt CSPs or whether we acquire them as well during map interaction. This question is addressed in study 2 of this thesis (see section 4.3.2).

3.2.2 Relating Conceptual Structuring Processes

This section further elaborates on the question of whether an entity exists that relates the three (conceptual) structuring processes depicted in the interaction triangle (see Figure 18). This question is of special relevance when an external representational medium is employed in information processing. In other words, I propose a model that captures all three interactions and answers the question of how research on the interaction between the world and the wayfinder, and the map and the wayfinder influences the characterization of route information and the choice of appropriate basic map construction elements.

MacEachren (1995) (see section 3.2.1) has stated that the application of the 'correct' schemata, which guide our interaction with the world, to map making fosters the interpretation of information presented in the map. While MacEachren dealt primarily with the application of spatial schemata to 3D or non-spatial (thematic) information, the work at hand focuses on the question of how to conceptualize *locational spatial information* and how to apply the conceptualizations of it to map making. In other words, I pursue the question of how I–wayfinding choremes can be integrated into map construction.

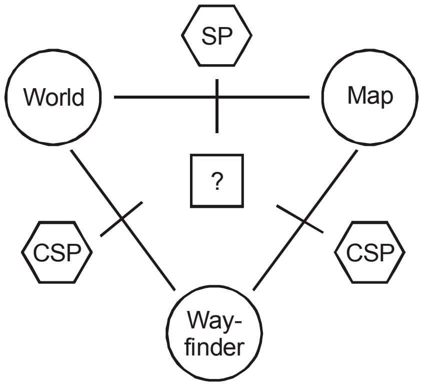

Figure 23. The basis for the cognitive conceptual approach: The interaction triangle revisited.

The question of spatial information—*locational spatial, 3D, or thematic*—represented in maps is confusing. I categorize spatial information by relying on the fundamental work of Bertin (1974). Bertin grounds his work on visual variables on an investigation of the information that can be depicted in the plane, or, to be more precise, by the properties of the plane. He starts with analyzing the two dimensions the plane offers for representing information. For diagrams this is the x and the y axis, which can be used for all kinds of information, for example, depicting change in the amount of precipitation during a year for a certain place on the earth surface. While this is a convenient way to depict the relation of two kinds of information, maps encounter the problem (or the advantage, e.g., Palmer, 1978; Larkin & Simon, 1987; Freksa, 1999) that the two dimensions of the plane are assigned to represent locational spatial information, what Bertin terms the *geographic component*. This simple fact necessitates the use of the *third dimension* for depicting any other information. Bertin's terminology should not be confused with the third dimension in 3D-space, i.e. height information. Yet, his original idea is motivated by the fact that we are able to perceive depth in space and he copies these ideas to the visual effects that provide information without the need to leave 2D-space. He is not interested in depicting height information but thematic information, for example, that a green colored area represents a meadow. Inspired by experimental work on perception he built his theory on how to use visual variables to appropriately depict information other than locational spatial information. His six visual variables—shape, orientation, color, pattern, hue, and size—are the standards for depicting thematic information even today[27]. Against this background, I categorize spatial information in the following way:

> **Locational spatial information –** Information about the location of spatial objects with respect to a given spatial reference system. Locational spatial information therefore can be absolute, relative, or intrinsic. Locational spatial information is also called the geometric attribute.
>
> **3D spatial information –** Height information.

---

[27] Several authors provide extensions and modification of Bertin's work, for example, Spiess (1970), McCleary (1983), Morrison (1984), and MacEachren (1994).

Thematic information – In geography this is information on the semantic content of a spatially located object. Thematic information is also called the substantial attribute.

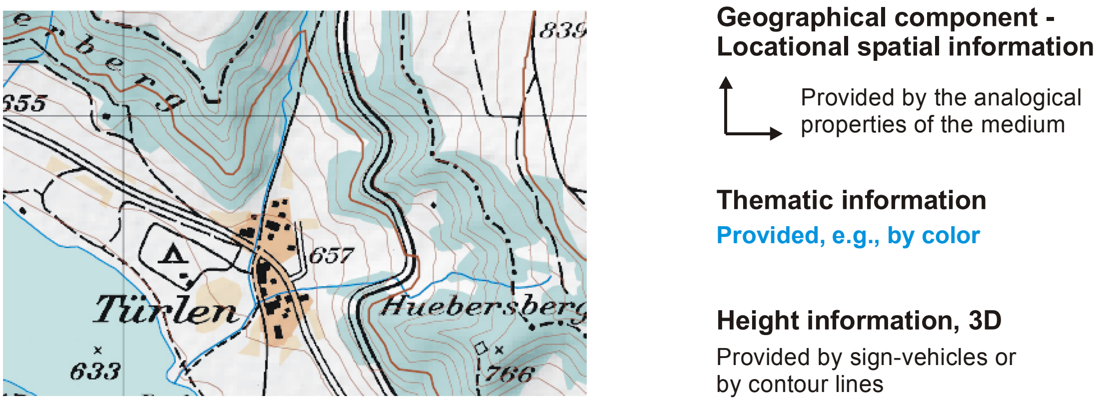

Figure 24. Categorizing spatial information based on Bertin (1974) (Interactive Topographic Map "Tuerlersee", A. Neumann, http://www.carto.net/papers/svg/tuerlersee/).

3.3 Routes, Paths, and Beyond

In the following sections, I will clarify the terminology for the wayfinding choreme theory. I set out from the distinction between *paths* and *routes* by Montello (in press) and add concepts according to the requirements of this thesis.

3.3.1 Differentiating Routes and Paths

An analysis of wayfinding terminology and route direction terminology (e.g., Eschenbach et al., 2000; Habel, 1988; Hart, 1995; Klein, 1979; Lynch, 1960; Maaß, 1996; Pick, 2000; Werner et al., 2000; Winter, 2002a; see also section 2.2.2 and section 2.4.2) shows, that a clarification of the terminology on the basis of its commonsense or even its technical usage is nearly impossible. Therefore, I focus on one distinction that is pertinent to this thesis and is reflected in a definition made by Montello (in press). Montello defines paths as linear physical features in the world upon which travel occurs. Examples are roads or trails. Routes in his dichotomy are linear patterns of movement by travelers. Routes of travel may occur on paths or across areas that contain no paths, like open fields[28]. I will show that this reading of the path-route dichotomy reflects a critical distinction for cognitively adequate route directions: the physical environment versus movements that occur in the physical environment.

[28] This distinction corresponds to the definition of wayfinding by Golledge (1999b; see section 1.1).

I set out from this general distinction by Montello that routes denote behavioral patterns and paths denote linear physical entities[29]. Paths, as understood by Montello, are unbounded entities, they have no starting point and no endpoint. Routes, on the other hand, have an origin (O) and a destination (D). For the present work, a refinement of these concepts is indispensable to meet the requirements of the wayfinding choreme theory.

Paths are linear physical entities; they can be combined to networks, for example, city street networks. The ontological status of these networks is cetral to phenomena in geographic space as it has already been noted (cf. Brunet, 1986; Ruggles & Armstrong, 1997). I refer to these networks as *path-networks*. Travel or travel planning takes place within path-networks. I will refer to linear patterns that result from travel or travel planning as routes.

Additionally, the necessity of a correspondence between parts of a path-network to routes has been emphasized in works on route directions (Klein, 1979; Habel, 1988; Carstensen, 1991; Maaß, 1996). To have a term for this 'entity', I introduce the concept of *R-path* (short for Route-path). The rationale behind the concept of R-path is the following: A route has a defined origin and destination. Both the origin and the destination have a spatial address, i.e. they are each located at a certain position within the path-network. An R-path is defined as the part of a path-network that is demarcated by the route. Origin and destination of a specific route define the endpoints of the corresponding R-path. While paths in the reading of Montello (in press) are unbounded linear physical features, R-paths are linear physical entities that obtain endpoints by origins and destinations of the corresponding routes. The left part of Figure 25 shows a path-network. If we refer to the linear features of the path-network as paths, I agree with Montello that it is not possible to 'see' any endpoints. The right part of Figure 25 visualizes behavioral patterns that take place in the path-network, here referred to as routes. The routes demarcate parts of the path-network. Therefore, for each route an R-path is defined with endpoints that correspond to the route's origin and destination. To sum up, the following definitions are pertinent to the work at hand:

Paths – linear physical features in the world upon which travel occurs.

Path-networks – the conjunction of paths to path-networks.

Routes – linear patterns of (planned) movements.

R-path – those parts of a path-network that are demarcated by one route.

[29] The use of this terms in computer science is different (e.g., Werner et al., 2000).

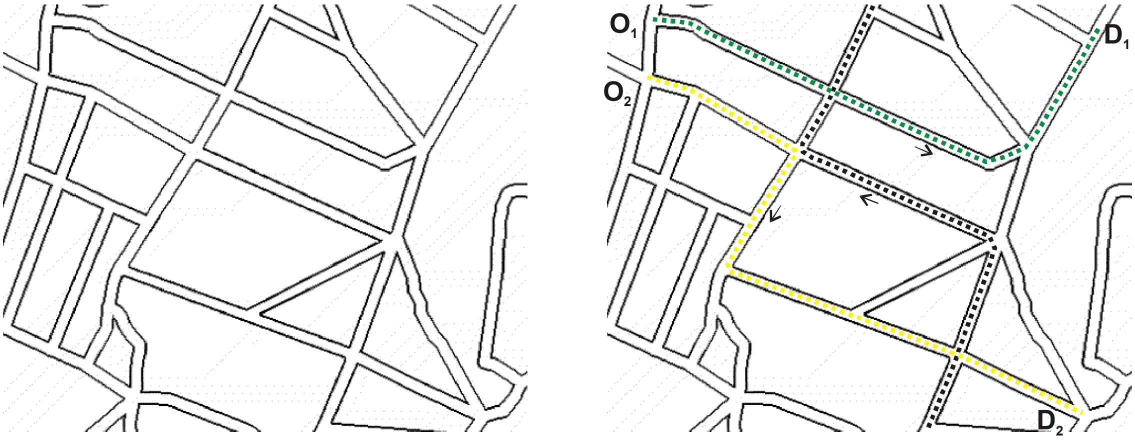

Figure 25. Differentiating between paths, routes, and R-paths. The left figure represents a path-network. In the right part of the figure, routes are drawn into the path-network that somebody has taken or plans to take. The routes induce corresponding R-paths.

3.3.2 Partitioning

Now that I have made the distinction between paths, routes, and R-path I will turn again to the question of what are the basic elements of path-networks essential for wayfinding and route directions. I will characterize general possibilities of partitioning path-networks. Note that this discussion refers to path and R-path and that the corresponding basic elements of routes are derived from these results.

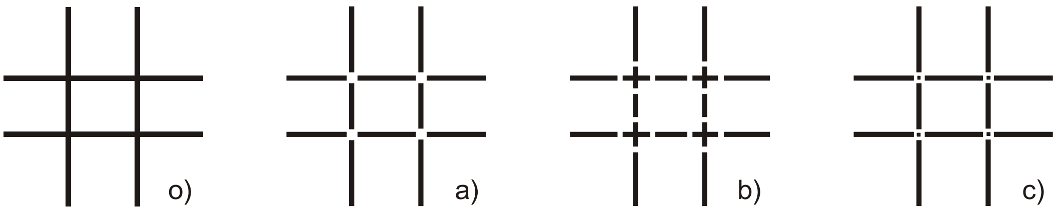

Figure 26. Three possibilities (a, b, c) of partitioning a path-network (o).

Figure 26 illustrates the subsequent discussion. For the sake of simplicity I look at path-networks consisting of simple linear entities that may stand for all kinds of linear entities in networks. Informally then, the partitioning processes and their results can be characterized as follows:

1. The first possibility (a) partitions a network (o) at points where two or more linear entities—paths—meet. This approach results in a set of segments that formerly were connected at their endpoints: the points of connection are not further specified. For wayfinding and route directions, this approach is inappropriate from a cognitive point of view, because the crucial function of the meeting points of segments has to be explicitly calculated. The ATKIS data model, for example, does not model intersections. This is also the case in most internet-based route planners, i.e. intersections are not individually modeled.

2. The second approach (b) is cognitively oriented, in the sense that the resulting entities have mental conceptual counterparts. It partitions a network (o) somewhat around points where two or more paths meet. This results in what I will call *branching points* that consist not only of an abstract point where the linear structures meet but also of parts of the meeting paths, preserving the characteristics, i.e. the structure, around a branching point. Structure refers to the number of branches and the angles between them. Branching points are connected via *path segments*, i.e. the linear entities that prevail between them. In this informal characterization, the starting points and endpoints of path segments are not further specified. This form of partitioning builds the basis for assigning the role of *decision points* to branching points, i.e. a distinct point where a decision regarding the direction to take is necessary. This approach fits a cognitive analysis best as revealed by human experimental studies (cf. Tversky & Lee, 1998, 1999; see section 2.4.3). Humans do not move like robots (i.e. reach a decision point, reorient, and move on) but conceptualize a decision point integrated into a movement, for example, *turn right at the next intersection*.[30] The resulting spatial structures correspond to human spatial concepts like intersections (section 2.4.3; toolbox by Tversky & Lee, 1999).
3. The third possibility (c) follows the approach of graph theory (see section 2.4.2), where the meeting points of linear entities are denoted as *nodes* (vertices) and the connecting linear entities are termed *edges* (arcs). Nodes, as well as edges, can be attributed with additional information, either concrete information, for example the length of an edge (i.e., the corresponding real world distance), or abstract information, for example, a scenic factor (0-25). In some cases, for example, in *RouteGraph theory* (Werner, et al., 2000), nodes model extended objects—places in their terminology. Places may have a complex structure, even though this structure is not specified in detail in their work.

Whereas the second approach is the one that is cognitively 'most' adequate the third approach has to be looked at as it is computationally the easiest solution and has possibilities for modeling cognitive approaches to route characterization (cf. Werner et al., 2000). This analysis has revealed the concepts we have to add to our basic vocabulary for wayfinding and route directions. Note that the only difference between a path and an R-path is that the R-path has endpoints. Therefore, I avoid to inflate the terminology by introducing for each path element a corresponding R-path element.

> **Path segment** – A path segment is that part of a network that lies between two branching points. By this definition it is left underspecified where it starts and where it ends exactly as the branching points comprise parts of the segments in between.

[30] Actually this is what wayfinding support is all about. The user of modern wayfinding support systems should be freed from the need to make time consuming decisions at decision points and instead arrive at a decision point with suitable knowledge to choose the right path.

Branching point – A branching point is defined as a point where three or more path segments meet.

With this introduction to basic elements of path-networks, I now take up the distinction between paths and routes again, and look at the consequences of the partitioning of path-networks that apply to routes. Superimposing routes on a path-network, for example (see Figure 25), keeping in mind the 2nd partitioning approach, yields the following results.

Corresponding to the partitioning of a network structure, a route can be partitioned into *route segments* and *decision points*. A route segment corresponds to a path segment but additionally has a direction, i.e. at one end we 'enter' a route segment, at the other end we 'leave' it. Decision points correspond to branching points but only in a broader sense. As the decision point belongs to a behavioral pattern, it has no structure like a branching point, i.e. it is an unbranched linear structure. It is only the location plus direction information. The location corresponds to the location of the branching point and the required direction information is induced by the structure of the branching point.

Route segment – A linear structure between two neighboring decision points. A route segment is directed, as it denotes traversing a path segment in a given direction.

Decision point – A location where direction changes along a route occur or are possible. A decision point must correspond to a branching point; at least three path segments meet. Decision points can be further distinguished into decision points where a change in direction is necessary (DP+) and those where the direction does not change along the route, (DP-). For example, *turn left* versus *keep going straight at the next intersection*.

Origin – The starting point of a route.

Destination – The endpoint of a route.

Routes lead from an origin to a destination in the case of a complete route, and from a decision point DP_n to a decision point DP_{n+1} in the case of route segments, where DP_n is passed before DP_{n+1} along the route. Therefore, a route enforces an ordering structure on concatenated path segments and distinguished points. In contrast, path segments without a route are not ordered.

To conclude, I summarize the terminology of wayfinding and route directions. There are two levels at which basic entities involved can be differentiated. These two levels are the following:

1. The level of the linear behavioral pattern, i.e. the actual movement through the environment or the planning of such a movement. The associated concepts are:
   - route
   - route segment
   - decision point
   - origin
   - destination
2. The level of the linear physical structures. The associated concepts are:
   - path
   - R-path
   - path segment
   - branching point
   - endpoints of an R-path induced by origins and destinations of routes

3.4 A Basic Grammar for Routes

In this section I develop a basic grammar for routes. The reason for applying a grammatical notation is to allow for a systematic of routes and route information. The identification of route primitives, i.e. terminals in the grammar, provides the basis for working out their combinatorial potentials. The results of this section also reveal what is needed to specify a wayfinding choreme route grammar, i.e. they clarify the research questions for the behavioral experiments in chapter 4. A second reason for applying a grammatical notation is conceptual transparency.

3.4.1 Analysis of Route Characteristics

In section 3.3 I defined the vocabulary of the wayfinding choreme theory to characterize routes and their embedding in spatial environments. To start with, I analyze routes as such to reveal their most basic characteristics. Starting with simple assumptions and subsequently adding more complex aspects provides a clearer idea of what the basic elements actually are and how they interact. This is also an acknowledged starting point for cognitive-scientific analyses, especially from a computer science perspective (Habel & Eschenbach, 1996).

Common to all routes as behavioral patterns, and route directions as instructions to behavioral patterns, is that they provide information for traversing an R-path—the concatenation of path segments induced by following or planning a route (see section 3.3.2)—from an origin *O* to a destination *D*. This means that along a route, each specified point, be it a point in a mathematical or in a modeling sense (i.e., a named location, a place, a spot, or a node) is traversed once in a given direction. Thereby, the route between *O* and *D* can be characterized as a linearly ordered structure (cf., e.g., Kulik & Eschenbach, 1999). If we further pursue this thought, we obtain a spatial structure that can be characterized as an oriented curve with the two endpoints, *O* and *D*, where the origin *O* is the starting point and the destination *D* is the endpoint (see Figure 27), and with intermediate points that obey axioms provided, for example, by Eschenbach, Habel, and Kulik (1999).

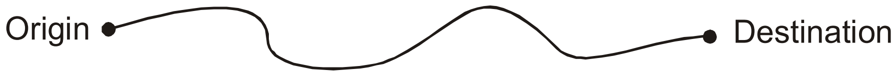

Figure 27. The most basic conception of a route is an oriented curve consisting of three basic parts: Origin, destination, and a route segment in between with a linearly ordered structure.

On the other hand, oriented curves are an abstract concept. They do not sufficiently express, for example, direction changes: "Since one objective is to identify general characteristics of linear structures in space, we develop a description of curves that does not make any particular assumptions about the properties of curves, that is to say, whether they are smoothly bent, have vertices, are rectifiable, etc." (Eschenbach et al., 1999).

Eschenbach et al.'s (1999) basic formal description is a valuable initial characterization for different kinds of applications. It also serves as a description of the general characteristics of routes. Their proposal, though, does not reflect all the aspects of everyday behavior. It encloses 'passive' transportation—such as a flight trip from Hamburg to Munich—while neglecting the actual travel to, within, and from the airports. It does not account for direction decisions[31].

Nevertheless, ordering information is **the** commonality of all routes. For routes, as a behavioral pattern embedded in space but also in time, this problem can be untied. Examples can be found in approaches on human cartography (e.g., Szegö, 1987) and human geography (e.g., Golledge & Stimson, 1997). The same place cannot be traveled twice at the same time (see Figure 28). Hence, a spatio-temporal behavioral pattern is always an unbranched, non-intersecting linearly ordered structure.

[31] Other problematic cases are: circuits, turning around, or loops.

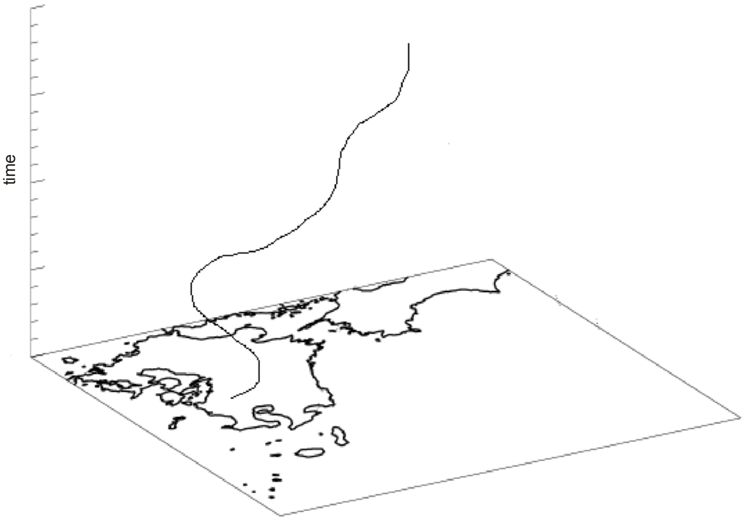

Figure 28. The basic characteristics of routes revealed by combining space and time. This Figure shows a trajectory. The z-axis is the time. Projecting this movement to the geographic space, the route would cross itself.

We normally expect during travel that we encounter places along the route where we have to make decisions. These decisions comprise a choice between at least two possible directions[32]. The two most general possibilities for decision points in street networks, where we have to decide between at least two directions, are decision points with direction change (DP+) and decision points without direction change (DP-) (Lovelace et al., 1999; Corona & Winter, 2001; Klippel & Tappe, 2001). This distinction is researched on in empirical studies (e.g., Denis, 1997; Klippel, Tappe, and Habel, 2003) and is further accounted for in the experimental design in chapter 4.

If we add the abstract concept of a decision point to the basic description of routes, we obtain two more elements, adding up to five necessary elements. These elements are the previously introduced origin *O* and destination *D* of a route, a decision point *DP*, and two route segments (rseg), i.e. a route segment between the origin and the decision point and a route segment between the decision point and the destination. In this first approximation, I will not specify the internal structure of a decision point induced by the underlying branching point. In the present context it suffices to introduce DPs as structuring entities for differentiating route segments, i.e. the one I am coming from and the one I am going to. Figure 29 depicts the basic route inventory. With this general description, we are in a position to characterize the most basic assumptions about route directions (cf. Denis, 1997; Kuipers, 1978). The ordering information on the

[32] Every point along a route could be seen as a decision point as we almost always have the choice of turning around, even with a car we could decide to stop and take the backwards gear. This is a very special situation and occurs mostly when people have lost their way. In this characterization I therefore neglect this case and focus attention on true decision points whose physical correlates are branching points (see section 3.3.2). In contrast, going backwards or turning, i.e. visiting the same spatial location twice (exceptions: circuits, round tours), is referred to as *pseudo decision points* if necessary.

route segments prevails, and in addition a precedence relation can be specified for the three explicitly named points, i.e. origin, decision point, and destination.

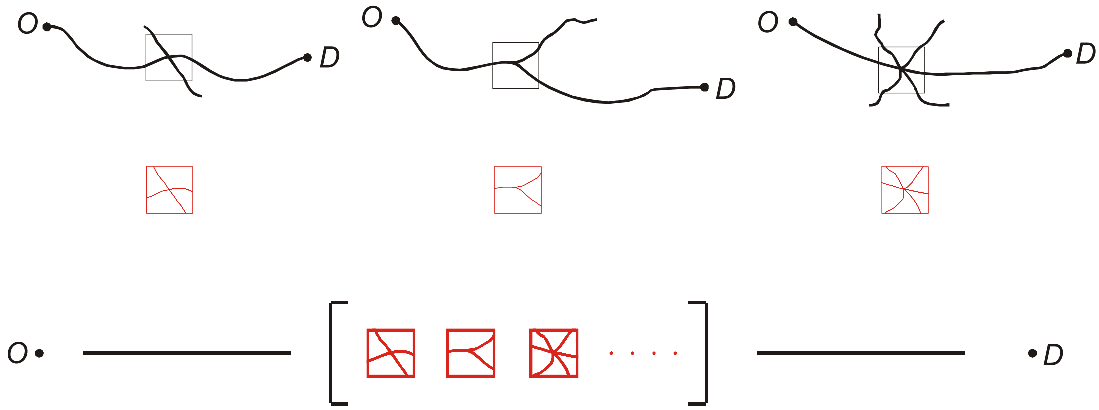

Figure 29. This figure depicts the first set of basic concepts necessary for the characterization of routes. A decision point is inserted into a route, dividing it in 2 parts, i.e. the one before and the one after the decision point. Hence, 5 elements are obtained: Origin and destination, the decision point, and two route segments.

Up until now, the characterization of basic route elements and their interaction has been rather informal. I proceed by defining a grammatical notation for the route characteristics. This allows for handling the combination of additional route elements as we encounter, for example, many decision points before we reach a destination. I continue starting off from the simplest assumptions to build up characterizations that are more complex.

Again, the basic route (<Route>) is composed of origin (<Origin>), destination (<Destination>), and route segment (<rseg>)

<Route> ::= <Origin>< rseg><Destination>

If we add a decision point (<DecisionPoint>), we also have to add another route segment (<rseg>). These two concepts together will be referred to as route part (<RoutePart>). The optional nature of this is indicated by square brackets.

<Route> ::= <Origin><rseg>[<RoutePart>]<Destination>

<RoutePart> ::= <DecisionPoint><rseg>

The pattern is the same for every new decision point, i.e. an additional decision point requires an additional route segment. We can add as many decision points as needed, hence, we can write

<RoutePart> ::= <RoutePart><RoutePart>

Note that the superordinate concepts, i.e. the nonterminals <Origin>, <Destination>, <DecisionPoint>, and route segment (<rseg>) in this characterization, are identical to concepts for the terminals, as the general characterization of routes remains on an abstract level. The 'terminals' are specified further in the next section and their instantiations are characterized, i.e. routes and their components are structurally described by paths. Therefore, I keep the semi-formal notation simple and I will not introduce any additional terms here (see also Figure 31).

3.4.2 Basic Route Characteristics Extended

The next step focuses on supplementary concepts needed due to the structural aspects of R-paths. As I already have identified decision points as crucial parts of route behavior (route planning, route directing, route following, etc.) I will now turn to the information that has to be provided at decision points. If we look at branching points as they occur in path-networks, we find all kinds of combinations, i.e. different numbers of branches and different angles between these branches. We therefore have to cope with all kinds of directional decisions we have to make during route following. One possible taxonomy of branching points is provided in the pictorial toolkit by Tversky and Lee (1999; see Figure 14). Another taxonomy that takes into account a finer granularity of angular information at decision points is provided by Casakin et al. (2000). The taxonomy by Casakin and coworkers is not meant to serve as a toolkit for route directions; it focuses on the schematization of maps per se. The toolkit by Tversky and Lee on the other hand explicitly serves to provide route directions. If we consider mental conceptualizations and analyze the state of the art on qualitative knowledge representation, we can assume that we can identify prototypical structures for decision points (see toolbox by Tversky and Lee, 1999 in section 2.4.3).

Therefore, the next element we have to determine in this grammar for route directions is the number of directional information units, i.e. the different types of branching points (intersections). The number of branches is used as a basic criterion for a taxonomic order, i.e. the concepts for 3-way intersections, 4-way intersections, 5-way intersections, and so on are introduced (cf. Figure 29).

The nonterminal concept <DecisionPoint> includes nonterminal concepts for different branching points, here referred to by <x-wayInt> where *x* is the number of branches.

<DecisionPoint> ::= <3-wayInt> | <4-wayInt> | <5-wayInt> | ...

The combinatorial possibilities of branches at intersections are nearly unrestricted. Therefore, a prototypical instantiation that determines terminal concepts is the next step. For further specification of the type of an intersection, i.e. the angular information provided by the branches of an intersection, the classification of Casakin et al. (2000) is employed as an example. As there are no natural language concepts for differentiating the various shapes of 3-way intersections, 4-way intersections, etc. according to an 8-sector model, the symbols they use are presented.

<3-wayInt> ::= |  | ...

<4-wayInt> ::= |  | ...

<5-wayInt> ::= |  | ...

....

We have to acknowledge the fact that not only branching points take various shapes but that route segments also vary in their appearance due to their isomorphic correspondence to path segments. Tversky and Lee (1998, 1999) differentiated between straight route segments and different but prototypical forms of curved route segments[33]. This can be expressed as follows:

<rseg> ::= <s-rseg> | <c-rseg>

Figure 30. The figure illustrates the distinction between straight and curved streets (paths segments).

Route segments can be followed by other route segments rather than by decision points when complex shapes must be represented. For example, a (c-rseg) is followed by another (c-rseg), or by a (s-rseg), or if a (s-rseg) is followed by a (c-rseg).

<rseg> ::= <c-rseg>[<c-rseg>] | <c-rseg>[<s-rseg>] | <s-rseg>
[<c-rseg>]

Summarizing, this inventory of routes embedded in path structures is built on prototypical assumption for the parts specified in section 3.3 and found in the literature. It leads to the following grammar for routes: G_{Route} = (N, T, P, S) where

N = {<Route>, <Origin>, <Destination>, <RoutePart>, <DecisionPoint>, <rseg>, <3-wayInt>, ...}

T = , , , ...

P = {<RoutePart> ::= <RoutePart><RoutePart>, <RoutePart> ::= <RoutePart><RoutePart>, ...}

S = <Route>

Figure 31 illustrates the discussion of the last two sections and shows the different levels of characterization, i.e. the route and the path level.

[33] In their pictorial toolkit they use the term ‘path segment’ (see section 2.4.3).

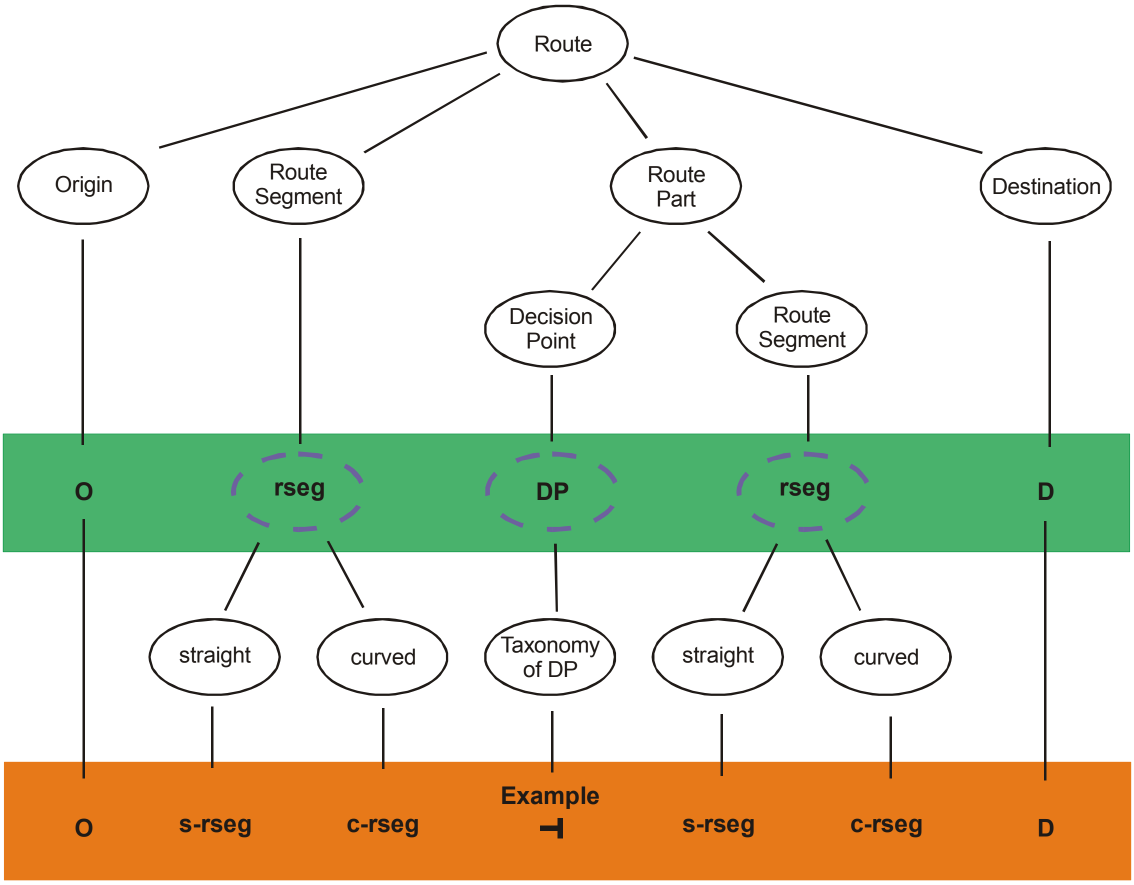

Figure 31. Illustration of essential parts of a route and path grammar. Green denotes the route level, corresponding also to an abstract characterization; orange indicates the path level, in this case route segments that vary in their appearance due to their isomorphic correspondence to path segments.

The two levels of characterizing wayfinding and route direction elements can now be related. To sum up:

- Decision points are vital parts of route directions.
- Decision points 'obtain' a structure as they coincide with branching points.
- Prototypes of intersections, as, for example, proposed by Tversky and Lee (1998, 1999) are not sufficient to characterize routes. The finer distinction of prototypical branching points adopted by Casakin et al. (2000) allows for a better characterization but also increases the number of basic elements: their taxonomy contains 34 different types of intersections. Both the work by Tversky and Lee, and the work by Casakin and his collaborators, focus on structural aspects of branching points (intersection) and not explicitly on the perspective induced by the route, i.e. the behavioral pattern.

The next section acknowledges this problem by discussing the distinction between routes and paths from a structural and functional perspective.

3.5 Structure and Function

What is the difference between thinking of an intersection per se and thinking of an intersection at which one has to perform a specific action? Ample research explains how humans conceptualize spatial information at different scales (see Montello, 1993) from general organizational–structural aspects (e.g., Stevens & Coupe, 1978) to small-scale characteristics (e.g., Evans, 1980; Moar & Bower, 1983). Mental conceptualizations can be applied to objects (e.g., an intersection), as well as to actions (e.g., *turn right at the next intersection*). Following Quine (1996), Zacks and Tversky (2001) argue that actions can be treated analogously to objects.

Wayfinding actions take place in environmental spatial structures that consist of objects and relations between objects. Hence, we can differentiate conceptualizations of objects and conceptualizations of actions. Moreover, the present work is concerned with the characterization and the representation of adequate spatial information in a spatio-analogical medium. Therefore, my focus is on spatial aspects of map-like representations. The following terminology will stress these aspects. With *structure* I refer to the object level, i.e. the spatial structure as physically present in the environment. In contrast, with *function* I indicate the conceptualization of route related actions in a street network. Action concepts in this restricted sense are termed I–wayfinding choremes. I–wayfinding choremes demarcate functionally relevant parts of the structure. This distinction is partially reflected in the differentiation between a route (see section 3.3)—denoting a behavioral pattern—and an R-path—denoting the corresponding physical structure. The important distinction between structure/function and R-path/route is: The functional perspective stresses the fact that the conceptualization of an action in the context of wayfinding and route directions demarcates parts of the physical structure.

Graphic representations are closer to structural aspects of path-networks because the representational medium shares constraints with the represented domain (Sloman, 1971, 1975; Palmer, 1978; Larkin and Simon, 1987). Linguistic expressions, on the other hand, are more flexible due to their higher level of abstraction in which spatial constraints are resolved. Whereas in graphic representations structural aspects play a great role, verbal expression are flexible to focus on functional aspects or structural ones. They are sparser due to their high level of abstraction and therefore they condense the relevant information. For example, *turn right at the intersection* provides sufficient information for the action that has to be performed at the next intersection whereas it does not go into detail about the structure of the intersection, i.e. the number of branches and the angles between them. While linguistic expressions thus offer many possibilities for referring to one spatial situation, this flexibility can cause problems because the underspecified spatial reference leaves structural details unexpressed.

Wayfinding choremes as a limited set of spatial models characterize and depict a variety of spatial situations. The wayfinding choreme model combines the advantages of the functional and the structural level. Functional means the conceptualization of a route related action in a street network that in turn demarcates parts of the structure. Essential elements of route directions comprise the identification of a critical point, plus the specification of turning (direction) information; for example, *turn right at the next intersection*. This enables a focus on abstract concepts of a piece of route and demarcates those parts of the structure that are most relevant—the path segment the wayfinder is coming from, and the path segment she is going to. The difference is that the wayfinding choreme remains the same, whereas the spatial structure into which it can be embedded varies according to different spatial situations. The surrounding spatial structure provides 'only' *context dependent landmark information*, i.e. a decision point relevant in the given context (the next intersection), and specifies the necessary direction information.

To sum up, the wayfinding choreme theory bridges the gap between the two general approaches to the conceptualization of route information—a structural and a functional approach; Figure 32 illustrates the perspective of the wayfinding choreme theory: a functional perspective in contrast to more structural perspectives discussed in Tversky and Lee (1998, 1999), Casakin et al. (2000), and partially in Werner et al. (2000). At the same time, it does not entirely rely on functional information but embeds unambiguous turning concepts (wayfinding choremes) into veridical path-networks.

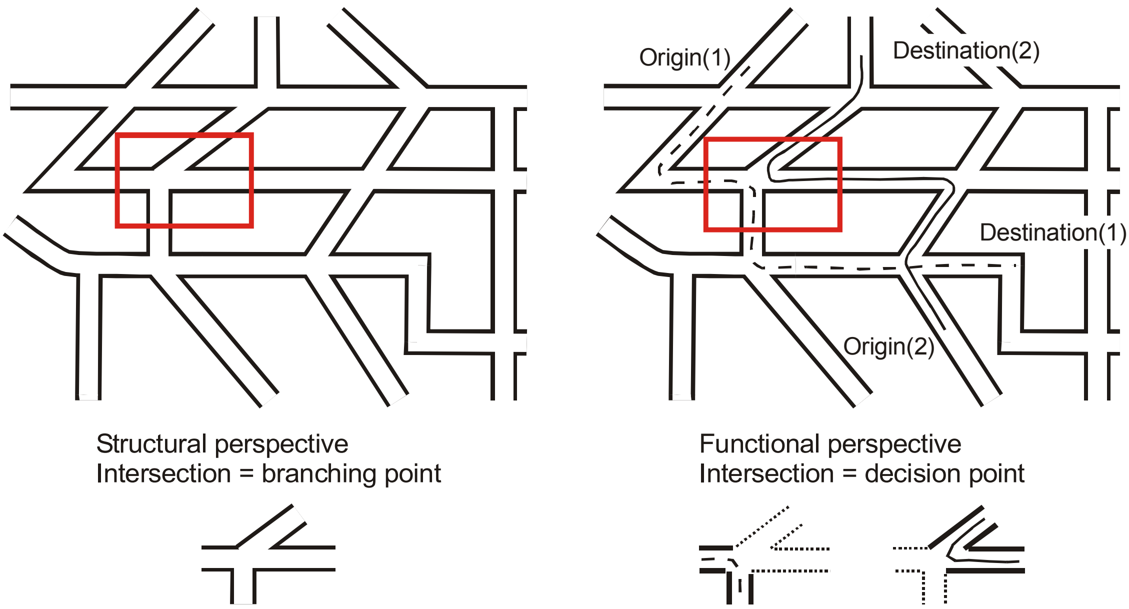

Figure 32. Functional and structural perspective. The left part illustrates the structural perspective (a paths-network; intersections are branching points). The right part of the figure highlights the functional perspective: Two routes (dotted and solid line) with origins (1, 2) and destinations (1, 2) assign different meanings to an intersection. The intersection becomes a decision point with functionally relevant parts demarcated by the routes (1, 2).

Structure – Denotes the layout of elements physically present in the spatial environment relevant for route directions and wayfinding. This comprises, for example, the number of branches at an intersection and the angles between those branches.

Function – Denotes the conceptualization of actions that take place in spatial environments. The functional conceptualizations demarcate parts of the environment, i.e. those parts of the structure necessary for the specification of the action to be performed.

I-wayfinding choreme – A mental conceptualization of a primitive functional wayfinding and route direction element.

E-wayfinding choreme – The graphical or verbal externalization of a mental conceptualization of a primitive functional wayfinding and route direction element, i.e., the externalization of an I-wayfinding choreme.

3.6 Outline of the Wayfinding Choreme Model

Following the argumentation of the preceding sections, I will now outline the basic model for map construction and route characterization following the cognitive conceptual approach to map construction. Figure 33 depicts its the basic components and the general procedure. The first two steps—spatial data on street networks and route planning—are necessary; route planning is a prerequisite for the work at hand but not a central topic. The partitioning of routes and paths, respectively, has been analyzed in section 3.3; the functional nature of wayfinding choremes has been discussed in section 3.5. The behavioral studies in the next chapter further elaborate this perspective. To this end, prototypical conceptualizations of direction (turning) concepts at decision points are specified that are necessary for the instantiation of graphic E–wayfinding choremes. Additionally, the combinatorial possibilities of wayfinding choremes and their interaction with additional environmental information is investigated. Chapter 5 then will develop further two major aspects: first, a route grammar based on wayfinding choremes as basic entities (terminals); second, how wayfinding choremes can be employed in a cognitively adequate way to present route information in a wayfinding context.

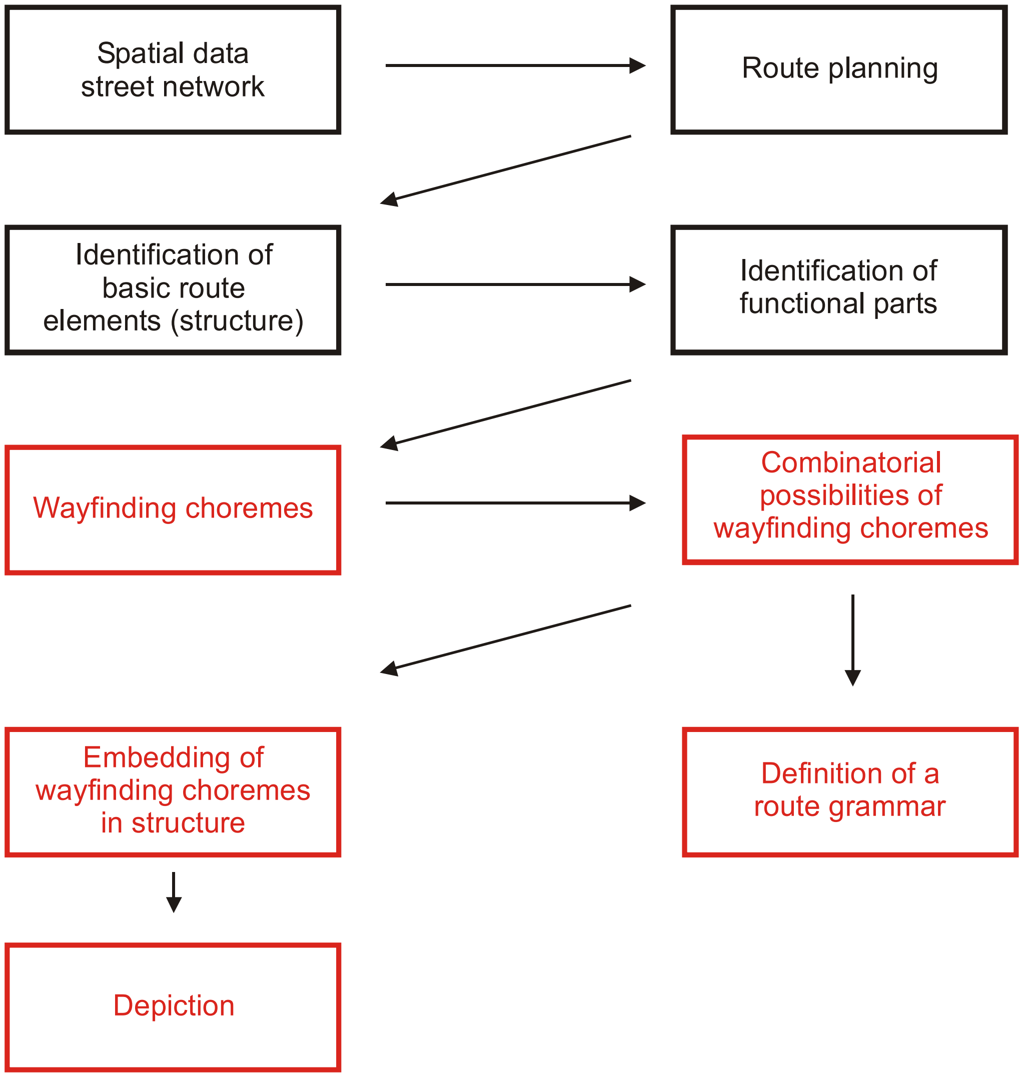

Figure 33. Outline of the components and the general procedure underlying the wayfinding choreme model. The red boxes denote parts that are further explicated in the next chapters.

It must be hard for humans, forever floundering through inconvenient geography. Humans are always slightly lost. It's a basic characteristic. It explains a lot about them.
—*Lords and Ladies*, by Terry Pratchett, 1992

4 Empirical Investigation

In the present chapter, three behavioral studies are detailed that provide further insight into the following three questions pertinent to wayfinding choremes:

- The conceptualization of direction (turning) information at decision points and their graphical externalization (study 1, section 4.3.1).
- The combination of wayfinding choremes to **H**igher **O**rder **R**oute (**D**irection) **E**lements (HORDE) by means of chunking (study 2, section 4.3.2).
- The importance of placing landmarks at decision points with a direction change and some further chunking principles (study 3, section 4.3.3).

Before I report on these studies section 4.1 provides the necessary background from the psychological literature.

4.1 Review of Behavioral Experiments

For the purpose of the work at hand and according to the three questions raised above, the review of behavioral experiments is grouped into three sections. Section 4.1.1 discusses aspects of the mental conceptualization and representation of direction information at decision points. Section 4.1.2 illustrates work on chunking route direction elements, and section 4.1.3 defines and evaluates landmarks with respect to routes and wayfinding. Additionally, the segmentation of routes is briefly discussed in section 4.1.4.

4.1.1 On Processing Angular / Direction Information

The processing and representation of angular / direction information is essential for human spatial cognition and especially for wayfinding (e.g., Sholl, 1988; Montello & Frank, 1996; Montello, Richardson, Hegarty, and Provenzy, 1999; Waller, Montello, Richardson, and Hegarty, 2002). A growing number of experimental results (e.g., Denis et al., 1999) indicate that route directions and wayfinding basically consist of making direction choices at decision points. Pursuing this line of thought, wayfinding can be characterized as: following a route segment up to a decision point, making a directional choice, following the next route segment up to the next decision point, making a directional choice, and so on. As shown in section 3.3.2 decision points can be operationalized as belonging to two main categories, i.e. decision points with a direction change (DP+) and decision points without a direction change (DP-) (see Figure 34). The question arises, how do humans conceptualize directions at decision points, especially at (DP+)? What are prototypical direction (turning) concepts and what do their graphical externalizations look like?

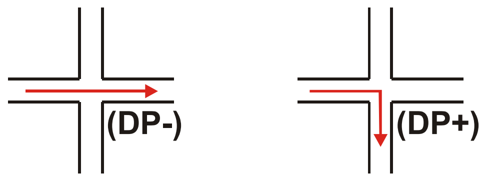

Figure 34. Decision points with and without a direction change.

First, humans do not conceptualize every direction that our body potentially could turn to, i.e. infinitely precise direction information. For most situations, qualitative information of direction—in the sense of a small number of equivalence classes—is sufficient. In their discussion of the computational modeling of this phenomenon Montello and Frank (1996) suggest the term *qualitative metrics*. Especially in city street networks, which constrain the environment, directional choices of exact angular information are rarely necessary. Various studies show that angular information in city street networks—as well as in geographic space in general—is conceptualized and remembered qualitatively by humans (e.g., Griffin, 1948; Byrne, 1979; Tversky, 1981; Moar & Bower, 1983; Sadalla & Montello, 1989; May & Wartenberg, 1995). Verbal route directions reflect this qualitativeness. Precise, i.e. very fine grained, direction information is exceptional (e.g., Denis, 1997; Allen, 2000). If we take the perspective of conceptual spatial primitives the question arises how many different categories of directions are necessary, and how many categories humans employ. Additionally, we can pose the question whether there are prototypical turning concepts.

Evans (1980; see also Griffin, 1948) reported three major strategies that occur in representing directional information mentally. These aspects are (see Figure 35):

- straightening curved paths,
- squaring oblique intersections, and
- aligning nonparallel streets.

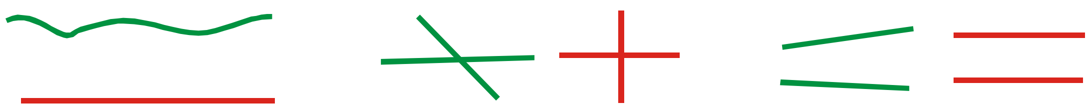

Figure 35. On processing angular / direction information (green - environmental layout, red – mental representation (simplified)).

People rely on this schematized information when they wayfind without additional help. Therefore, I conclude that the aspectualization at work in mentally representing environmental knowledge is efficient. From the viewpoint of conceptual map construction, it also provides input for representing these aspects of environmental knowledge externally, either graphically (e.g., in sketch maps, schematic maps, and wayfinding chorematic maps[34]) or verbally (e.g., in spatial terms).

Evans' second observation reveals a characteristic of the mental representation of direction information at intersections: Angular information between path segments is distorted towards 90°. The importance of this constraint on representing angular information at intersections is stressed in further research. Tversky (1981), for example, reports on prototypicalization that represents even 60° angles as 90° angles. This view has its strongest commitment in the already discussed toolkits (Tversky & Lee 1998, 1999; see section 2.4.3). In the pictorial toolkit only rectangular intersections are employed.

Even though a perpendicular angle framework plays an important role in the schematization of spatial knowledge, it is not the end of the story (Montello, 1991). Montello's experiments indicate that given a regular environment participants are capable of pointing to objects in the environment or to oblique cardinal directions (Northeast) with relative accuracy. Additionally, Sadalla and Montello (1989) conducted detailed experiments testing participants' ability to perceive direction changes during locomotion. The participants had to walk short routes with one change in direction. The angle of the turn was varied in 15° steps (left and right). The participants had a restricted field of vision. At the end of the route they made three inferences: the original direction of traveling, the angle of the turn, and the direction towards the origin. These judgments were measured with a pointing device. The results of this experiment confirmed the importance of the right angle framework. Traversed angles close to 0°, 90° and 180° from the direction of the initial forward motion were the most accurately remembered and the least disorienting directions. On the other hand, the experiments show that participants perceive and represent various degrees of direction change even though with less precision and with the tendency to distort them towards increments of 90°. Sadalla and Montello did not find support for a claim made by Rosch (1975) that diagonals are strong reference axes for judging angles.

The only approach I have found that claims that directions at intersections are represented as increments of 45° is work by Chown (1999). He does not further detail the foundation of this assumption; he quotes Byrne (1979) as an example for experimentally validating the 45° increment. Yet, Byrne does not explicitly make this assumption.

The 90° framework does not work for most naturally occurring routes except for some North American downtown areas (cf. Agrawala & Stolte, 2001). Hence, I report

[34] Our strategies to wayfind through the spatial environment strongly depend on the interaction of the wayfinder with her actual environment, especially as the environment provides information and structure(s) that enable wayfinding. This perspective provides further support for representing aspectualized knowledge in maps: information that the environment offers can reduce the amount of information necessary in the map.

findings that establish the representation needed for intersections. Important is the research by Montello and Frank (1996) who relate formal approaches on qualitative spatial reasoning to experimental psychological studies. They stress the amazing fact that qualitative models seldom rely on experimental results.

> "It must be noted that AI researchers in general, and qualitative spatial modelers in particular, are not motivated exclusively or even primarily by a desire to simulate human knowledge and behavior accurately. In many cases, they may simply wish to design an intelligent system that works. Such an approach may only implicitly or incidentally produce a model of human spatial thought, if at all." (Montello & Frank, 1996).

In order to overcome this shortcoming, they reviewed the experimental work by Sadalla and Montello (1989) in detail and ran various simulations on this data to render current qualitative models more precise. In a first simulation, they showed that an 8-proportional sampling is superior to 4-single, 8-single, and 4-proportional samplings. However, even the 8-proportional model failed to reproduce some previous empirical results, for example, a minimal variability near orthogonal turns and maximal variability at oblique turns. Therefore, in a second simulation, they adopted the size of the sectors. They found that differently sized sectors fit empirical results best; in their case: minimal variability near orthogonal turns, maximal variability for oblique turns, and greater variability for acute turns. They also found that the exact size of the sectors is not critical as long as orthogonal sectors are smaller than the oblique ones (see also section 6.3.3.3).

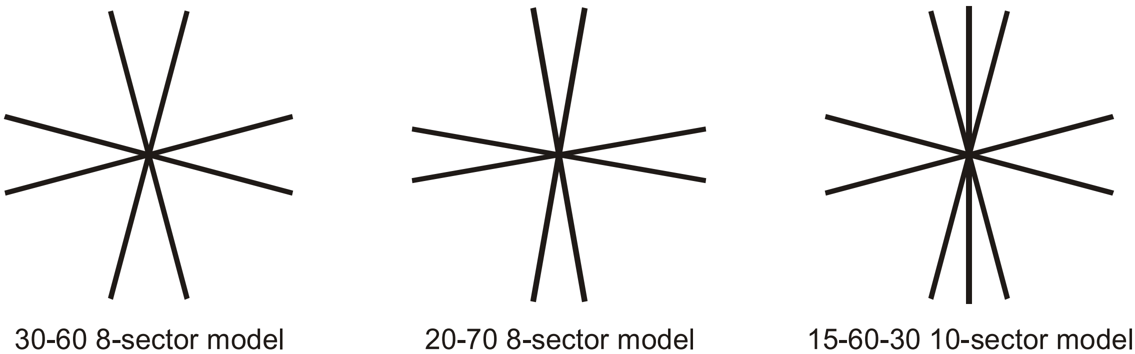

Figure 36. Heterogeneous 8- and 10-sector models used by Montello and Frank (1996). The numbers, for example, 30-60 indicate the size of the sectors in degrees.

Whereas the research by Montello and Frank (1996) is intended to model empirical evidence for direction knowledge, further work is needed that sheds more light on the conceptualization of direction information. The most critical aspect in the work of Montello and Frank is the maximal variability for oblique turns. Even though the diagonals may be the weakest in our memory we rely on them in several spatial situations and an appropriate modeling is needed. Consequently, I proceed with further work on the 45° constraint.

Winter (2002a) states that, depending on the network structure, different formalizations are necessary. For a rectangular grid structure, directions such as *turn left* or *turn right* may be sufficient whereas for other kinds of network structures (cf. Arthur & Passini, 1992) a more detailed categorization becomes necessary. The 45° constraint has been adapted, for example, in map schematization processes reported in Casakin et al. (2000). Their study showed that participants are able to schematize spatial information under the 45° constraint resulting in a schematic map. The 45° constraint also provides the basis for various studies and it supports qualitative systems that make use of direction information (see Figure 37; see section 2.3.3). The 45° constraint is the next logical step after the 90° constraint to evenly partition space from an egocentric perspective (Raubal, 2001; von Wolff, 2001; Baus, Breihof, Butz, Lohse, and Krüger, 2000). But, for route directions the 45° constraint has not been validated even though it is often assumed.

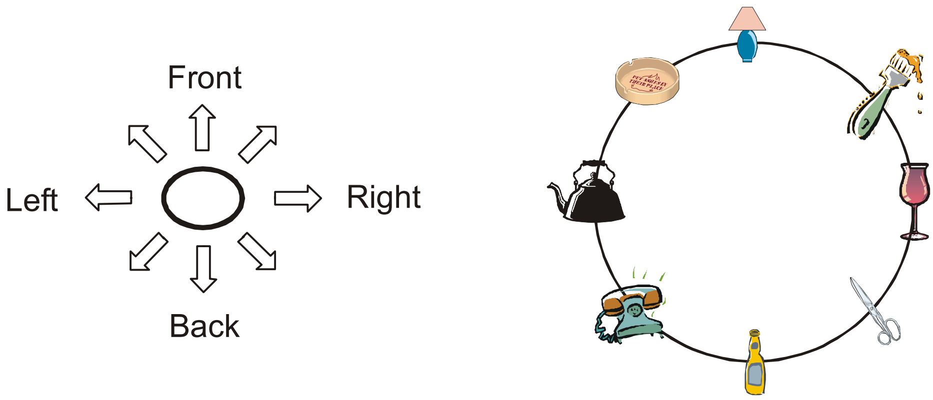

Figure 37. 45° increments used in computational models (Raubal, 2001) and in psychological experiments on direction memory for objects from an egocentric perspective (von Wolff, 2001, symbols changed).

4.1.2 On Chunking Route Segments

Chunking processes can be applied to primitive route elements. Allen and his collaborators (Allen, 1981; Allen, 1988; Allen & Kirasic, 1985; Allen, Siegel, and Rosinski, 1978) have carried out major research in this area. They investigated various effects on organizing route knowledge. The main research question of their work concerned the difference between the acquisition of route knowledge from logically sequenced and scrambled route presentations. Within this approach, they made essential findings concerning the general structuring, or better segmentation, of route knowledge. In one experiment (Allen et al., 1978) they differentiated between locations of high and low landmark potential along a route. They regarded locations with high landmark potential as effective structuring elements for route knowledge. At these locations routes were partitioned on a coarser level of granularity.

In another experiment (Allen & Kirasic, 1985) they explicitly asked participants to segment a given route by designating the boundaries of the segments. In this latter paper they equated chunks and segments. It is worthwhile to rethink this terminological decision. A chunk in my conception is made up from individual entities that are grouped together under a given perspective or according to grouping principles. A segment comes into existence the other way round. First, an entity exits as a whole; afterwards it is split into pieces, the segments. The criteria Allen and Kirasic give for segmentation are rather general and the route segments are associated with places: a wooded park, a college campus, a block of fraternity houses, a street under construction, and blocks of large single-family dwellings. Likewise obvious were the separators of these segments: a small parking lot, a heavily traveled street, a change of the kind of building along the street, the beginning of street construction, a major thoroughfare, and 90° turns. Their findings provide support for the proposition that information gathered while traversing a route is partitioned. Their results on distance estimates show that these partitioning strategies belong to our cognitive reality: When subjects acquire route knowledge from a route that is constituted by different route segments, distance estimates tend to be influenced by apparent boundaries between these segments. "Judgments of distances to environmental locations across segment boundaries tend to be exaggerated, and estimated-to-actual distance functions based on estimates to locations in two adjacent segments tend to be much steeper than do functions based on estimates to locations within a single segment." (Allen, 1988, pp. 183-184).

An additional source for the identification of chunking principles is language data. Especially verbal route directions provide evidence for the chunking of route elements. Route directions differ from other kinds of spatial discourse in a prominent way. For language production, especially in discourse on spatial configurations, it has long been recognized that a problem exists with the linear organization of spatial information, i.e. how two- or three-dimensional information is organized into a linear sequence. This is known as the *linearization problem* (Levelt, 1982). The language producer is forced to decide among various choices and many possibilities which results in an additional cognitive load (e.g., Levelt, 1982; Denis, 1996). In contrast, for verbal route directions it is stated that the linearization problem does not exist as a route is already a linear structure:

> "The first remarkable feature of route directions is that they offer a type of spatial discourse in which the linearization problem is not crucial. The object to be described—the route—is not a multidimensional entity but one with an intrinsic linear structure. The discourse simply adheres to the sequence of steps to be followed by the person moving along the route." (Denis et al., 1999, p. 147)

Therefore, it may seem that the subject of organizing route information is superfluous as an intrinsically linear structure has simply to be transferred into another linear structure. Yet, it is evident by thinking of routes and the great number of objects that are potentially available for verbalization that different organizational principles interact (see section 4.1.2; Allen, 1997, 2000; Denis, 1997). For example, Daniel and Denis (1998, p. 47) state:

> “[...] friendly route descriptions are generally expected to provide their users with advance information by listing the **main nodes or places** that are to be connected by the route segments." (Emphasis by the author)

Additionally, this topic is established as central in recent investigations in cognitive linguistics. Tappe (2000) acknowledged as one major goal of research on language production the identification of speaker preference regarding the ordering of features along routes. She made the important observation that the question what speakers regard as a natural order can be answered only with respect to a given context.

> "Demzufolge [nach dem Linearisierungsproblem von Levelt] besteht eine zentrale Konzeptualisierungsaufgabe während der Sprachproduktion darin, in der zu beschreibenden Struktur eine natürliche Anordnung aufzudecken und diese bei der Verbalisierung heranzuziehen.
> Jedoch ist das Konzept der natürlichen Anordnung äußerst vage, so daß ein wichtiges Ziel der Sprachproduktionsforschung darin besteht, zu ergründen, welche Anordnungen von natürlichen Sprechern präferiert werden." (Tappe, 2000, p. 71)

> “Accordingly [with respect to the linearization problem proposed by Levelt], the central conceptualization task during language production is the following: To detect a natural order in the to-be-verbalized structure and use it in verbalization. The concept of ‘natural order’, however, is extremely vague. Thus, it is an essential goal of language production research to investigate which kinds of ordering are preferred by natural speakers.” (Translation by author)

4.1.3 On Representing Landmarks

Landmarks are defined as spatially located objects that somehow stand out from the multitude of information environments provide (e.g., Presson & Montello, 1988; Klippel, 2002; Sorrows & Hirtle, 1999). Landmarks are an integral part of spatial cognition in many ways. In the basic classification of kinds of spatial knowledge—landmark, route, and survey knowledge—they are the information that is first acquired according to the original model by Siegel and White (1975). Upon them spatial knowledge crystallizes, they function as anchor points by structuring and focusing the information we gather from the environment (Couclelis, Golledge, Gale, and Tobler, 1987), and we use them in interaction with the environment. Besides their general role in organizing spatial knowledge, they function as important markers along routes. They partition routes into segments (according to Couclelis, 1996), demarcate decision points (Ward, Newcombe, and Overton, 1986; Lovelace et al., 1999), or, ascertain that someone is following the correct route (Appleyard, 1970; Presson & Montello, 1988; Blades & Medlicott, 1992; Deakin, 1996). Hence, their importance in route directions cannot be overestimated: "Siegel and White (1975) similarly [to Lynch] argued that landmark knowledge is a necessary condition for ‘way finding’ to occur: landmarks are described as the strategic foci to and from which an individual travels." (Sadalla, Burroughs, Staplin, 1980, p. 516).

Whereas the leading notion of landmarks requires them to be salient with respect to their surroundings, i.e. they have to be prominent by their features (visually, cognitively, culturally, or socially), landmarks along a route dispense with less outstanding characteristics. They acquire their individual meaning only through traveling along a particular route in a particular direction; Routes comprise *context dependent landmarks*. For example, the instruction *turn right at the third intersection* only makes sense when it is part of a route direction and the wayfinder has knowledge about her current location and orientation. In this case then, the intersection—not necessarily an outstanding environmental feature—functions as a landmark, i.e. it becomes a distinguishable element of the environment. This view is seldom expressed explicitly in the literature (for an exception see, e.g., Cohen & Schuepfer, 1980).

Hence, for route directions the broader definition of a landmark has to be chosen, that counts intersections as landmarks, too. Additionally, as there are not only landmarks at decision points but also along the route, the results of the segmentation process also would vary with respect to the number and the location of landmarks present. Herrmann, Schweizer, Janzen, and Katz (1998) and Schweizer, Katz, and Janzen (2000) acknowledge this fact by introducing two concepts, i.e. *Wegemarken* (*pathmarks* or *waymarks*) that are along one's way, in between decision points, and *landmarks* that actually demarcate turning points (see also section 5.1.2.3). The general notion also fits with a distinction made by Daniel and Denis (1998, p. 46) into two basic sets of actions that exist in route directions, i.e. *progression* which is the movement along a route, and *reorientation*. If necessary, I will use this distinction in the following.

Recently, there have been approaches on automatically identifying landmarks (Raubal & Winter, 2002; Elias & Sester, 2002, 2003). The task specific focus of maps and their cognitively adequate on-the-fly construction will greatly benefit from this line of research.

4.1.4 On Obtaining Route Segments

Route segments are part of route directions (Werner, Krieg-Brückner, Mallot, Schweizer, Freksa, 1997; Werner et al., 2000). The most basic assumption for obtaining a route segment is that it is bounded at decision points (*places* in the terminology of Werner et al., 2000; see section 2.4.2), i.e. those points along the route that correspond to branching points. This can be gained partially from analysis of verbal route directions (e.g., Habel, 1988; Denis, 1997) as well as from more computationally oriented approaches (e.g., Werner et al., 2000). Couclelis (1996) offers a slightly different view that route segments are demarcated by landmarks. In this case the problem emerges: What counts as a landmark (see section 4.1.3)? In this line of argument, bearing in mind also the distinction between pathmarks and landmarks, the question has to be answered if the segmentation should take place at pathmarks and landmarks or only at landmarks which would result in quite different sets of route segments.

4.2 Remaining Open Questions

The review of behavioral experiments showed that there are answers to the questions raised in the work at hand: the conceptualization of directions (turns) at decision points, how route segments can be obtained, and the role of landmarks for organizing route knowledge. Nevertheless, there is not enough information for the functional modeling context of this work, i.e. for wayfinding choremes and their employment in route characterization. The following topic areas need further research:

- There has been some work on applying a 45° constraint to spatial reasoning and to the design of schematic maps. Yet, there is little research relating this question to route directions and to their functional characterization. If we assume that a 45° constraint is a sensible assumption for the specification of wayfinding choremes, the questions raised at the beginning of this chapter have to be answered: How do people conceptualize directions at decision points in a route direction task? What are prototypical turning concepts and what do their graphical representations look like?
- The discussion of paths and routes, of structure and function, and of objects and actions revealed an important set of distinctions in research on route directions. A question that has to be answered is how this set of distinctions affects the specification of wayfinding choremes and, in a next step, the characterization of routes and their application to the construction of maps. In other words, does a functional perspective influence the specification of primitive route elements, i.e. wayfinding choremes, in opposition to a structural perspective?
- If wayfinding choremes are specified as the primitive functional elements in wayfinding and route directions in a street network, the next question concerns the possibilities of their chunking. This is important for two reasons: First, it is the basis for a further specification of the wayfinding choreme route grammar that is developed in the present work; second, it will influence the presentation of route information as the focus is on cognitive adequacy. In the present context this means that chunks of information according to cognitive principles will be applied to route characterization and map construction.
- One last aspect concerns the influence of landmarks on the conceptualization of route direction elements. Whereas this has been proposed for the syntax, semantics, and pragmatics of landmarks (Raubal & Winter, 2002) it has not been accomplished yet from the perspective of locational spatial conceptualization.

4.3 Wayfinding Choreme Studies

The studies were conducted by the author and some collaborators at the Universities of Hamburg, Santa Barbara (UC Santa Barbara, California), and Stanford (California). The focus of the studies was on ecological validity of the experiments. The results are integrated to the modeling context of this work (see chapter 5). The applied methods—sketch map drawings, verbalizations (route directions), and memory tasks—have found acceptance in the psychology community (e.g., Blades, 1990; Huber & Mandl, 1994; Mark, Comas, Egenhofer, Freundschuh, Gould, and Nunes, 1995; Tversky, 1999). The mixture of methods is judged fruitful especially in complex areas like human map interaction (Bollmann, Heidmann, and Johann, 1997). I intend to stick to some established organizational features to report on psychological experiments (American Psychological Association, 1999).

Three studies have been set up. In the first study (section 4.3.1), the conceptualizations of turning directions at decision points are analyzed by employing sketch map drawings. I use this method because the medial constraints of sketch maps are equal to the medial constraint of maps. Furthermore, sketch maps of route directions are supposed to have the same underlying abstract mental concepts as verbal route directions (Tversky & Lee, 1998; 1999). From this study the wayfinding choremes will be derived. The second study (section 4.3.2) focuses on the chunking of primitive route elements, i.e. wayfinding choremes. By juxtaposing static and dynamic presentation of route information, the question of different chunking principles is elaborated. In the third study (section 4.3.3), the importance of landmarks at decision points with a directional change (DP+) is analyzed by juxtaposing again static and dynamic, and additionally a mixed presentation mode.

4.3.1 Study 1: Conceptualizing Directions at Decision Points

Based on study 1, I analyze turning concepts at decision points and elaborate on the distinction between the structural and the functional perspective. Tversky and her coworkers (1998, 1999, and 2000) propose that common conceptual structures (see section 3.1), underlie both verbal and pictorial route directions. They advocate two toolkits for route directions containing primitive elements that establish a basic set for each of the two forms of external representation (see section 2.4.3). They emphasize that the semantic and syntactic correspondences of these toolkits can be used to translate between them, i.e. the verbal and the graphic elements map onto one another (Tversky & Lee, 1999).

An analysis of the two toolkits together with considering general differences between the two forms of representation, leads me to challenge this assumption. At least in the current state the relation between the two toolkits is not obvious. First, if we look at the two toolkits from the distinction between structure and function, we find that the pictorial toolkit stresses the structural aspects. More precisely, the pictorial toolkit primarily contains path elements—branching points and path segment. Aspects of the route are superimposed by arrows, for example, which path segment should be taken at a branching point. In contrast, the verbal toolkit stresses route aspects. Here, most elements are turning concepts such as TURN LEFT, whereas the majority of structural aspects are left underspecified. Second, a further comparison of the two toolkits reveals an important distinction between verbal (propositional) and graphic representations. Visualizing spatial information always requires choosing **one** depiction, which is rendered specific (given specific spatial coordinates/features) in its externalization on a two-dimensional, spatio-temporally fixed representational medium. The propositional character of language frees the verbal toolkit from this requirement. In a verbal route direction like *turn right at the star shaped intersection* no commitment has to be made to the structure of the branching point. The number of branches and the angles between branches are left underspecified.

A more general criticism could be raised but this one focuses on a different topic that is not handled intensely in the present work and is only mentioned for matters of completeness. This concerns the general question whether linguistic concepts are identical with mental concepts or not. A discussion of this problem can be found, for example, in Knauff (1997) and in Wiese (1999). In the psychological tradition this problem is seldom discussed (cf. Engelkamp, 1991). Tversky and Lee actually avoid this discussion as they state that verbal and graphical route directions are grounded in the same conceptual structure. I agree with them on this claim.

As decision points are regarded as the most important aspects in route directions (Denis, 1997; Allen, 1997) I will focus on them in the following. One main question is, how can we represent functional aspects in pictorial representations more directly.

In chapter 3, I have discussed the distinction between structural aspects of a spatial situation as opposed to functional aspects of conceptualizing a behavioral pattern or parts of it while following or planning a route. Rethinking the approach of turning concepts—especially for pictorial route directions—by this distinction poses the question whether the structure or the functional aspects are treated as the invariant in mental conceptualizations. In other words, is the configurational information of a branching point or the conceptualization of a turning action that demarcates parts of the branching point the prototypical element?

The structure of a prototypical intersection seems to be evident, i.e. two paths meeting at a right angle. This concept, however, is invalidated in a variety of situations, for example, when an uneven number of branches occurs like in the case of a 5-way intersection; when many branches have to be arranged (e.g., a 6-way intersection), or when the provided concept is underspecified, like in the case of star-shaped intersections.

Thinking about the complications to conceptualize these spatial structures and bearing in mind the proposed functional perspective leads to the following questions: First, does more attention need to be assigned to functional aspects especially in the graphic representation of route information? Second, what are prototypical functional primitives and which instantiation is needed if they are represented in a map-like medium? The hypothesis offered in this section is that mental conceptualizations rely on functional prototypes of turning concepts and not on structural concepts for branching points.

4.3.1.1 Methods

4.3.1.1.1 Participants

19 participants volunteered for the study, 8 female and 11 male. They were native German speakers between the ages of 20 and 33, most of them holding an academic degree. They did not receive payment for their participation.

4.3.1.1.2 Design

Each participant constructed 42 individual drawings of a list of spatial expressions. Either these spatial expressions denoted general spatial concepts important for route directions, like *intersection* (*Kreuzung*) or *turn right*, or they were actually parts of route directions like *at the star shaped intersection you turn right* (*an der Sternkreuzung biegst Du rechts ab*). The verbal spatial expressions were systematically varied according to different kinds of intersections, for example, 3-way or 5-way intersections, and to prototypical directions covering most of the actions required at decision points found in route traveling in outdoor networks on an average level of detail. These functional aspects, i.e. the conceptualized actions to be taken at decision points, were chosen from direction models of qualitative spatial reasoning (e.g., Frank, 1992; Hernandez, 1994; Raubal, 2001). According to an 8-direction model seven turns can be individualized, excluding the 'going back' concept. The functional concepts are: SHARP RIGHT (scharf rechts), RIGHT (rechts), HALF RIGHT (schräg rechts), STRAIGHT (geradeaus), HALF LEFT (schräg links), LEFT (links), SHARP LEFT (scharf links). STRAIGHT, RIGHT, and LEFT. They are referred to as *basic (turning) concepts*, when modified by 'sharp' or 'half' they are referred to as *modified turning concepts*. The directions were pretested to see if they were understood by the participants.

The six concepts that actually require a direction change were tested for every kind of intersection, i.e. 3-way (3-er Kreuzung), 4-way (only referred to as intersection (Kreuzung)), 5-way (5-er Kreuzung), 6-way (6-er Kreuzung), and star shaped (Sternkreuzung). The STRAIGHT (geradeaus) concept was only tested for the 4-way intersection (Kreuzung) and the 6-way intersection (6-er Kreuzung). Additionally, the participants obtained written expressions for route direction concepts: INTERSECTION (Kreuzung), TURN RIGHT (rechts abbiegen), STRAIGHT (geradeaus), or *turn right at the 3rd intersection* (an der dritten Kreuzung rechts).

4.3.1.1.3 Material

The participants were provided with 44 single sheets of paper. The first page carried general instructions. Each of the following pages had one spatial expression printed on the top margin of the page leaving the rest of the page as drawing space. The last page contained a questionnaire on general participant information.

4.3.1.1.4 Procedure

Participants provided a graphical representation, i.e. a drawing, for each spatial expression within the space supplied resulting in 42 single drawings on 42 pages. They could pursue the task in a self-paced manner and were unrestricted regarding orientation and scale.

4.3.1.2 Results

The main result I will focus on is evidence for the distinction of functional and structural aspects of route directions and of people's conceptions of turning concepts at decision points. Further results are provided as they add insight to mental conceptualizations of route direction elements or elaborate the functional / structural distinction. Some examples of the participants' drawings are depicted in the following Figures[35].

Some general remarks: As the study is not meant to test the participants' ability to differentiate between left and right, these errors were not counted as long as the turning concept was right. Different conceptions of the same intersection are not accounted for either. This is the case, for example, when a participant drew a 5-way intersection with 6-branches.

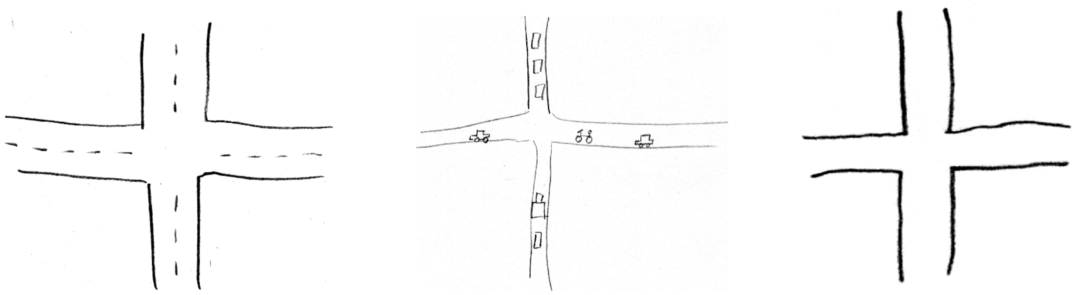

Figure 38. Drawings of the concept of an INTERSECTION.

The prototypical drawing of an intersection as a *structural concept*, the participants received the expression *intersection*, meets the expectations entirely, i.e. a 4-way intersection where the branches join at a right angle (see Figure 38). This prototypical concept is also adhered to when the route direction provided one of the three *basic (turning) concepts* at a 4-way intersection: TURN RIGHT, GO STRAIGHT, and TURN LEFT. 84.2% of the participants followed this scheme for the TURN RIGHT concept, 84.2% for the TURN LEFT concept, and 100% for the GO STRAIGHT concept[36].

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[35] The depictions are scanned from the original material and touched up to enhance contrast. They are also, to different degrees, reduced in size to fit the current format. These adjustments do not change the interpretability.

[36] Some exceptions in more detail: Participant 2 used the 'prototypical' concept of an intersection throughout his (4-way) intersection drawings without varying it, no matter what kind of action was required at the intersection. Participant 4 ignored the difference between the basic concept, i.e. *left* and *right*, and the *sharp* modification resulting in 'identical' depictions. Participants 8 and 9 used 3-way intersections for the basic concepts *left* and *right*. One participant drew only the functional concept, i.e. an E–wayfinding choreme.

When the action required at a 4-way intersection became more specific, i.e. the basic turning concepts were modified either by *sharp* or *half*, for example, TURN HALF LEFT AT THE NEXT INTERSECTION, the prototype of the INTERSECTION concept disappeared (see Figure 39). This resulted in a varying number of branches ranging from three to five and a differing orientation of the branches that were not functionally involved. These differences occur between subjects and—for different turning concepts—also within subjects.

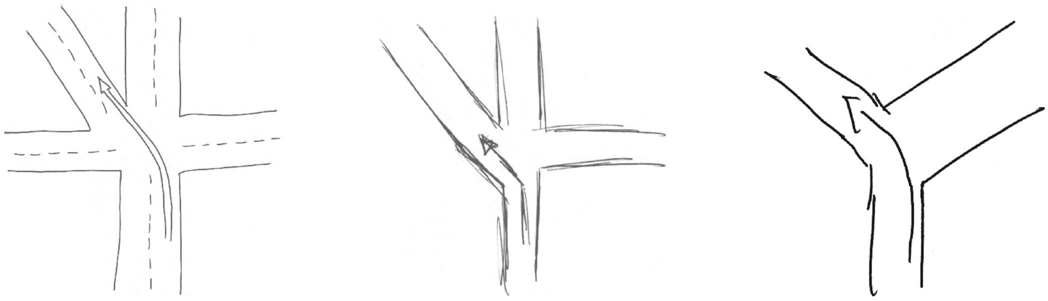

Figure 39. The non-existence of a prototypical concept for *intersection* if a modified turning concept is required, for example, HALF LEFT.

Hence, the prototypical concept of an intersection holds as long as the required action corresponds to one of the three basic turning concepts but disappears if more specific actions are compulsory, i.e. there is no prototypical 4-way intersection if one has to turn half left or half right at this intersection.

Likewise, the missing intersection prototype became apparent when the participants were required to draw intersections that do not match a 90° increment scheme, such as the 3-, 5-, or 6-way intersection, or the underspecified star-shaped one (see Figure 40).

Figure 40. Drawings for the concept SHARP RIGHT at a star-shaped intersection.

To sum up the results so far:

- The concept of an intersection changes according to the action (behavioral pattern) that takes place at the intersection. The basic concept of an intersection as it is evident as a stand alone concept, i.e. a four branch intersection where the branches meet at a right angle, can change, especially when the route direction affords a turn other than the standard turns (right, straight, left), resulting, for instance, in four branches plus the 'turning branch'.

- There is no homogenous concept for 5- and 6-way intersections (sometimes even the number of branches is mixed up).
- Star shaped intersections only exist in interaction with real environments, i.e. intersections are sometimes characterized as being star shaped, but there is no general concept of star shaped intersections.

On the other hand, the examples show that whereas the structure of an intersection changes, the turning concepts, i.e. the functional aspects, seem to be a constant factor of the participants' conceptualization, in this case in their drawings.

Hence, I now turn to the analysis of the conceptualization of turning concepts and put forth the following hypotheses: 1) Prototypical turning concepts, i.e. the functional aspects, are a stable factor in people's conceptualization of route direction elements independent of the kind of intersection at which they are required. 2) This holds equally well for all 6 turning concepts specified according to an 8-direction model, i.e. 45° increments.

This analysis was done by relying on an 8-direction model. That is, each time a participant drew a turning concept that matched with the 45° increments of the 8-direction model, the externalization of the concept was counted as a prototypical functional externalization. As 19 participants took part in the experiment, 100% were achieved if all 19 participants drew a turning concept as the same 45° increment (see Figure 41).

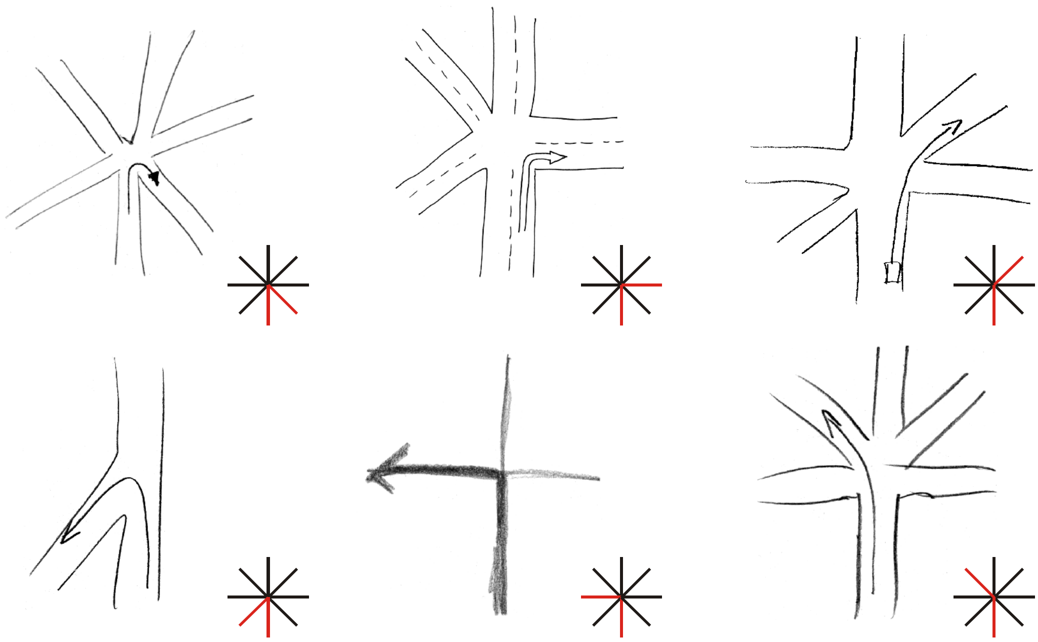

Figure 41. Prototypical turning concepts plus derived wayfinding choremes (red lines).

Table 1 displays the analysis of the drawings with respect to the decision points' functional aspects, which relates to the question whether prototypical functional turning concepts exist for the 6 specified direction changes.

Table 1. Results (N=19; absolute frequencies and percent values (in brackets)) for the externalization of prototypical functional of turning concepts. The following abbreviations are used: sr (SHARP RIGHT), r (RIGHT), hr (HALF RIGHT), hl (HALF LEFT), l (LEFT), sl (SHARP LEFT). 'Pure' in the intersection column denotes turning concepts without the specification of a type of intersection, for example, TURN RIGHT.

(N = 19) abs & (%)	sr	r	hr	hl	l	sl
pure	14 (73.68)	19 (100.00)	19 (100.00)	18 (94.74)	19 (100.00)	15 (78.95)
3-way	12 (63.16)	14 (73.68)	18 (94.74)	19 (100.00)	14 (73.68)	16 (84.21)
4-way	15 (78.95)	18 (94.74)	18 (94.74)	18 (94.74)	19 (100.00)	16 (84.21)
5-way	17 (89.47)	17 (89.47)	18 (94.74)	19 (100.00)	16 (84.21)	14 (73.68)
6-way	13 (68.42)	16 (84.21)	16 (84.21)	19 (100.00)	14 (73.68)	17 (89.47)
star	15 (78.95)	13 (68.42)	18 (94.74)	17 (89.47)	14 (73.68)	16 (84.21)
mean	14,33 (75.44)	16,17 (85.09)	17,83 (93.86)	18,33 (96.49)	16 (84.21)	15,67 (82.46)

The data shows that participants generally agree on the prototypicality of turning concepts, hence, the functional aspects of intersections in route directions seem to be the constant factor. This holds for each of the five types of intersections and for the 'pure' turning concepts, i.e. the one not instantiating intersections. In addition, this holds for each of the six turning concepts. The values range from 63.16% for the SHARP RIGHT turning concepts at a 3-way intersection to various 100% agreements, for example, LEFT at a 4-way intersection or HALF LEFT at a 6-way intersection. The mean agreement to the six prototypical turning concepts ranges from 14.3 out of 19 for the SHARP RIGHT turning concept to 18.3 for the HALF LEFT turning concept (from 75.44% to 96.49%).

4.3.1.3 Discussion

The study provides evidence for a distinction between structural and functional aspects in the conceptualization of primitive route elements, i.e. direction (turning) concepts at decision points. This difference is relevant, especially for complex route elements that can be found in many European downtown areas, for example, in Trier or in Paris. From a structural perspective, not every intersection can be prototypicalized in the same way, i.e. *the* prototypical intersection as externalized by the participants (cf. Figure 38). Beyond this aspect, the data analysis reveals that the required action is of utmost importance. Functionally relevant aspects play a major role in the conceptualization and prototypicalization of route direction elements, especially in situations in which a prototypical representation cannot be expected—i.e. intersections with a number of branches that do not allow for a regular 90° division of space—or if the turning concept affords a specific action, like *turn **half** left*. The reported results show a common ground for a functional characterization of turning concepts at decision points according to an 8-direction model, rather than relying strictly on structural prototypes of intersections. This further elaborates the graphic instantiation of wayfinding choremes. It offers a new perspective on characterizing routes and on aspectualization of spatial information in maps.

Hence, if the domain comprises actions, the characterization and aspectualization has to consider them, as they are in focus of a wayfinder while structural information plays a secondary role. This requirement is stressed by I–wayfinding choremes. Their pictorial counterparts are obtained by externalizing them into a spatio-analogical medium, i.e. E-wayfinding choremes (see Figure 41).

Furthermore, the data shows some differences within the agreement with prototypical turning concepts that will be looked at in greater detail as they reveal some peculiarities about intersections in interaction with turning concepts. The HALF LEFT and HALF RIGHT concepts at the 3-way intersection were the most consistently represented. Compared with this result, the basic turning concepts were rather weak at this type of intersection. Even though not significant, this effect can be explained as some participants equated *take the right part of the fork* with *turn right*. Consequently, the intersections were depicted in fork shape which does not allow for a prototypical TURN RIGHT concept, i.e. a 90° angle. The comparatively low values for the basic turning concepts at 6-way and star-shaped intersections can be partially explained by the fact that some participants drew the intersection before they drew the turning concept. As they used the same shape for these intersections during the entire experiment the correct representation of basic turning concepts was not possible. This result strengthens the criticism on the pictorial toolkit of Tversky and Lee (1999).

4.3.2 Study 2: Conceptual Chunking of Route Direction Elements[37]

The main concern of this experiment was to access conceptual chunking of wayfinding choremes to higher order route (direction) elements. As not all possibilities of chunking can be analyzed I focus on three general kinds of chunking: *landmark*, *numerical*, and *structure chunking*. These chunking principles are explained in detail in section 4.3.2.1. This study complements study 1. The method of language data analysis is adopted. The meaning of linguistic expressions is systematically underspecified—brought about by propositional encoding (cf. Levelt, 1989), and information reduction arising from selection and linearization processes (Habel & Tappe, 1999). This constitutes language analysis as a valuable means to elicit mental conceptualization. On the other hand, the underspecificity of language necessitates a combination of verbal data analysis with methods posing more constraints on the externalization of conceptualization like sketch maps (see study 1). This study also fills a gap in current research, i.e. the

[37] This research was carried out in collaboration with Heike Tappe, Christopher Habel, and Dan Montello.

conceptualization of veridical spatial information. Most investigations use memory tasks to elicit conceptualizations of route directions. In opposition, this survey on conceptual chunking of route direction elements provided the participants with 'all' the spatial information available, i.e. they obtained locational spatial information (see discussion on spatial information in section 3.2.2) as it can be found in a topographic map.

The guiding questions in this study are: How do humans chunk wayfinding choremes during a route direction task when they have access to a veridical representation (e.g., a topographic map[38])? These conceptualization processes result in different kinds of chunking, for example, *turn left at the third intersection* versus *follow the street to the post office, and then turn left*. A question that can also be raised in this context is whether the chunking processes given in interaction with a veridical external medium vary from those given from memory.

Two presentation modes are employed, a static and a dynamic one, to elicit chunking and to prove that chunking is an organizational feature that occurs independently of the presentation mode. As this study was conducted with German participants in Hamburg and with US-American participants in Santa Barbara, an interesting question is, if cultural differences occur in the conceptualizations of route segments, i.e. if there are different chunking principles. The most intriguing question is, of course, how these conceptualizations can be applied to route characterization and to map construction.

I use verbalizations as an empirical method because they have been proven a valuable means to gain access to otherwise difficult to access mental conceptualization processes. The method has the advantage that we get longer discourse, where the structuring of the textual information partly reveals the presumable structure of the underlying internal representations (for example, the verbalization is directly related to the chunking process).

4.3.2.1 On Different Kinds of Chunking in Route Directions

The concept of *chunking*[39] is central for this study. Lovelace et al. (1999) state that every route direction typically adheres to a sequential description of the route, comprising spatial objects, i.e. landmarks and decision points as well as spatial structures and basic motor activities. Moreover, as Denis et al. (1999, p. 147) claim that the linearization problem is not crucial for route directions (see section 4.1.2), I further differentiate route linearity by introducing three kinds of *chunking*. This is necessary, because contrary to the implied simplicity and straightforwardness in Denis' statement, even in route directions the mapping between the spatial structures and linguistic expressions is not simply a 1:1 relationship. Rather, route-direction-givers may choose at least four distinguishable strategies to linguistically encode the spatial structures along a route.

[38] To be more precise, a spatial layout of a street network based on spatial information obtained from a topographic map.

[39] The chunking in this study is different from chunking in, for example, SOAR (e.g., Laird et al., 1986).

Consequently, I differentiate *complete* route directions from the following kinds of chunking: *numerical chunking, structural,* and *landmark chunking*; and from the rather exotic *movement-focused chunking* (cf. Habel & Tappe, 1999, for similar observations concerning event descriptions). Chunking is only specified with respect to decision points.

Complete route directions: Completeness here is defined with respect to potential decision points, (DP+) and (DP-). Every branching point that lies on the route qualifies as a potential decision point as it offers the opportunity to either change or keep the direction of movement. A verbalization exemplifies complete route directions when no decision point or intersection is left out, i.e. they are all mentioned **explicitly** in the verbal direction. Complete route directions of the route fragment depicted in Figure 42 could read, for example: *Go straight until you arrive at a first intersection. Do not turn but continue until you arrive at the next intersection. There you turn right...* or *at this intersection do not take the right turnoff, go ahead, turn right at the next intersection*.

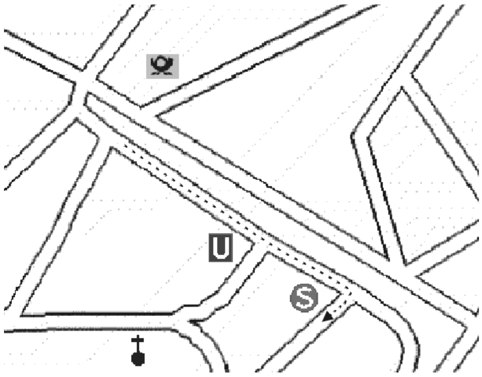

Figure 42. A map fragment: The dotted line/arrow depicts a part of the route that may be verbalized by mentioning every decision point explicitly, i.e. as a complete route direction.

Numerical chunking characterizes a verbal description in which various parts of a route are assembled into larger units by employing numbers. Speakers may adopt numerical chunking in situations where they think the spatial structure of the route environment allows them to leave out decision points in their instruction, i.e. to not mention every potential decision point. An example would be for a speaker to utter *turn right at the third intersection* while the hearer is still at the position indicated by (a) in Figure 43.

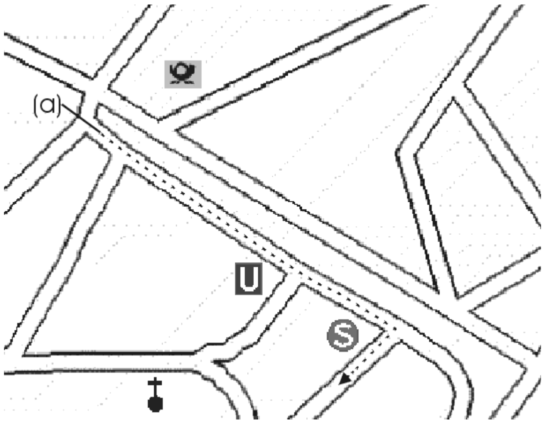

Figure 43. An example of numerical chunking. The dotted line depicts a part of the route that has to be verbalized. (a) denotes the position for the onset of the example descriptions provided in the text.

Landmark chunking underlies route directions where the speaker focuses on landmarks. As a result, other route features—like decision points—are not included and their number is not explicitly indicated. Examples are: *Turn left at the post office* or *Follow the street up to the post office and turn left* (see Figure 44).

Structure chunking. Using a spatial structure to chunk (*structure chunking*) is a special kind of landmark chunking. The spatial structure of a branching point can be employed if it allows a non-ambiguous reference to a decision point. For example, *follow the street until it dead-ends*. Structure can greatly decrease the complexity of a route (Mark, 1986).

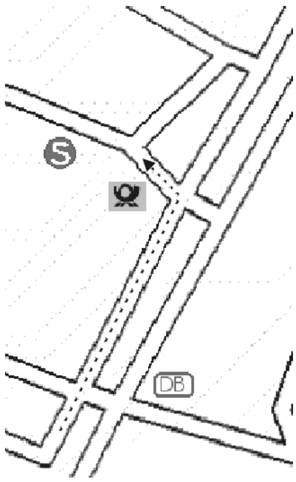

Figure 44. Example of landmark-oriented sequentiality. The dotted line depicts a part of the route to be verbalized.

Movement-focused chunking is an exception. The speaker chooses to describe the route entirely from the perspective of an entity that is actually traveling along the route. In the present study, this strategy might be relevant in route directions generated from the dynamic presentation of the route. If the verbal description is closely related to the actual movement of the dot, or, if speakers impose movement on the statically presented route (i.e. the line), they could describe the route as a sequence of movements only implicitly related to the structure: *Follow the route* (a), *go straight* (b), *go further straight* (c), *keep going straight* (d), *turn right* (e), (see Figure 45 for the indices and the corresponding route parts).

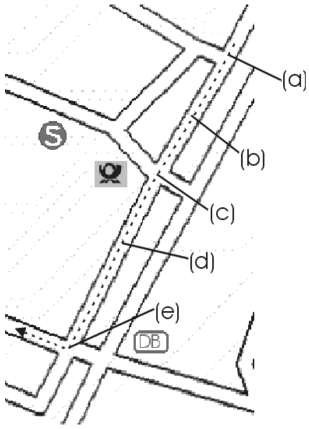

Figure 45. An example of movement-focused sequentiality. The dotted line depicts a part of the route to be verbalized. The letters correspond to the possible verbalizations of movements provided in the text.

I acknowledge that route directions in which one of the strategies introduced above is employed throughout will rarely occur. Yet, the prevalence of a certain kind of chunking may reveal how a speaker conceived of the spatial environment.

4.3.2.2 Methods

4.3.2.2.1 Participants

Forty students from the University of Hamburg (Germany), and forty-two students from the University of California, Santa Barbara (USA) participated in the study. The German participants were undergraduates in computer science and received payment for their participation. US-American participants were undergraduates in an introductory geography class at the University of California, Santa Barbara, and received course credit for their participation. Two German and three US-American participants had to be excluded from the sample because their language output was difficult to comprehend (low voice quality).

4.3.2.2.2 Design

Presentation mode is the independent variable, i.e. a dynamic or a static presentation of a route in a map from which route directions had to be generated. Each participant is tested on one of these two conditions.

4.3.2.2.3 Materials.

Each map (see Figure 46 for the English version and Figure 47 for the German version) was built on a topographic data set of the street network of a middle-sized city in Germany, slightly changed to fit the task. Different kinds of landmarks were added to allow reference to them. Whereas the geometry of the street network was identical in the English and German study the landmarks are different. This was necessary as abstract landmarks, like colored dots, were not accepted by participants in a pilot study. All landmarks had to be identifiable by the participants without reference to a legend. The acceptance and recognizability of the landmarks has been verified in a prestudy. A recorder was used to tape the verbalizations. The route to be described was chosen by the following criteria:

- To allow the participants to use different kinds of chunking the route comprises five data points at which chunking can be applied to route directions (see Figure 48).
- The route leads basically from right to left, i.e. against the usual writing direction.
- The route is long enough to have a number of left and right turns.
- The route passes different kinds of intersections.
- The landmarks are set in just two different ways as this is not a study on a landmark taxonomy but in pretests we found that landmarks make the task more natural.

Figure 46. The English version of the map used as stimulus material. Depicted is the static condition.

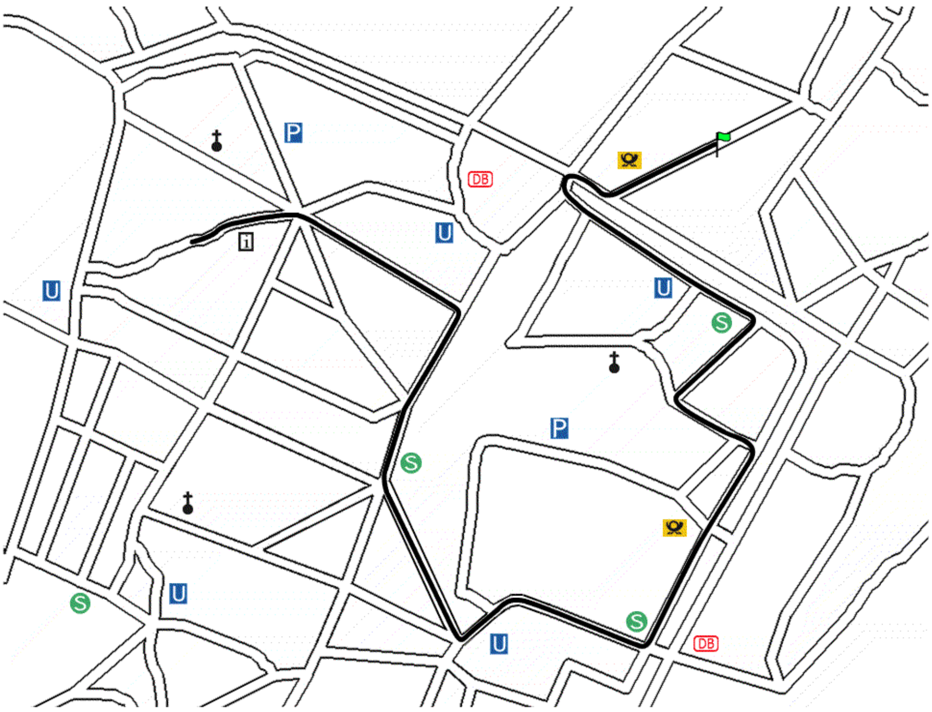

Figure 47. The German version of the map used as stimulus material. Depicted is the static condition.

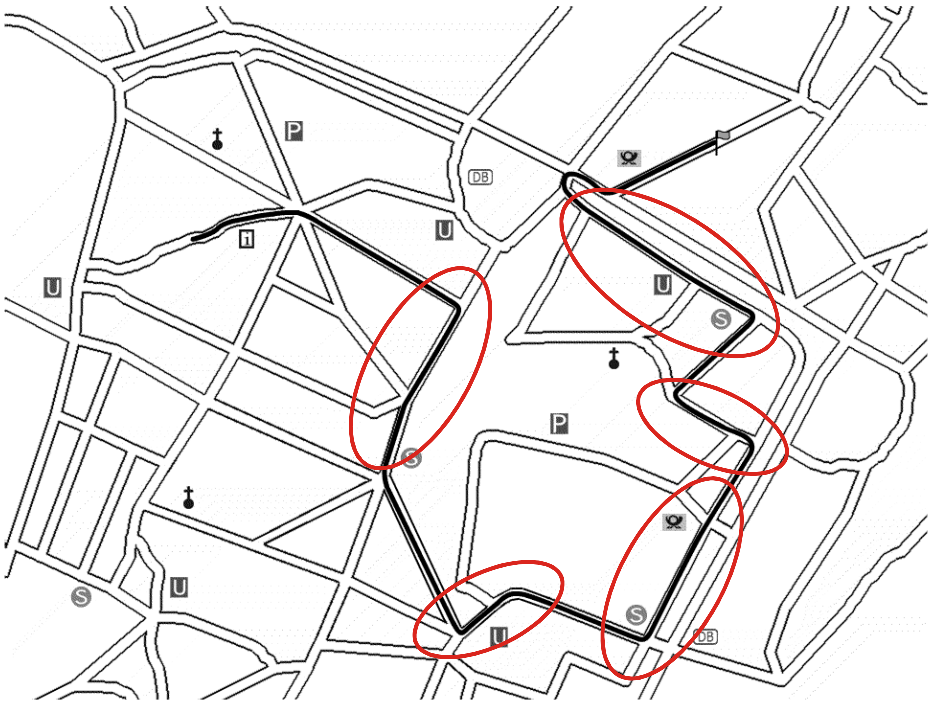

Figure 48. The data points for analyzing different kinds of chunking.

The presentation is realized as a *Flash* movie. The presentation time is the same in all four conditions (120 seconds). Presentation time is such that a naturally fluent speech production is possible, which has been verified by several prestudies.

The participants in the *dynamic condition* received the map with a point moving through it. The verbalizers generated route directions on-line on the basis of the movements of the point, i.e. they began their route instruction as soon as the point appeared and they stopped shortly after it reached its destination.

The participants in the *static condition* received the same map. This time, though, instead of being presented a moving point, the trajectory of the point from condition one was drawn into the map as a line. Participants described the static route on-line.

4.3.2.2.4 Procedure

Participants were tested individually. Before the actual verbalization-task all groups were presented written instructions which included a scenario to embed the language production task in a communicative setting.

Text of the scenario for the *static* presentation of the route (English):

> Your task will be to put different things into words. We record what you are saying. Don't be afraid: we are not mainly interested in correct and complete sentences. We rather attach importance to you imagining a listener who does not know the things you describe.

> While describing, please imagine the following situation: You are an employee at the central office of a modern messenger-service. There are plans to create the technical means to observe the messengers' movements on a screen and - for example in case of delay due to the traffic situation - to transmit them alternative routes by radio.
>
> In order to practice a training scenario has been developed, which we are going to demonstrate now. In this scenario you can see a line that is drawn into the map and that suggests a path which one of the messengers could take. The green flag marks the starting position. Please try to give the messenger a route instruction that is as precise as possible.
>
> Altogether you have 2 minutes for that task. After one minute an acoustic signal will sound. You will hear a second signal 30 seconds before the map will disappear from the screen.

Text of the scenario for the *dynamic* presentation of the route (English):

> Your task will be to put different things into words. We record what you are saying. Don't be afraid: we are not mainly interested in correct and complete sentences. We rather attach importance to you imagining a listener who does not know the things you describe.
>
> While describing, please imagine the following situation: You are an employee at the central office of a modern messenger-service. There are plans to create the technical means to observe the messengers' movements on a screen and - for example in case of delay due to the traffic situation - to transmit them alternative routes by radio.
>
> In order to practice a training scenario has been developed, which we are going to demonstrate now. In this scenario you can see a dot that moves across a map and that suggests a path which one of the messengers could take. Your task is to describe this route to the messenger. The green flag marks the starting position. Please try to give the messenger a route instruction that is as precise as possible.

The participants are instructed to watch carefully what happens and to simultaneously produce a route instruction that is suitable for reaching the destination at the end of the presented route.

After reading the instructions the participants of both groups turned to the display. All groups had to press the ‘O.K’ button visible on the screen to start the program, i.e. the *Flash* movie. After a mouse-click on the ‘O.K.’-button there was a countdown from 5 to 1. The map appeared for 120 seconds. The starting point was marked by a little green flag and was at the same position as the count-down-numbers. During the presentation time the participants produced a verbal route direction to the imagined bike messenger. In the static condition they heard a single acoustic signal after 60 seconds and after 90 seconds to give them an idea of the time remaining. After this time the map disappeared. In the dynamic presentation mode the map disappeared when the point reached the destination. The destination is not explicitly marked on the map.

4.3.2.3 Scoring / Coding of Data

As discussed in section 4.3.2.1, I distinguish between different principles of chunking in route directions. Chunking is evidenced in the language data, when decision points are not explicitly mentioned but are integrated into higher order route (direction) elements; as a result wayfinding choremes are combined. The stimulus route comprised five route parts that allow for spatial chunking (see Figure 48). Here we counted whether or not spatial chunking occurred and which kind of chunking was employed by the participants. At each of these route parts one or more than one kind of chunking can be employed. More specifically: Numerical chunking can be used at all five data points, landmark chunking is applicable in three cases, whereas structure chunking is only available twice. This latter point is closely linked to the interaction with the external medium. In the stimulus map only T-intersections were unambiguously identifiable as compared to intersections with several branching-off streets. In the scoring procedure, we accounted for the fact that not all types of spatial chunking can be realized in all route parts by weighting the scores accordingly.

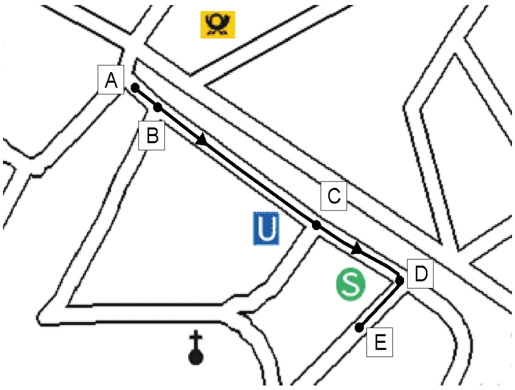

Figure 49. Route segments (AB, BC, CD, DE) can be chunked to HORDE in different ways. A route direction from the origin A to destination E can employ numerical chunking, i.e. *turn right at the third intersection*, or landmark chunking: *turn right after the S-Bahn station*. The number of in-between decision points is unspecified in the latter case.

The participants' route directions were tape-recorded and transcribed in full. The transcripts were analyzed in terms of kind and quantity of chunked route segments. For the analysis of content, each transcript was divided into discrete utterances, and the authors rated relevant utterances according to the chunking types listed in Table 2. For each verbalization, the number of complex noun phrases were counted that indicate a spatial chunking process. In cases where speakers employed more than one kind of chunking in one phrase, only the first chunk was counted. An example like: *Turn right at the McDonalds, which is the second intersection* was coded as landmark chunking, i.e. at the McDonalds. An independent rater checked reliability of the analysis. Inter-rater agreement was 96% for chunking scores.

Table 2. Categories used to code utterances and examples.

Label	Category Name	Examples
LC	Landmark chunking	*turn left at the station*, *go straight after the post office*.
NC	Numerical chunking	*turn left at the third intersection*, *it's the second street to the right*
SC	Structure chunking	*turn left at the T-junction*

In a first step we kept analyses for the German and the US-American verbalizers apart. Since we did not find significant differences between the two language groups, the results are discussed as one body.

4.3.2.4 Results

In general, we found that spatial chunking figures in about 53,8 % of all cases across conditions. Thus, the prediction that speakers avoid spatial chunking in accompanying route directions, i.e. in the dynamic condition, was not fully met. Instead of adhering to the ordering of the spatial objects along the route in a strict sense, in half the cases they chose to form higher order route (direction) elements, HORDE. Thus, our investigation underpins the finding that route instructors are striving to structure the to-be-conveyed spatial environment and to present relevant, non-redundant information. This holds despite the fact that they were producing accompanying route directions on-line.
Figure 50 depicts the mean values for the occurrence of the three kinds of chunking specified above for the two conditions—static and dynamic—weighted according to the possibility to employ each type of chunking at each of the five route segments in question.

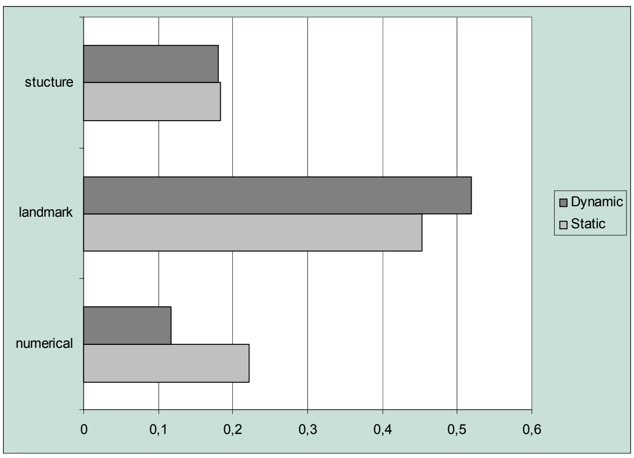

Figure 50. Weighted mean values (numerical 5; landmark 3; structure 2) for three different kinds of chunking for the two conditions.

The results show the following pattern: Landmark chunking is the most common way to group primary route segments into HORDE underpinning the relevance of landmarks for route directions from a procedural point of view. The significance of this finding is emphasized by the fact that for landmark chunking we did not find significant differences between presentation modes. Structure chunking was employed to a far lesser extent than landmark chunking. Yet, the presentation mode did not yield significant differences either. Quite different from this pattern are the scores for numerical chunking: Presentation mode had a clear impact and we found a significant difference (p=0.009, ANOVA).

4.3.2.5 Discussion

As we see from the results of this study, spatial chunking of elementary route elements is used as a helpful and adequate strategy in the production of route directions. It is employed even in a setting where it might add to the cognitive processing load of the speakers, i.e. the dynamic presentation mode. Here, planning processes are hindered because attention has to focus on the near vicinity of the moving dot in order to produce adequate guidance for the addressee. Even though speakers may visually scan the surroundings, the continuation of the route is not unerringly predictable. A description of actions at every decision point—with or without directional change—seems appropriate. Yet, even if verbalizers could in principle use all the information they had access to, they often chose not to do so. For example, instead of explicitly including every intersection along a straight part of the path into the route direction, people were likely to chunk segments together. These findings indicate that speakers do not avoid spatial chunking in accompanying route directions. What we found in the case study data was instead, that speakers attempted to use spatial chunking where they found it appropriate to the situation, even if it enhanced cognitive processing costs. This was the case in about half the cases overall.

Moreover, the results presented indicate that the spatial chunking process especially employs landmarks and unambiguous spatial configurations—T-intersections in the stimulus material—in the same manner for both presentation modes. The unambiguous ability to identify T-Intersections seems to result from the interaction with the external graphical medium, i.e. the map. Whereas T-intersections present themselves as a salient feature largely independent of their orientation in a map, they might not function as such in route directions derived from memory of a real-world environment. This issue, however, awaits further investigation.

In contrast to landmark and structural chunking, we found significant differences between the presentation modes for numerical chunking, which is clearly favored in the static condition. This latter finding confirms our first prediction, i.e. visual accessibility influences spatial chunking. Whereas landmarks and salient spatial structures are visually accessible by quickly scanning the route and are obviously judged by the route instructors to be good cues for guidance, as they are assumed to be recognizable for the addressee of the route instruction independently of her or his current localization on the route, this is not the case for numerical chunking. First, in the dynamic presentation mode it might be difficult for the most part to keep track of the exact number of branching-off streets while producing the on-line instruction. Second, the instructors have no feedback as to the current localization of the addressee. Therefore, they seem to take into consideration that a direction like *turn left at the third intersection* is to a great extent dependent on the progression of the addressee along the route and therefore prone to potential confusion. Despite the fact that chunking is an omnipresent characteristic of route directions overriding even the guidance of the presentation mode, there remain differences in the processing of static versus animated presentations.

4.3.3 Study 3: Memory for Landmarks

This study is tied up to the study on the chunking of route elements. It was conducted in collaboration with Paul Lee and Heike Tappe. The study intended to shed more light on the importance of landmarks along a route, especially on the relation between directional changes and landmarks. The study used the same distinctions as in study 2, i.e. a dynamic versus a static presentation. Furthermore, we added a third condition, namely a combination of the static and dynamic presentation mode resulting in a moving dot superimposed on a solidly drawn line on a map.

We hypothesized that the dynamic presentation of route information on a map, i.e. by a moving dot, creates equal emphasis on landmarks at the turns and landmarks along the route, stressing the general importance of landmarks at decision points. In contrast, the static presentation of route information, i.e. a solid line, should stress landmarks at turns resulting in a better memory for these landmarks. Therefore, a combined presentation should yield results that lie between those for the two other presentation modes.

4.3.3.1 Methods

4.3.3.1.1 Participants

Sixty four undergraduates, 36 male and 28 female, from Stanford University participated individually in partial fulfillment of a course requirement. The minimum criterion of 20% recall rate eliminated the data of two men and four women. The data of the remaining 58 participants were analyzed.

4.3.3.1.2 Design

4.3.3.1.3 Materials

The map used this time depicts the street network of a fictitious town (see Figure 51). It was set up to counterbalance turning (DP+) and non-turning (DP-) intersections as well as to create unique intersections. The landmarks as such were not fictitious and recognizable such as McDonalds or K-Mart. In detail, the design adhered to the following criteria:

- The landmarks were pre-tested to be easily recognizable by the participants.
- Landmarks were placed only at intersections. Hence, it did not matter whether a turn occurred or not, they were equally good identifiers for potential decision points.
- The numbers of landmarks at turning (DP+) and non-turning (DP-) decision points were counterbalanced.
- The landmarks were all point-like.
- Street names were left out so as not to interfere with information processing.

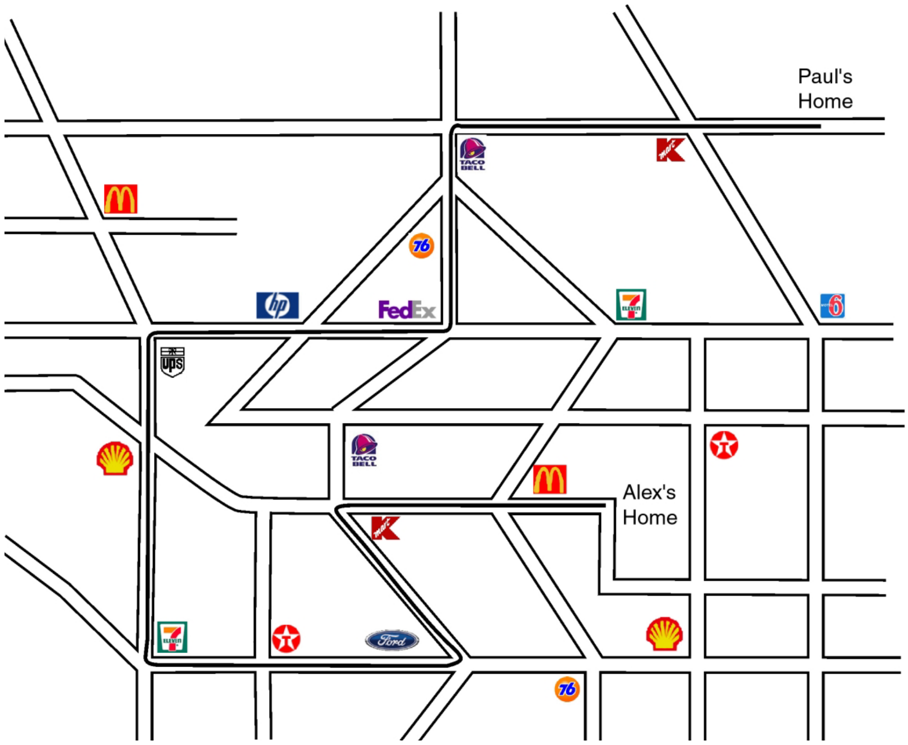

Figure 51. Static presentation of the map.

4.3.3.1.4 Procedure

The route in the map was presented dynamically, statically, or mixed. The origin and the destination of the route were marked as ‘Alex’s home’ and ‘Paul’s home’. In the dynamic condition, a dot moved towards the destination, as if an imagined navigator was traversing the route. In contrast, the static condition presented the complete route between the origin and the destination (see Figure 51). The mixed condition combined the static and dynamic components of the presentation of the route by superimposing a moving dot on the statically presented route.

The participants had to remember the route and its elements as they viewed the map. They were also asked to verbalize the route during the viewing session. They viewed and verbalized it three times, each for 1.5 minutes. Afterwards they were given a map with only the street network and were had to draw the landmarks they remember.

4.3.3.2 Results

Table 3 shows the percentages of recalled landmarks for the three presentation conditions—dynamic, static, and mixed. As predicted, recalling landmarks after the dynamic presentation of route information led to an equally good memory for landmarks at turning (DP+) and non-turning (DP-) decision points (52.0% vs. 50.9%; $t(55) = 0.153$, $p > 0.4$), but for the static condition landmarks at turning decision points were remembered more often (55.3%) than at non-turning decision points (44.7%) ($t(55) = 1.47$, $p < 0.074$). These results suggest that the presentation mode affects the memory for routes. In the dynamic condition, participants seemed to follow the movement of the dot along the route and attend equally well to all landmarks. In the static condition, participants seemed to attend to all landmarks during verbalization, but their subsequent recall showed better memory for landmarks at the turns, i.e. landmarks that are more pertinent to the route.

Table 3. Proportion of the recalled landmarks (in %).

	DP+	DP-	Total
Dynamic	52.0	50.9	51.5
Static	55.3	44.7	50.0
Mixed	59.0	43.3	51.2
All	55.5	46.3	

Surprisingly, when a moving dot was superimposed on a static route, participants recalled even more landmarks at turns (59.0%) than at non-turns (43.3%). We expected that this condition would yield results somewhere in between those of dynamic and static conditions, since the availability of both the complete route and the moving dot would give participants a choice to segment either by following the moving dot or by using the static route.

However, the results suggest that a combination of dynamic and static route presentation focuses their attention further onto the pertinent landmarks, namely the landmarks at the turns, than either presentation mode alone. This is noteworthy because the mixed condition did not provide any additional information to help recall landmarks as compared to the static route. Instead, the benefit seems to come from directing attention to the appropriate landmarks on the path segments.

Prior to the experiment, we also had concerns that the dynamic condition was significantly harder than the static condition because participants had to reconstruct the route from a moving dot in the dynamic condition. The total number of recalled landmarks, however, did not differ significantly between conditions (51.5%, 50.0%, 51.2% for dynamic, static, and mixed conditions, respectively), suggesting that the recall task was equally difficult for all conditions.

4.3.3.3 Discussion

The results of this study demonstrate first of all that the presentation mode of route information affects the memory for landmarks at decision points. This indicates that different presentation modes provide different foci on the two distinguished kinds of decision points, i.e. (DP+) and (DP-), and landmarks placed at these decision points, respectively. If we take up the discussion in the literature and the results of the two preceding studies, i.e. that decision points that require a direction change (DP+) are most vital to route directions, we find that a static presentation has slight advantages compared to the dynamic presentation of the route.

We also found that the combination of the two presentation modes further enhances the recall of landmarks at decision points with a direction change (DP+). Pursuing this line of thinking additional arguments for a functional perspective on route direction elements can be given. A route is a behavioral pattern which is best reflected by the dynamic presentation of route information. This behavioral pattern is instantiated within a physical structure that specifies the actions that have to take place during wayfinding and route following. Functionally relevant parts of the physical structure are demarcated by the behavioral pattern. A combination of both therefore best models the cognitive processes that have to take place. Yet, I assume to achieve this focus by employing static means alone with a strong focus on functional aspects, i.e. the approach of wayfinding choremes. As this statement is primarily drawn from the theoretical background of this study it awaits further investigation.

4.4 Summarizing the Results for Wayfinding Choremes

In these studies I identified the use of functional direction (turning) concepts, i.e. 45° increments as a cognitive principle for characterizing directions at decision points. This focus on functional primitives (wayfinding choremes) reduces the number of necessary primitives for decision points in the wayfinding choreme route grammar to seven (compared to the 34 elements, for example, in the taxonomy by Casakin et al., 2000). These are the wayfinding choremes for the turning concepts: SHARP RIGHT, RIGHT, HALF RIGHT, STRAIGHT, HALF LEFT, LEFT, and SHARP LEFT. The general agreement on functional, prototypical turning concepts found in study 1 and their realization in a map-like representational medium provide the basis for the characterization of routes within the wayfinding choreme model and for the specification for cognitive conceptual map construction.

Chunking wayfinding choremes is a major organizational principle for route directions. Hence, the seven wayfinding choremes are not intended as the final characterization of routes but are terminals that can be chunked into higher order route (direction) elements (HORDE). The chunking principles for numerical, landmark, and structure chunking are detailed in section 5.1.2 by the results of studies 2 and 3.

A focus is placed on landmarks at decision points that require a direction change (DP+) as they have been identified as the most important landmarks occurring along routes (see study 3; cf. also Ward, Newcombe, and Overton, 1986; Blades & Medlicott, 1992; Denis, 1997; Lovelace et al., 1999; Lee, Tappe, and Klippel, 2002). A suitable presentation mode, i.e. the combination of dynamic and static presentation, fosters the memory for these landmarks. Similar to the dynamic condition, wayfinding choremes focus attention on relevant information by employing a functional perspective. Yet, in this characterization they are static means as they are represented in a temporarily fixed spatio-analogical medium.

I assume, however, that wayfinding choremes benefit from the focus on essential route information as achieved in the mixed condition. In various studies (Avrahami & Kareev, 1994; Zacks & Tversky, 2001; Lee, Tappe, & Klippel, 2002) it has been argued that dynamic presentations are not perceived as a continuous pattern but that this pattern is broken down into information units. I–wayfinding choremes are the abstract conceptualization of such information units, i.e. the primitives of wayfinding and route direction in street networks. E-wayfinding choremes are their externalization and can be applied to cognitive conceptual map construction.

'Hold on, hold on,' said the Bursar. 'Yes indeed, *figuratively* a word is made up of individual letters but they have only a,' he waved his long fingers gracefully, '*theoretical* existence, if I may put it that way. They are, as it were, words *partis in potentia*, and it is, I am afraid, unsophisticated in the extreme to imagine that they have a *real* existence *unis et separato*. Indeed, the very concept of letters having their own physical existence is, philosophically, extremely worrying. Indeed, it would be like noses and fingers running around the world all by themselves—'.

—*The Truth*, by Terry Pratchett, 2000

5 A Model for Wayfinding Choremes

This chapter renders the theory of wayfinding choremes more precise. First, the deduction of wayfinding choremes from environmental information is specified from the viewpoint of qualitative spatial reasoning (section 5.1). Second, the route grammar sketched in chapter 3 (section 3.4) is extended to incorporate the empirical results on wayfinding choremes presented in chapter 4. It is called wayfinding choreme route grammar (WCRG). The concept of decision points is refined by the functional perspective of wayfinding choremes identified in study 1 (conceptualization of direction information at decision points, section 4.3.1). In section (5.1.2) the combinatorial possibilities of wayfinding choremes are discussed and integrated in the wayfinding choreme route grammar. This line of thought is based on study 2 (conceptual chunking of route direction elements, section 4.3.2) and study 3 (memory for landmarks, section 4.3.3). The processing of routes characterized by wayfinding choremes is described in section 5.3.

Second, the WCRG, as it is defined for a two-dimensional representational medium (the perspective of graphic E-wayfinding choremes), is used to illustrate how to construct maps by a cognitive conceptual approach (see section 5.4). Exemplarily, the resulting visualization is compared to the approach of Agrawala and Stolte (2000; 2001).

5.1 Wayfinding Choremes

After the review of research on conceptual spatial primitives (chapter 2), the theoretical considerations of chapter 3 and the empirical analysis of mental conceptualizations of turning concepts at decision points (section 4.3.1), I will now detail the set of wayfinding choremes for route characterization. Let us recall the most important aspects of wayfinding choremes:

- I–wayfinding choremes are **abstract mental concepts** that underlie verbal and graphical route directions and wayfinding.
- I differentiate between **structure** and **function**. Function denotes the conceptualization of an action that in turn demarcates part of the structure.
- Wayfinding choremes are **functional primitives** of direction (turning) concepts at decision points.
- There is a **limited number** of wayfinding choremes.
- Wayfinding choremes can be combined to **higher order route (direction) elements**, abbreviated as HORDE.
- I-wayfinding choremes are accessible via their graphical and verbal externalizations (E-wayfinding choremes). The externalization in graphical form requires the instantiation of precisely **one** possibility, whereas the verbal externalization is propositional and spatially underspecified.

5.1.1 The Set of Wayfinding Choremes

In the following, I detail the formal basis of wayfinding choremes. According to models of qualitative spatial reasoning discussed in section 2.3.3 I assume an 8-sector model from which an 8-direction model can be derived by calculating the bisecting lines of each sector. Hence, each sector is represented by 45° increments for prototypical directions (see Figure 52). This means that the two route segments relevant for a wayfinding choreme are represented by this 45° prototypes of the corresponding sector.

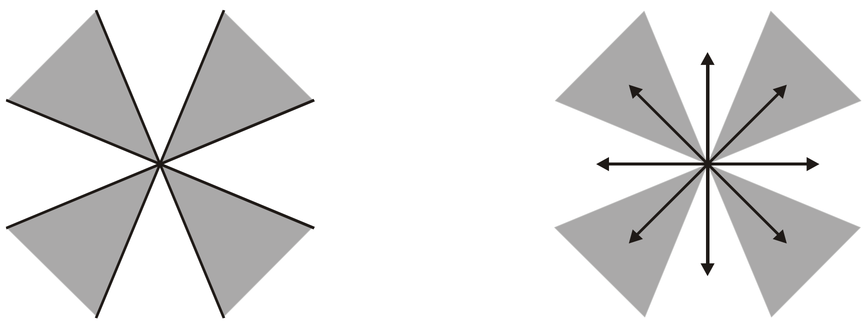

Figure 52. The 8-sector model (left part) and the derived 8-direction model (right part).

For route directions the route segment that leads to the center of the decision point specifies the *reference direction* (see Figure 53). For a goal-oriented movement, seven of these eight directions are valid for modeling route directions. This point of view is congruent with the functional perspective and the empirical results obtained, for example, in study 2 on chunking route (direction) elements (see section 4.3.2). Especially in a route direction context, people do not conceptualize possible directions at the center of a decision point but, instead, they mentally combine the functionally relevant parts, i.e. as far in advance as suitable in the current situation. The route segment of a decision point where one enters the center of the decision point constitutes the **reference direction** from which the other directions are conceptualized. Therefore, seven potential directions remain based on the 8–direction model (see Figure 53). This point of view is a modification of direction models used in the AI community (cf. Freksa, 1991; Freksa & Zimmermann, 1992), where it is possible to go back at a decision point. Yet, for goal-oriented movements this action plays a secondary role, it is not included in the characterization at this point. The special case of the BACK concepts and particular aspects of the STRAIGHT concepts are discussed in section 6.3.2.1.

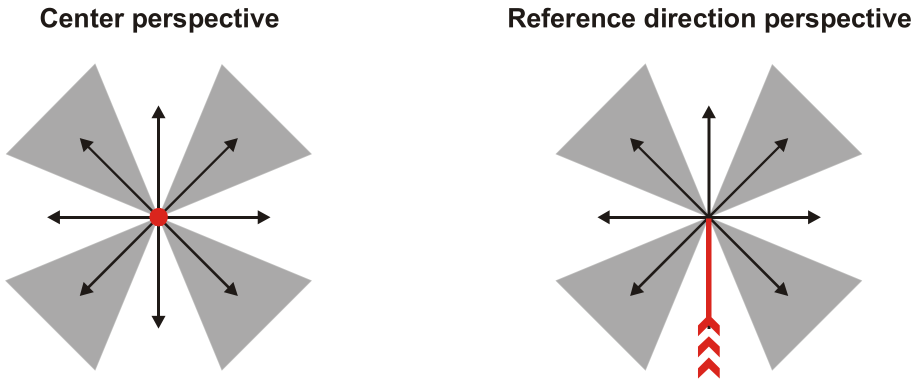

Figure 53. Seven potential directions based on an 8-direction model for a route direction context.

In the next step, the wayfinding choremes are extracted from this 8–direction model based on the functional perspective and the results of study 1 (see section 4.3.1). Seven directions conceptualized with respect to the reference direction constitute the seven wayfinding choremes: wc_{sr}, wc_{r}, wc_{hr}, wc_{s}, wc_{hl}, wc_{l}, wc_{sl}. Their linguistic externalizations are *sharp right*, *right*, *half right*, *straight*, *half left*, *left*, *sharp left*. Each wayfinding choreme is a conceptualization of parts of the route segment leading to the center of a decision point, i.e. the reference direction, and parts of a route segment conceptualized as the direction to take (see Figure 54).

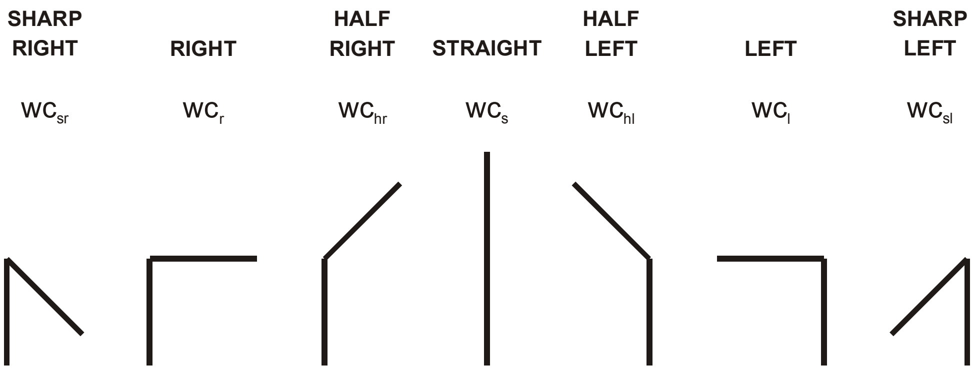

Figure 54. The seven wayfinding choremes.

According to findings from behavioral experimental work (e.g., Evans, 1980), the seven wayfinding choremes are organized in hierarchical categories. The first category comprises wayfinding choremes associated with *standard turns*. These are the wayfinding choremes for RIGHT (wc_r) and LEFT (wc_l). The second category includes wayfinding choremes dubbed as *modified turns*. These are the wayfinding choremes for standard turns modified by either SHARP or HALF; the wayfinding choremes for SHARP RIGHT (wc_{sr}), HALF RIGHT (wc_{hr}), HALF LEFT (wc_{hl}), and SHARP LEFT (wc_{sl}).

One further distinction has to be made between (DP+) and (DP-) (see section 3.3.2), i.e. between wayfinding choremes for decision points at which a direction change is necessary and wayfinding choremes for decision points at which **no** direction change is necessary. The only (DP-) wayfinding choreme is the one for STRAIGHT, wc_s, the other six wayfinding choremes belong to (DP+). Table 4 illustrates these distinctions. The straight wayfinding choreme (wc_s) plays a crucial role in section 5.1.2 where the chunking principles of wayfinding choremes are discussed. As turns are actions and STRAIGHT is a standard action, too, it is written in the 'standard' column (see Table 4). The resulting three categories of wayfinding choremes are termed:

- **S**tandard **T**urning **C**oncept (<STC>),
- **N**on-**T**urning **C**oncept (<NTC>), and
- **M**odified **T**urning **C**oncept (<MTC>).

Table 4. Three categories of wayfinding choremes.

	standard (turns)	modified turns
turning	wc_r, wc_l (<STC>)	wc_{sr}, wc_{hr}, wc_{hl}, wc_{sl} (<MTC>)
non-turning	wc_s (<NTC>)	

For the WCRG, wayfinding choremes specify the terminals for the category <DecisionPoint>. They replace the formerly necessary structural category of branching points, for example, <3-wayInt>. Therefore, the definition for <DecisionPoint> given in section 3.4.2

<DecisionPoint> ::= <3-wayInt> | <4-wayInt> | <5-wayInt> | ...

with all its implication, is radically simplified to

<DecisionPoint> ::= wc_{sr} | wc_r | wc_{hr} | wc_s | wc_{hl} | wc_l | wc_{sl}

Note that by defining a route grammar based on wayfinding choremes the intermediate structural category of different types of intersections like <3-wayInt> is dispensable. But additionally, the action oriented functional nature of the present characterization allows for three medium level categories defined above, i.e. *standard turning concepts* <STC>, *standard non-turning concepts* <NTC>, and *modified turning concepts* <MTC>:

<STC> ::= wc_r | wc_l

<NTC> ::= wc_s

<MTC> ::= wc_{sr} | wc_{hr} | wc_{hl} | wc_{sl}

We have now replaced the formerly structurally instantiated concept of decision point by a functional concept. The proposal advocated here is based on the well attested finding that decision points are the most vital elements of routes and route directions, respectively (e.g., Allen, 1997; Denis, 1997). In addition, the principle distinction between structure and function enhances the prominence of decision points in that they are the crucial segmentation points of a route, i.e. a goal-directed behavioral pattern.

Under the adopted functional perspective, the concept <RoutePart> merges into the concept of higher order route (direction) elements. HORDE denote chunks of wayfinding choremes that group functionally together, rather than from the structural perspective (the characteristics of the path). The functional perspective has the advantage of simplifying the characterization without neglecting the essential information. In contrast to the structural perspective the functional proposition offers an interface representation that mediates between various input and output modes.

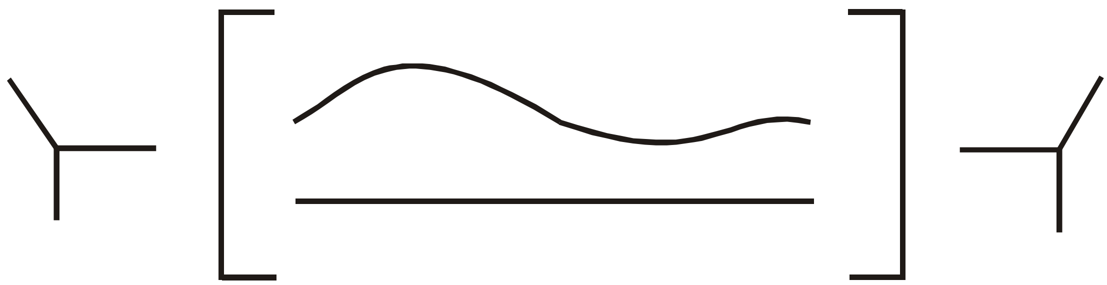

Figure 55. Winding and straight route segments.

5.1.2 Combining Wayfinding Choremes

The literature review on chunking (see section 4.1.2) and the analysis of the language data from the experiments (see section 4.3.2) show that participants use verbal expressions that chunk wayfinding choremes to HORDE. As chunking occurs even if a route is presented sequentially by a moving dot (see study 2), we concluded that HORDE are strong organizational features for routes. We confirmed and made results in the literature more precise (e.g., Allen, 1981, 1982; Denis, 1997; Golledge, 1999a) by introducing different kinds of chunking—numerical, landmark, and structure chunking. The wayfinding choreme route grammar is capable of reflecting not only the conceptualization of primitive elements or—by their straight forward concatenation—a complete route, but also the intermediate level, i.e. higher order route (direction) elements. HORDE show in verbalizations like *turn right at* ***the third*** *intersection*.

On the level of characterization adopted in the present work, I intend to provide cognitively adequate rules that allow for chunking route segments on a canonical basis. This means that the rules specified can be adopted to other spatial situations if this is required. As the environment provides us with rich and manifold information, it is well beyond the scope of this work to provide solutions for every spatial situation. Nonetheless, the wayfinding choreme theory is flexibly to handle individual or newly established concepts. This is demonstrated in section 5.1.2.2, Figure 61. The canonical assumptions that will be discussed in detail are grounded on the postulation of an idealized cognizer and an idealized environment (see section 1.2). They allow for a first structuring of route information in absence of situational peculiarities.

In the category of decision points those that require a change in direction, (DP+), are most pertinent to routes and route directions. It is therefore a sensible first step to structure route information by identifying (DP+). In a second step, the obtained groups of decision points are either further structured or grouped together. Figure 56 gives an overview of the different structuring principles that will be discussed in the following sections. It also reveals, which cases lead to straightforward solutions and for which cases further information is necessary.

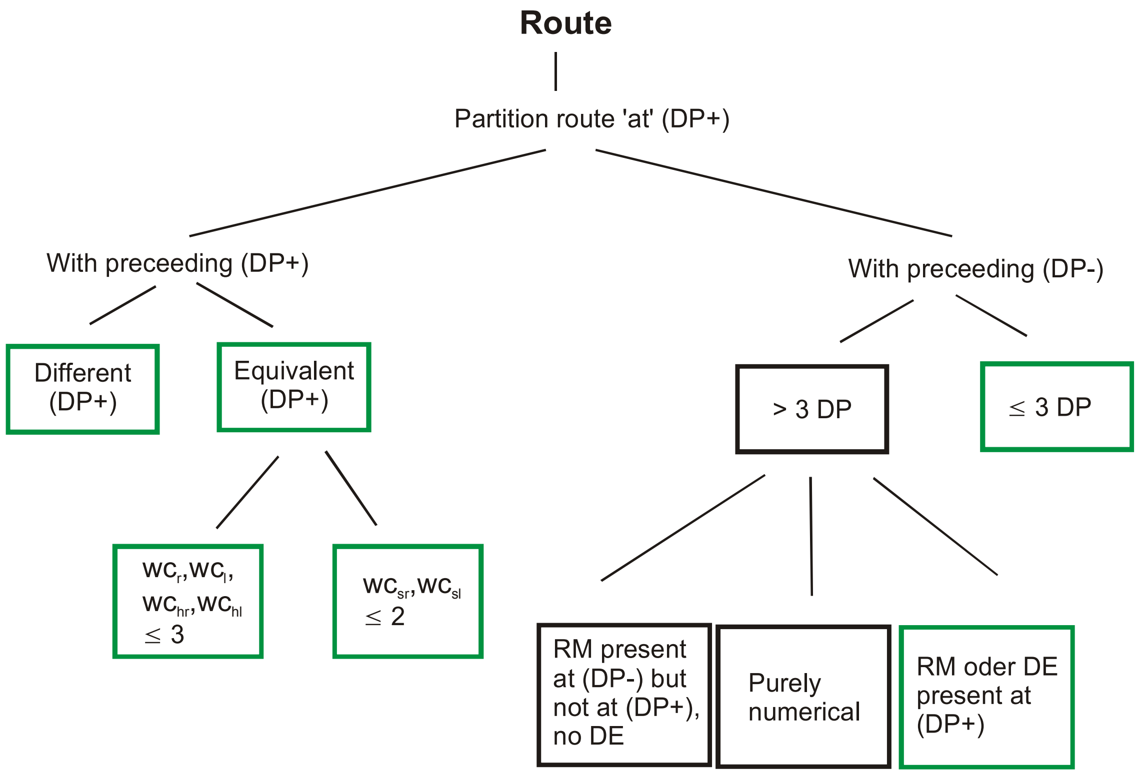

Figure 56. Overview of the chunking principles applied in this work. The green boxes indicate the cases that are unambiguously solvable in the WCRG.

Two general cases can be distinguished for chunking wayfinding choremes if no further environmental information is available. I use them to structure the subsequent argumentation:

- the chunking of functionally equivalent[40] wayfinding choremes (<CEWC>) and
- the chunking of functionally different wayfinding choremes (<CDWC>).

The concept <HORDE> comprises these two concepts:

<HORDE> ::= <CEWC> | <CDWC>

Additionally, section 5.1.2.3 illustrates the influence of environmental information, i.e. routemarks and spatial structures (e.g., T-intersections).

5.1.2.1 Combining Functionally Equivalent Wayfinding Choremes

Consider a sequence of (DP+) that contains consecutive, functionally equivalent wayfinding choremes, for example, $wc_r wc_r wc_l wc_l$. In this case, it is possible to define chunking principles on the basis of numerical chunking. The concept <CEWC> is detailed further. Nevertheless, there are restrictions to the combination of wayfinding choremes. Let us consider the following possible combinations:

[40] Functionally equivalent means the same wayfinding choreme, e.g., $wc_r wc_r$.

- two or more sharp turning concepts,
- two or more left/right turning concepts,
- two or more half turning concepts, and
- two or more straight concepts (a special case).

From a theoretical point of view, the maximum number of chunked wayfinding choremes is not restricted. Nevertheless, there are some reasons why the number of chunked items should be finite, at least for numerical chunking. Work on chunking (e.g., Miller, 1956; Cowan, 2001) does provide evidence for the number of chunks that can be stored in working memory. Unfortunately, it does not specify how many elements are allowed in one chunk. What is the 'correct' number for numerically chunked wayfinding choremes? Again, at this point I discuss canonical cases. Specific situations may require specific solutions. The WCRG is capable of them but, here, I restrict myself to the canonical cases (see section 5.1.2.2 and section 6.3.1). Natural language expressions like *turn nine times right* or *turn nine times sharp right* or *go nine times straight* are not canonical cases for route directions. *Turn four times right* (or *left*) already fosters the expectation to arrive at the very same place that one has started from. Therefore, I assume a canonical case of three elements that are combined to one chunk if we rely on numerical chunking.

Chunking SHARP turning concepts, i.e. SHARP RIGHT or SHARP LEFT is a case where the maximum number of chunked elements is smaller than three. Already the chunking of two wayfinding choremes of the kind wc_{sr} or wc_{sl} poses a demanding task from a conceptual perspective, as these cases are an exception in spatial structures of our environments. The path structures of city street networks do not support forming these combinations. Figure 57 depicts an example of chunking twice or three times SHARP RIGHT. The following three reasons—structurally and functionally—provide evidence against the chunking of more than two SHARP turning concepts:

- Such cases rarely occur in real spatial situations[41]. This holds especially for more than two SHARP concepts following one another. Our experience does not support a single mental concept of three of them naturally present, i.e. they build no higher order route (direction) element from a cognitive perspective. I have not conducted a calculation on various city street networks but it is discussed in the outlook (see section 6.3.4).
- These concepts do not occur unhesitantly in verbal route directions like *and then you turn three times sharp right*. Even if two sharp turns occur immediately one after another it is more likely that an emphasis is placed on this special situation by separating the two actions: *turn sharp right and immediately sharp right again*.

[41] Exceptions may occur in 3D environments, e.g., hilly recreational parks with bridges. Nevertheless, in this cases concepts for UNDER or ABOVE a bridge may function as last delimiting wayfinding choreme in a chunk (see section 6.3.2.2).

- The third reason is that the concepts SHARP RIGHT and SHARP LEFT yielded the least agreement in the study on conceptualization of route direction elements (see section 4.3.1.2). Therefore, I conclude that they are the hardest to conceptualize and combining two concepts that are difficult (even though the general agreement is still high) is avoided.

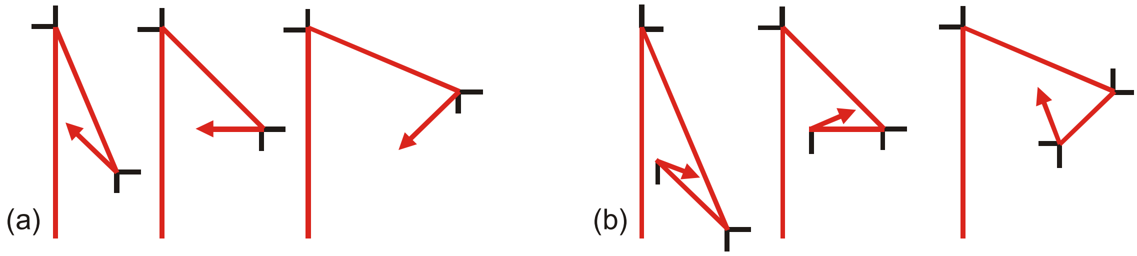

Figure 57. Chunking possibilities of SHARP turning concepts in city street networks. Depicted are the borderline cases—to the back and to the right sectors—and the prototypical case, for two (a) and three (b) chunked turning concepts according to the 8-direction/sector model.

It could be the case, however, that the borderline case closest to the RIGHT turning concept is not conceptualized as SHARP RIGHT but ‘only’ as RIGHT where the spatial situation allows for it. This is similar to the discussion of the combination of RIGHT and HALF RIGHT turning concepts (see Figure 60). Specifying a route grammar comprises the specification of idealized cases. Exceptions need further research to determine whether they are active conceptualizations (see, e.g., section 6.3.9). Summarizing, the following two chunking principles for SHARP turning concepts are added to <CEWC>:

<CEWC$_{sr}$> ::= $wc_{sr}wc_{sr}$

<CEWC$_{sl}$> ::= $wc_{sl}wc_{sl}$

Chunking LEFT/RIGHT turning concepts is a very natural chunking principle, as they constitute standard turns (<STC>), examples are TWICE RIGHT or TWICE LEFT. If two functionally equivalent standard turning concepts occur immediately one after the other and if the spatial situation allows for it, they can be conceptualized even as one action, for example, MAKE A U-TURN. Combining three functionally equivalent basic turning concepts is also possible: TURN THREE TIMES RIGHT (see Figure 57).

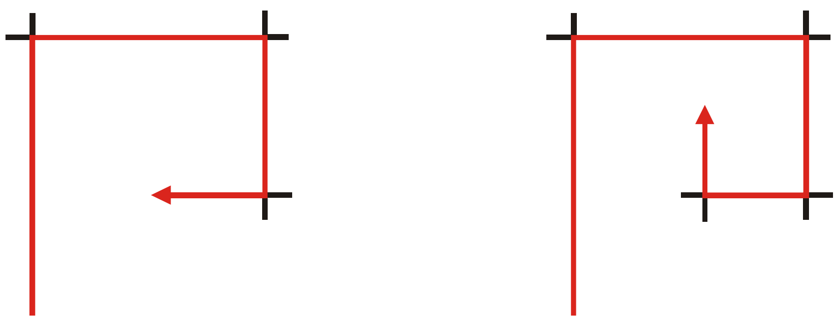

Figure 58. THREE / FOUR TIMES RIGHT.

Even though in canonical situations the number of chunked wayfinding choremes is restricted to three, a possible exception could be made for standard turning concepts (<STC>). A combination of <STC> results in a behavior that is akin to *wall following* implemented on robotic platforms (e.g., Krieg-Brückner et al., 1998). Wall following, among others, belongs to the class of basic behaviors and does not require any navigation tactics. Hence, it is easy conceptually although it may cause technical problems for robots. If such a spatial situation occurs in the real world it could be chunked as well. The problem arises that four times right is conceptualized as arriving at the same position one has started from. Additionally, there is a distinction between left and right. When a left turn is required, normally a street has to be crossed (bikers and drivers, not pedestrians), and this is not comparable to wall following anymore. To sum up, I restrict myself to the canonical case of three elements in one chunk and add the following chunking principles to the concept of <CEWC>:

<CEWC$_r$> ::= $wc_r wc_r \mid wc_r wc_r wc_r$

<CEWC$_l$> ::= $wc_l wc_l \mid wc_l wc_l wc_l$

Chunking HALF turning concepts, i.e. HALF RIGHT or HALF LEFT, is hard to specify. Regarding the change in direction, they afford the least effort and, additionally, they yielded the highest rates of agreement in study 1 (see section 4.3.1.2). Nevertheless, from a functional perspective a combination is unusual: TURN THREE TIMES HALF RIGHT. Again, this is an unlikely case to occur in real world spatial situations[42]. At subsequent decision points, the HALF turning concept may occur twice but three times is an exception. Maybe other concepts take over, i.e. *take twice the right branch* or as it is often the case when the branches are not equivalent, i.e. minor roads leading to or away from the main road. This should be examined in future experiments (see section 6.3.3.2). Here, I only define chunking principles for TWO TIMES HALF RIGHT / TWO TIMES HALF LEFT concepts:

<CEWC$_{hr}$> ::= $wc_{hr} wc_{hr}$

<CEWC$_{hl}$> ::= $wc_{hl} wc_{hl}$

Chunking <NTC>, i.e. STRAIGHT (wc_s). As wc_s belongs to the standard direction concepts, I assume the same criteria specified for LEFT (wc_l) and RIGHT (wc_r). This means that up to three wc_s are allowed in one chunk. The following chunking principles are added to <CEWC>:

<CEWC$_s$> ::= $wc_s wc_s \mid wc_s wc_s wc_s$

Summarizing this section, the following chunking principles constitute the concept of <CEWC>, i.e. the chunking of functionally equivalent wayfinding choremes:

<CEWC> ::= <CEWC$_r$> | <CEWC$_l$> | <CEWC$_{hr}$> | <CEWC$_{hl}$> | <CEWC$_{sr}$> | <CEWC$_{sl}$>

[42] Exceptions may be found in pentagon-shaped streets in Washington, DC.

5.1.2.2 Chunking Functionally Different Wayfinding Choremes

If we look at the conceptualizations of route elements as evidenced in the language data, the chunking concepts defined in section 4.3.2 all make use of the same principle. Several non-turning concepts (<NTC>) are terminated by a turning concept (<STC> or <MTC>). The basic chunking principles for combining the non-turning concept <NTC> with a turning concept (<STC> or <MTC>) can be differentiated by the number of non-turning wayfinding choremes (wc_s) that precede the terminating turning wayfinding choreme. I use <CDWC> (combining (functionally) different wayfinding choremes) for the combination of functionally different wayfinding choremes, or, to be more precise, the termination of a group of functionally equivalent wayfinding choremes (here wc_s) by one wayfinding choreme of a different kind (<STC> or <MTC>). An additional possibility is discussed at the end of this section (see Figure 61)[43]. The <CDWC> combination possibility is incorporated into the concept <HORDE>:

<HORDE> ::= <CEWC> | <CDWC>

The restrictions posed on the combination of <CDWC> follow the argumentation of the preceding section 5.1.2.1. The chunking principles for <HORDE> are not defined recursively here. The number of wayfinding choremes combined to a HORDE is restricted by canonical cognitive and pragmatic processing limitations encompassed during chunking. I start with two general chunking principles corresponding to verbal expressions such as *turn right at the second intersection* or *turn right at the third intersection*:

<CDWC> ::= <CDWC$_2$> | <CDWC$_3$>

<CDWC$_2$> ::= <NTC><STC> | <NTC><MTC>

<CDWC$_3$> ::= <NTC><NTC><STC> | <NTC><NTC><MTC>

There are various reasons to restrict the number of wayfinding choremes within one chunk:

- Numerical chunking of wayfinding choremes depends on unambiguously identifying decision points. Whereas this might be possible in a map interaction task, it is difficult in real spatial environments. Relying on unambiguous clues like landmarks is more appropriate. The effects of landmarks on chunking are discussed in the next section (5.1.2.3).
- Research on route directions relies on cognitive organization principles of route knowledge. As humans optimize their interaction qualitatively, numerical chunking occurs only in small areas (or as adaptation to highly specific

[43] Theoretically, various other possibilities are conceivable. For example, zigzag sequences (*jog about two blocks*): $wc_r wc_l wc_r wc_l$. It is possible to specify rules for these sequences. As they require further environmental information and many local 'exceptions' and peculiarities may exist, they are not accounted for in this discussion. Nonetheless, the wayfinding choreme theory can be extended if a specific spatial situation requires a specific chunk, for example: <ZIGZAG> ::= $\{XY\} \vee \{YX\},\ x \in \{wc_r\}, y \in \{wc_l\}$

situations). Humans do not store every intersection if easier organization means are available.

Therefore, the two rules for numerical chunking defined above are the only ones I will use.

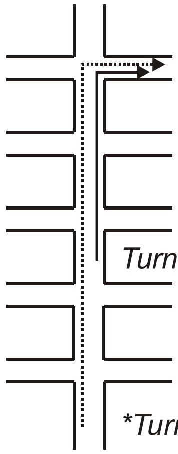

Figure 59. Chunking of functionally different wayfinding choremes.

The following discussion underlines the chosen limitation to the two chunking principles specified for <CDWC>. Imagine two successive decision points corresponding to 3-way branching points. Each of these branching points has only one branch on the right side that is the one demarcated by the route (see Figure 60). According to my model the first decision point belongs to the concept TURN RIGHT (wc_r), the second decision point belongs to the concept TURN HALF RIGHT (wc_{hr}). Would it be possible to chunk these route elements into a concept corresponding to the verbal expression *turn twice right*? If this is the case, then the chunking of the spatial situation is not a matter of combining two different wayfinding choremes but of 'misconceptualizing' one turning action.

This thesis establishes general rules for the combination of primitive route (direction) elements. A characterization of how single spatial situations are conceptualized, especially when it comes to borderline cases, is beyond the current scope of the work. In the outlook, I detail planned experiments based on research by Montello and Frank (1996) that will shed more light on influential factors of combination possibilities and the conceptualization of turning concepts at decision points (see section 6.3.3.3).

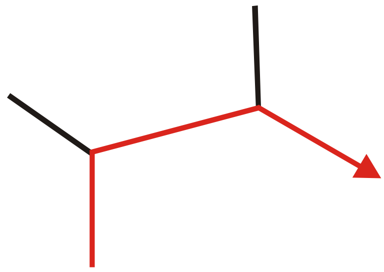

Figure 60. Exception for chunking two different wayfinding choremes? Forming the concepts TWICE RIGHT may be an option but is beyond the scope of the work at hand because it would mean that this spatial situation is 'misconceptualized' according to the 8-sector model.

It should be kept in mind that route segments play only a minor role in the present characterization of routes. The focus on decision points and wayfinding choremes, respectively, together with their combinatorial potential, i.e. HORDE, replaces the category <RoutePart> defined in section 3.4.1.

To finish this section I briefly illustrate one example for the combination of functionally different wayfinding choremes that is not included but still interesting for two reasons: First, it shows how conventions in traffic handling might play a role in the conceptualization of spatial structures. Second, it exemplifies a case where graphic and verbal concepts—even on this simple level—might not correspond. In city centers with a lot of turning restrictions it has become an established concept that one STRAIGHT and three RIGHT turning concepts are terminated by a STRAIGHT concept (see Figure 61). This situation occurs if a left turn is prohibited. Even though there may exist a graphical (analogical) concept for this combination of different actions, there is no established verbal expression. The term *p-turn* may, however, be an appropriate description. The formal treatment of this situation within the wayfinding choreme theory is detailed in section 5.3.

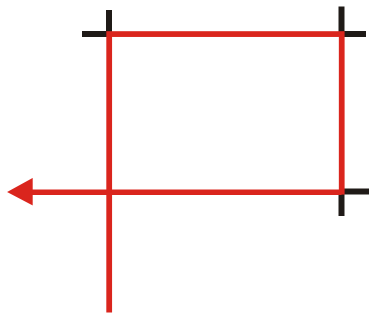

Figure 61. P-TURN: Terminating a STRAIGHT and three RIGHT turning concepts with a STRAIGHT concept to detour a forbidden left turn.

5.1.2.3 Wayfinding Choremes, Routemarks, and Structure

In the current work, the concept of a *landmark* is used in a focused sense (see section 4.1.3). In the present section, I will concretize the terminology. The following discussion is illustrated in Figure 62. First, I am only concerned with landmarks that occur along a route and that are close to the corresponding path. For this kind of landmark some researchers have coined the term *routemark* (e.g., Krieg-Brückner et al., 1998; Werner et al., 1997). I use the term routemark as a generic term including all landmarks that effect the organization of route knowledge, i.e. distant **and** close landmarks (off route and on route landmarks in the terminology of Lovelace et al., 1999). Distance is not a criterion for exclusion, for example, *follow the street until you see the castle distant on your right*. Distant routemarks fulfill a variety of functions, for example, global orientation, reassurance, and confirmation (e.g., Golledge, 1999b; Presson & Montello, 1988). Their effect on chunking is rather complex. Therefore, they are not accounted for in the present work.

Second, I distinguish between routemarks at decision points and routemarks between decision points. Herrmann and his coworkers (e.g., Herrmann et al., 1998) introduced this distinction. They termed routemarks between decision points *pathmarks* (Wegemarken). Within my systematic I coin them *routemark*^{0}.

Third, as I have already differentiated between decision points with direction change (DP+) and decision points without direction change (DP-), this distinction has to be accounted for in the categorization of routemarks. Study 3 (see section 4.3.3) has shown that landmarks at (DP+) are more pertinent to routes (cf. also Lovelace et al., 1999; Michon & Denis, 2001).

To sum up, I introduce three categories of routemarks: *routemark*$^{+}$ denotes landmarks at (DP+), *routemark*$^{-}$ denotes landmarks at (DP-), additionally, the term *routemark*^{0} denotes landmarks close to the route (path) but between two decision points (see Figure 62).

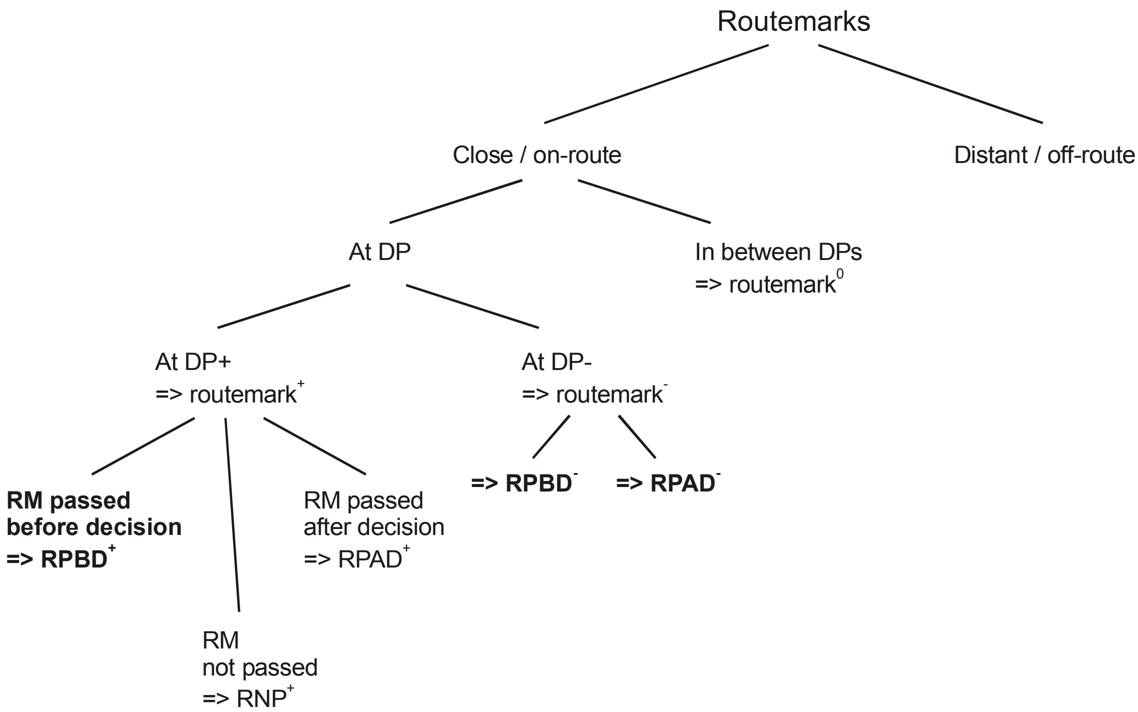

Figure 62. A taxonomy of routemarks. Categories that enter the WCRG are in bold type. The abbreviations are detailed in the text.

Additionally, it is of interest where with relation to a decision point, (DP+) or (DP-), a routemark is placed (see Figure 63, and Figure 64). Not every routemark is suited equally well to aid wayfinding and to be integrated into route directions. Note that this is a characterization based on locational spatial information (see section 3.2.2) and not on the syntax, semantics, or pragmatics of landmarks as such (cf. Raubal & Winter, 2002). The discussion of landmarks in the current work is orthogonal to work by Raubal and Winter (2002), Elias and Sester (2003), and Elias (2003). It is a specification of the locational spatial information from the perspective of mental conceptualization processes. In the experimental settings (see chapter 4) we made sure that at (DP+) primarily those routemarks are used that can be easily integrated into a route direction. This integration is afforded by their placement with respect to the decision point. More specifically this means, we chose routemarks at (DP+) that are passed immediately before a turning decision. These routemarks may be located either on the left, or, on the right side of the route. Based on this specification, I introduce a further sub-concept for routemarks, namely *routemarks passed before decision* (RPBD). The two supplementary concepts depicted in Figure 63, i.e. *routemarks not passed* (RNP) and *routemarks passed after decision* (RPAD) are not integrated in the WCRG at this point.

At (DP+) routemarks passed before decision (RPBD) work equally well for **all** turning concepts. That is, they are straightforward to conceptualize as the turning occurs immediately after them: TURN SHARP RIGHT AFTER THE POST OFFICE. Compared to TURN RIGHT AT THE INTERSECTION WHERE THE POST OFFICE IS (AT THE OPPOSITE CORNER). Especially at more complex intersections, where it is difficult to conceptualize the location of a routemark a RPBD is the only unambiguously identifiable routemark (see lower part of Figure 63). Henceforth, I refer to these routemarks at (DP+) as RPBD$^+$.

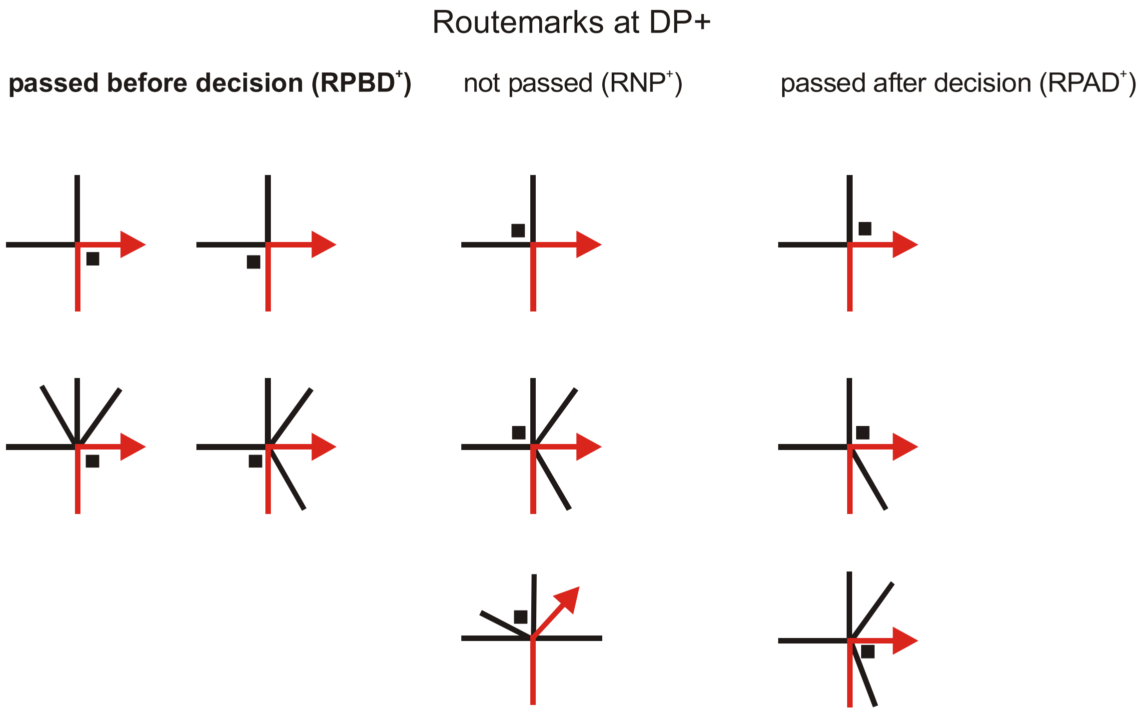

Figure 63. Possible positions of routemarks at branching points with respect to a route at a (DP+). The different positions result in different conceptualizations and not every position of a routemark functions equally well as an identifier for the required decision. The focus of the present work are routemarks passed before decision (RPBD$^+$).

Routemarks can affect chunking in a variety of ways. The discussion of all potential possibilities is well beyond the scope of the present work. This holds especially since for all placements of routemarks at (DP+) other than those passed before the decision (RPBD$^+$) further contextual parameters come into play. For example, the visual saliency of a landmark as compared to the visual saliency of the decision point itself. In the interest of the systematic treatment I concentrate on the chunking possibilities of wayfinding choremes in the specified context of RPBD$^+$. This is in congruence with the fact that RPBD$^+$ are applicable to all turning wayfinding choremes equally well (see Figure 63).

In the example: TURN RIGHT AFTER THE POST OFFICE it is obvious that the wayfinder has to follow the route until the post office is passed before the respective turn is required. It is also clear that potential decision points in between are all of the kind (DP-) with the corresponding wayfinding choreme (wc_S). A specification of the number of (DP-) is not required.

Therefore, the presence of a RPBD$^+$ increases the number of wayfinding choremes of the type wc_S that can be chunked with, i.e. terminated by, a turning wayfinding choreme to a HORDE. This means that if a RPBD is present at a decision point (DP+) all preceding wayfinding choremes of the kind wc_S can be chunked. The restriction proposed to the numerical chunking of wayfinding choremes (if no routemark is present) is overridden in the presence of a RPBD^{+}. Two reasons are decisive:

- first, no reconceptualization is necessary and
- second, the information that has to be kept in mind is very simple because the routemark disambiguates the intersection at which a turn is required[44].

The concept <CDWC>, i.e. the combination of functionally different wayfinding choremes, and the concept of higher order route (direction) elements, <HORDE>, respectively, have to be specified if routemarks are present. As I stated that a routemark passed before decision at a (DP+), i.e. RPBD^{+}, annihilates the restriction on the number of wc_s allowed before the turning wayfinding choreme, an additional concept becomes necessary, *combined straight wayfinding choremes* <CSWC>, which is defined as:

<CSWC> ::= {wc_s}

Theoretically, <CSWC> allows for combining an infinite number of straight wayfinding choremes (wc_s). In the presence of a RPBD^{+} the concept <CDWC> therefore becomes <CDWC^{R+}> that is defined as

<CDWC^{R+}> ::= <CSWC><STC^{R+}> | <CSWC><MTC^{R+}>

<STC^{R+}> ::= wc_r^{R+} | wc_l^{R+}

<MTC^{R+}> ::= wc_{sr}^{R+} | wc_{sl}^{R+} | wc_{hr}^{R+} | wc_{hl}^{R+}

Routemarks at decision points with no direction change (DP-), routemark^{-}, although they are less pertinent, are employed when several (DP-) occur in a sequence. I discuss several examples of how they might influence the chunking of wayfinding choremes. As their influence is strongly context dependent, they are excluded from the formalization. Routemark^{-} have two functions: First, they are used to identify a decision point resulting in verbalizations such as *go straight at the intersection where the McDonalds is*. Second, they are used in a way analogous to *routemarks^{0}*. A linguistic example for employing a routemark^{-} analogous to a routemark^{0} would be *pass the McDonald's and turn right after the Shell gas station*. Here it is not specified whether the routemark^{-} is placed at a decision point or between two decision points.

Two distinctions are pertinent for routemark^{-}. First, whether the routemark is passed before the decision (RPBD) or whether it is passed after the decision (RPAD). Henceforth these routemarks at (DP-) are referred to as RPBD^{-} and RPAD^{-}. Second, if a routemark is present at the corresponding (DP+), i.e. the wayfinding choreme that terminates the chunk. Both cases influence the assignment of routemark^{-} to chunking. A routemark^{-} only functions as a routemark^{0} if at least one and possibly both of the following conditions are met: (a) the routemark^{-} is of the type RPAD; (b) a routemark is

[44] Note again, that I am not concerned with the perceptual characteristics of routemarks and that for the characterization at hand I assume that they are identifiable.

additionally present at the corresponding (DP+). Figure 64 illustrates these assumptions. The following cases can be distinguished:

- Routemark^{-} is passed before decision (RPBD^{-}) and a routemark (RPBD^{+}) is present at the corresponding (DP+). The resulting concept is: PASS 'FIRST ROUTEMARK' AND TURN RIGHT AT 'SECOND ROUTEMARK'. This concept is over-specified, when only two decision points are present, the first routemark should be left out. The definition of further rules becomes problematic.
- Routemark^{-} is passed before decision (RPBD^{-}) but no routemark is present at the corresponding (DP+). This spatial situation has to be put in a rather complex concept: AFTER THE INTERSECTION WHERE A MCDONALD'S IS AT THE RIGHT CORNER TURN RIGHT AT THE NEXT INTERSECTION. Therefore, it is yet not accounted for in the WCRG.
- Routemark^{-} is passed after decision (RPAD^{-}) and a RPBD is present at the corresponding (DP+), i.e. RPBD^{+}. The resulting concept is similar to the first case: PASS 'FIRST ROUTEMARK' AND TURN RIGHT AT 'SECOND ROUTEMARK'. When only two decision points are concerned, the first routemark is left out.
- Routemark^{-} is passed after decision (RPBD) but no routemark is present at the corresponding (DP+). Here, routemark^{-} is used as a routemark^{0}: TAKE A RIGHT AFTER THE MCDONALD'S.

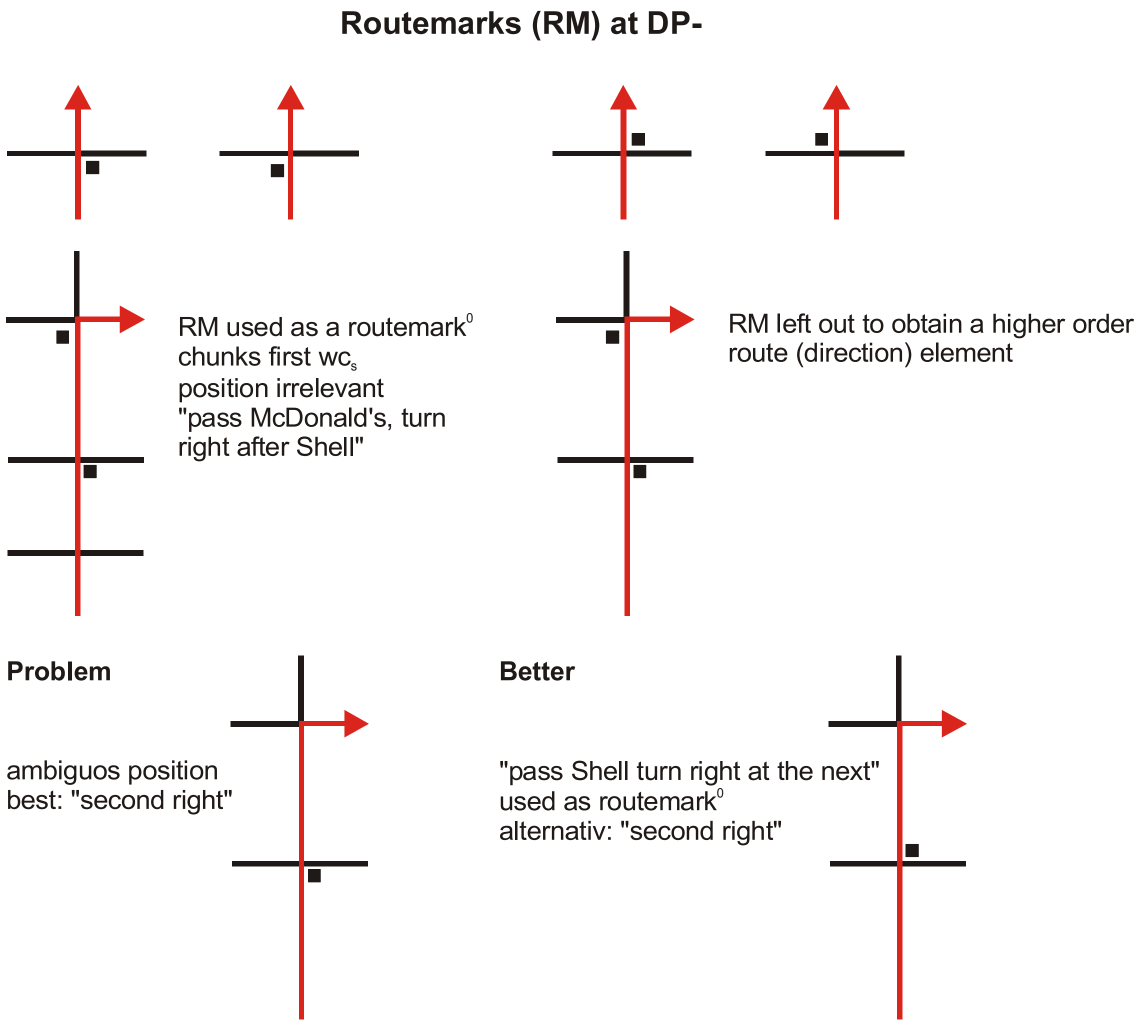

Figure 64. Routemarks at decision points without direction change (DP-).

Note that these are general rules that do not account for distances, for example. A further restriction has to be assigned to the use of routemark^{-} in chunking principles. Routemark^{-} are preferably left out when only two wayfinding choremes can potentially be chunked, independent of whether the subsequent (DP+) is marked with a routemark or not. In linguistic terms this means that a chunk like *turn right at the second intersection* or *turn right after the post office* (if only one (DP–) is passed) is preferred to non chunked wayfinding choremes: *go straight at the intersection where the McDonald's is and turn right at the next intersection* or *go straight at the intersection where the McDonald's is and turn right after the post office*.

With this characterization of routemark^{-}, I have also characterized the role of routemark^{0} for chunking principles. The straight wayfinding choreme (wc_s) can be employed at routemarks^{0} as well as at decision points. This perspective adds another aspect to the possibilities of partitioning a route suggested by Couclelis (1996) (see section 6.3.2.1).

Study 2 on chunking (see section 4.3.2) has shown that **structure** can be employed as a very efficient 'routemark' (cf. also Mark, 1986). For structure chunking only those intersections are employed that enforce a turn at a decision point, i.e. a route dead-ends. This is the case when a T-Intersection occurs along the route and is traversed in dead-end fashion. Corresponding verbalizations are, for example, *follow the route until it dead ends and turn right*. Therefore, a T-intersection influences the rules for chunking even stronger than those specified for routemarks at decision points with a direction change. First, the restriction on STRAIGHT wayfinding choremes is annihilated, i.e. the recursively defined category of combined straight wayfinding choremes <CSWC> is applied. Second, the presence of landmarks before the T-intersection is completely ignored.

The concept <CDWC>, i.e. the combination of functionally different wayfinding choremes, and the concepts of higher order route (direction) elements, <HORDE>, respectively, have to be specified if a T-intersection occurs. In the presence of a T-intersection the concept <CDWC> therefore becomes <CDWC^T> that is defined as

$$\langle CDWC^T \rangle \quad ::= \langle CSWC \rangle \langle STC^T \rangle$$

$$\langle STC^T \rangle \quad ::= wc_r^T \mid wc_l^T$$

SHARP and HALF turns are no cardinal concepts at dead ends. They are not accounted for in the present state of the work. Further behavioral research is necessary to work out the interaction between dead ends and SHARP and HALF turning concepts.

5.2 The Wayfinding Choreme Route Grammar

In the preceding sections, I elaborated on the basis for characterizing routes by means of wayfinding choremes. It was important to show that not only wayfinding choremes and complete routes can be characterized, but additionally, that chunking principles for an intermediate level can be defined. I refer to chunked wayfinding choremes as HORDE.

The grammatical notation is an appropriate tool for a systematic analysis of routes. It provides a means for route characterization based on of wayfinding choremes and determines rules for their combination. The grammar reflects mental conceptualization processes. The WCRG is also intended to guide the depiction of routes, i.e. route information, in modern navigation systems, for example, LBS/GPS based PDA navigation (see section 5.4). The WCRG is a context free grammar. It is not intended to prove whether a given route in its completeness is a valid part of the wayfinding choreme route grammar. Several spatial situations, such as roundabouts or places, are not yet part of the characterization. For the time being, they are left undefined. Some suggestions how to deal with them are discussed in section 6.3.1.

The wayfinding choreme route grammar is a tuple WCRG = (*N, T, P, S*) where

- *N* is a finite set of nonterminal symbols
- *T* is a finite set of terminal symbols (disjoint from *N*)

- P is a finite set of production rules of the form α ::= β where α is a nonterminal symbol.
- The start symbol is <Route>

N = {<DecisionPoint>, <DecisionPoint^2>, <STC>, <NTC>, <MTC>, <HORDE>, <HORDE^2>, <CEWC>, <CEWC$_r$>, <CEWC$_l$>, <CEWC$_{hr}$>, <CEWC$_{hl}$>, <CEWC$_{sr}$>, <CEWC$_{sl}$>, <CDWC>, <CSWC>, <CDWC$_2$>, <CDWC$_3$>, <CDWC^{R+}>, <CDWC^T>, <Route> }

T = {Origin, Destination, wc_{sr}, wc_r, wc_{hr}, wc_s, wc_{hl}, wc_l, wc_{sl}, wc_r^{R+}, wc_l^{R+}, wc_{sr}^{R+}, wc_{sl}^{R+} wc_{hr}^{R+}, wc_{hl}^{R+}, wc_r^T, wc_l^T, ε}

P = {

<Route> ::= Origin<X>Destination

<X> ::= <X><DecisionPoint^2> | <DecisionPoint^2> | <X><HORDE^2> | <HORDE^2> | ε

<DecisionPoint^2>::= <DecisionPoint> | <DecisionPoint><DecisionPoint>

<DecisionPoint> ::= <STC> | <NTC> | <MTC>

<HORDE^2> ::= <HORDE> | <HORDE><HORDE>

<HORDE> ::= <CEWC> | <CDWC> | <CDWC^{R+}> | <CDWC^T>

<CEWC> ::= <CEWC$_r$> | <CEWC$_l$> | <CEWC$_{hr}$> | <CEWC$_{hl}$> | <CEWC$_{sr}$> | <CEWC$_{sl}$>

<CDWC> ::= <CDWC$_2$> | <CDWC$_3$>

<CDWC$_2$> ::= <NTC><STC> | <NTC><MTC>

<CDWC$_3$> ::= <NTC><NTC><STC> | <NTC><NTC><MTC>

<CDWC^{R+}> ::= <CSWC><STC^{R+}> | <CSWC><MTC^{R+}>

<CDWC^T> ::= <CSWC><STC^T>

<STC> ::= wc_r | wc_l

<STC^{R+}> ::= wc_r^{R+} | wc_l^{R+}

<STC^T> ::= wc_r^T | wc_l^T

<NTC> ::= wc_s

<MTC> ::= wc_{sr} | wc_{hr} | wc_{hl} | wc_{sl}

<MTC^{R+}> ::= wc_{sr}^{R+} | wc_{sl}^{R+} | wc_{hr}^{R+} | wc_{hl}^{R+}

<CEWC$_r$> ::= $wc_r wc_r$ | $wc_r wc_r wc_r$

<CEWC$_l$> ::= $wc_l wc_l$ | $wc_l wc_l wc_l$

<CEWC$_{hr}$> ::= $wc_{hr} wc_{hr}$

<CEWC$_{hl}$> ::= $wc_{hl}wc_{hl}$

<CEWC$_{sr}$> ::= $wc_{sr}wc_{sr}$

<CEWC$_{sl}$> ::= $wc_{sl}wc_{sl}$

<CSWC> ::= $\{wc_s\}$

}

5.3 Term Rewriting

In the wayfinding choreme route grammar (WCRG) I specified valid combinations of wayfinding choremes, i.e. higher order route direction elements (HORDE). For the application of the chunking principles it is not sufficient to merely describe valid chunks. It is necessary to show how these chunks can be extracted from a route characterized by wayfinding choremes. A formal language is determined by its strings over a finite alphabet. In the present work, the wayfinding choremes constitute the finite alphabet; HORDE represent finite strings of wayfinding choremes. A route is formally described by its corresponding string of wayfinding choremes, for example:

$R := wc_swc_swc_rwc_swc_{sr}wc_rwc_{sl}wc_swc_{hr}wc_swc_swc_r$

From the route string, R, HORDE can be identified as substrings. For example, a spatial situation corresponding to the natural language expression *turn right at the third intersection* is a concatenation of the following three wayfinding choremes: $wc_swc_swc_r$. Whereas valid combinations of wayfinding choremes are determined by the WCRG, the extraction of HORDE from a route is modeled with *term rewriting* (Dershowitz, 1993). This method has recently been applied to the modeling of terrain silhouettes as linear patterns with a limited set of shape primitives (Kulik & Egenhofer, 2003) that bear similarities to wayfinding choremes. The rules for HORDE are taken from the WCRG.

R denotes a string representation of wayfinding choremes (a route). To obtain HORDE from R, the string is processed sequentially (see also Figure 56). The rules defined below are processed in the order given. Each rule is applied to the complete string before the next rule is used. The first rules handle the extraction of HORDE in which functionally different wayfinding choremes are chunked, abbreviated here as **dwc** (different wayfinding choremes). The destination of a route (Destination) is formally treated as a turning wayfinding choreme with a routemark.

I start with the two most straight forward cases. These cases occur when a routemark or a 'correctly' aligned T-intersection (it hinders moving straight on) is present at a turning wayfinding choreme that terminates a string of STRAIGHT wayfinding choremes. As discussed in section 5.1.2.3 these spatial situations bear the possibility to form large chunks because the number of wc_s before the turning wayfinding choremes is not restricted. Rules (D1) and (D2) specify these cases. (D1) characterizes the case when a routemark is present at the turning wayfinding choreme; (D2) is the rule for T-intersections.

(D1)	$(n\ wc_s)tc^{R+}$	→	dwc^{R+}	$n \in \mathbb{N}, tc^{R+} \in \{<NTC^{R+}>, <MTC^{R+}>, \text{Destination}\}$
(D2)	$(n\ wc_s)stc^{T}$	→	dwc^{T}	$n \in \mathbb{N}, stc^{T} \in \{wc_r^T, wc_l^T\}$

If no routemark or T-intersection is present at the turning wayfinding choreme, further structuring is possible. The easiest instances are those where only one or two STRAIGHT wayfinding choremes precede a turning wayfinding choreme and no additional environmental information is available for any wayfinding choreme. The three elements case (see rule D3) is a combination of two wayfinding choremes for STRAIGHT, wc_s, and a turning wayfinding choreme, for example, *turn right at the third intersection*. The rule for 2 elements is given in (D4).

(D3)	$wc_s wc_s tc$	→	dwc^{3tc}	$tc \in \{<NTC>, <MTC>\}$
(D4)	$wc_s tc$	→	dwc^{2tc}	$tc \in \{<NTC>, <MTC>\}$

Given the unlikely case that a sequence of more than two STRAIGHT wayfinding choremes is terminated by a turning wayfinding choreme and no additional information is available, it is possible to adopt further chunking principles. These rules are discussed in section 5.1.2.1. (D5) specifies the case of three wc_s, (D6) supplies the rule for two wc_s.

(D5)	$wc_s wc_s wc_s$	→	dwc^{3s}
(D6)	$wc_s wc_s$	→	dwc^{2s}

The influence of other routemarks is discussed in section 5.1.2.3. Chunking with respect to routemarks is strongly dependent on the properties of the routemark, as, for example, discussed in Raubal & Winter (2002). I leave it with the discussion in section 5.1.2.3 and turn to the chunking of functionally equivalent wayfinding choremes, here abbreviated as **ewc**. The rules are again derived from the valid combinations specified in the WCRG. Therefore, I do not motivate them here in detail. The order of their processing is provided in rules (E1) to (E8).

(E1)	$wc_r wc_r wc_r$	→	ewc_r^3
(E2)	$wc_r wc_r$	→	ewc_r^2
(E3)	$wc_l wc_l wc_l$	→	ewc_l^3
(E4)	$wc_l wc_l$	→	ewc_l^2
(E5)	$wc_{sr} wc_{sr}$	→	ewc_{sr}^2
(E6)	$wc_{sl} wc_{sl}$	→	ewc_{sl}^2
(E7)	$wc_{hr} wc_{hr}$	→	ewc_{hr}^2
(E8)	$wc_{hl} wc_{hl}$	→	ewc_{hl}^2

I show the potential of this approach by illustrating the integration of one special concept that has been illustrated in Figure 61, i.e. the P-TURN. This is the spatial situation where a left turn is prohibited but an alternative is given by 'driving around the block'. In this case five wayfinding choremes are chunked: $wc_s wc_r wc_r wc_r wc_s$. I termed this concept *p-turn*, pt. It is formally specified in rule (P1). For the term rewriting process, it is crucial at which position in the order of processing this rule is added. To avoid conflicts with other HORDE, (P1) could be processed as the first rule, i.e. before (D1). This is an example of how to integrate new rules.

(P1) $wc_s wc_r wc_r wc_r wc_s \rightarrow pt$

To summarize this section I detail the procedure with one example illustrated in Figure 65. The first step is to transduce the route into a string of wayfinding choremes. This is accomplished by assigning every decision point the corresponding wayfinding choreme according to the 8-direction model. The string R is the description of the route depicted in Figure 65.

$$R := wc_s wc_s wc_r wc_s wc_s wc_s wc_s wc_l^T wc_s wc_r wc_s wc_s wc_r^{R+} wc_l wc_l wc_r wc_r wc_s wc_l$$

Applying rules (D1) and (D2) extracts those substrings that can be chunked due to additional information that is available at turning wayfinding choremes that are preceded by wc_s.

$$R := wc_s wc_s wc_r dwc^T wc_s wc_r dwc^{R+} wc_l wc_l wc_r wc_r wc_s wc_l$$

Rules (D3) and D4) simplify the route string to

$$R := dwc^{3r} dwc^T dwc^{2r} dwc^{R+} wc_l wc_l wc_r wc_r dwc^{2l}$$

Finally the rules for chunking functionally equal wayfinding choremes, (E1) to (E8), are applied. Resulting in the concluding characterization of the route by wayfinding choremes and HORDE, respectively:

$$R := dwc^{3r} dwc^T dwc^{2r} dwc^{R+} ewc_l^2 ewc_r^2 dwc^{2l}$$

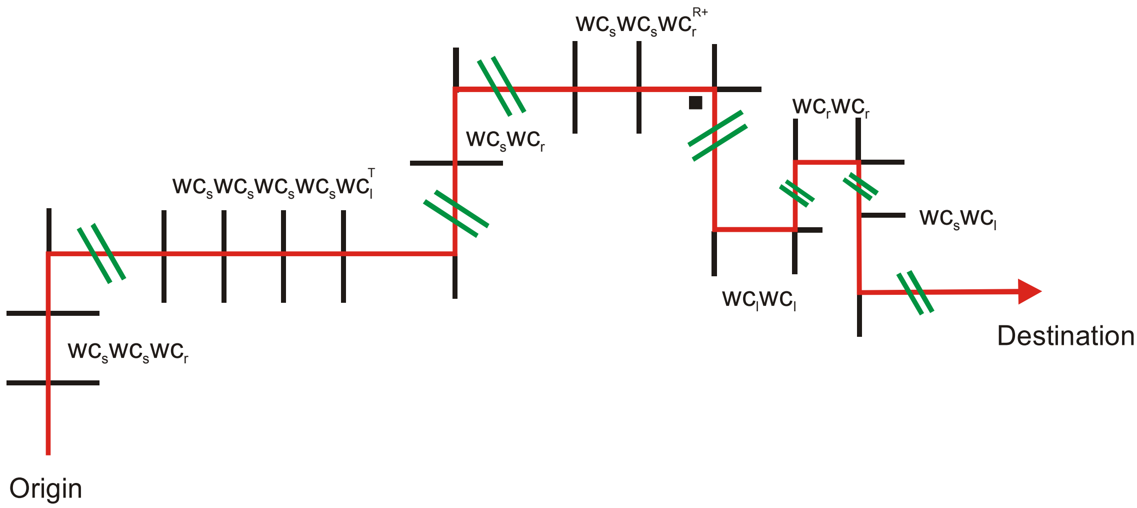

Figure 65. Example of a route characterized by chunks of wayfinding choremes.

5.4 Wayfinding Choremes and Their Depiction

In the remaining sections of this chapter I detail how wayfinding choremes can be used to depict route information. To start, section 5.4.1 discusses the contradiction within Brunets theory between conceptual models and their visualization. I argue how this contrariety can be overcome within the present work by focusing on route directions and empirical analyses. The abstract conceptual characterization of routes by I–wayfinding choremes (see section 5.1-5.3) may bear ambiguities in certain spatial situations. Most ambiguities are resolved by the graphical representations. Section 5.4.2 details this solution. Three steps are compulsory for the visualization of wayfinding choremes (see section 5.4.3): Focus on a decision point, replacement of functionally relevant parts by a wayfinding choreme, and the alignment of the depiction. Finally, section 5.4.5 demonstrates how the sketch map-like depictions of route information suggested by Agrawala and Stolte (2000, 2001) and Agrawala (2001), and their realization in mapblast (www.mapblast.com), can be improved by employing wayfinding choremes, i.e. by taking a cognitive conceptual approach.

5.4.1 On Theory and Practice

> "Geographers have always aspired to represent environments on maps and have been concerned with how effectively their maps communicated information about environments. It is this desire to communicate spatial information effectively that has caused geographers to be interested in the cognitive processes people use when interacting with cartographic maps. Some environments have unique characteristics that make their representation especially interesting." (Lloyd, 1993, p. 141)

Consider the choreme table by Brunet (see Figure 6 in section 2.2.4) and the example of chorematic depiction (see Figure 66). It is easy to recognize that the choremes detailed in the table of choremes are not directly applicable to map construction. Even in their graphical realization, they are not intended as one unalterable instantiation. Rather, they provide the map designer with ideas of how to structure the spatial information available. Therefore, the automatization of their application is not achieved yet and many design decisions lie in the hands of the cartographer/geographer (cf. unsolved problems of generalization, e.g., Beard, 1991; Meng, 2003). As I restrict myself to the characterization and the depiction of route information the problem of automatically depicting spatial information can be solved in this case for the following reasons:

A restriction to route information. The empirical study on conceptualizing turns at decision points has affirmed that humans conceptualize behavioral patterns prototypically. In contrast to more abstract concepts, for example, schemata (see section 2.2.1), I showed that it is possible to specify **one** functional prototype for 7 basic turning concepts at decision points (E–wayfinding choremes).

Employing an 8-direction model. If, for example, a constraint is set up that every intersection has to be schematized by employing 90° angles it becomes obvious that a map as a whole cannot be schematized this way. The result would be a city block raster that obviously does not fit every spatial configuration. This problem is relaxed somewhat when we focus on route maps, i.e. depicting a route from an origin to a destination (cf. Agrawala & Stolte, 2000). Nevertheless, the 90° constraint set up by Tversky and Lee (1998, 1999) is disproved here. According to the data on drawings of turning concepts (see section 4.3.1) a 45° constraint is confirmed instead. This constraint fits the needs of European street layouts better and is in congruence with functional conceptualizations (I–wayfinding choremes). Nonetheless, the need for further refinements may arise (see section 6.3.2.2).

Taking a functional perspective. In several chapters of this work I stressed the importance of a functional perspective. This reduces the number of primitives and focuses on the essential aspects from a cognitive scientific point of view. As a concequence, only the functionally relevant parts of a branching point are re-coded by an E–wayfinding choreme; it is embedded in the structure that is otherwise left ‘unchanged’.

For these reasons, it is possible to automate the depiction of route information by wayfinding choremes. The specifications set up here are supported by empirical evidence. Thus, the wayfinding choreme approach allows for cognitive conceptual map construction.

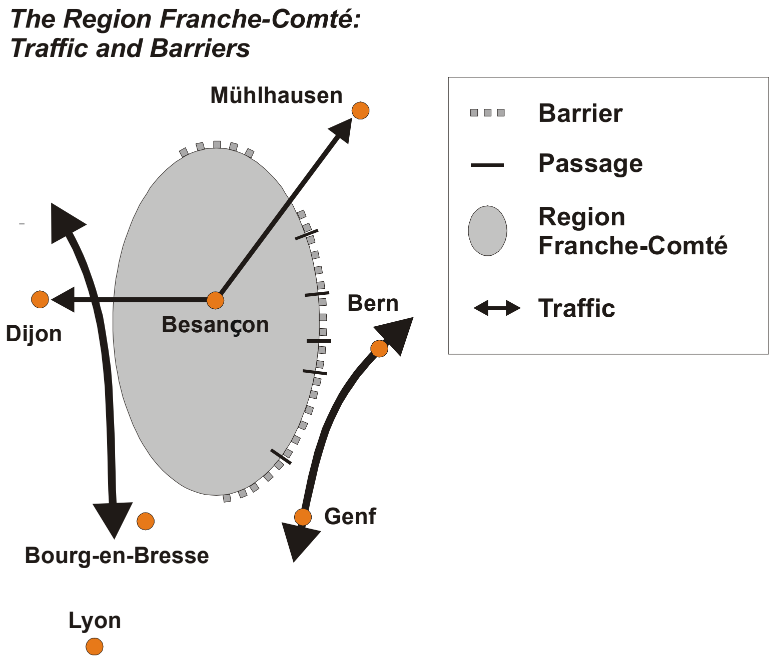

Figure 66. Example of a choreme map (Moine, 1994, modified).

5.4.2 Resolving Ambiguities

The graphical representation of E–wayfinding choremes resolves ambiguities that may arise by I–wayfinding choremes. Graphic E–wayfinding choremes are rooted in a spatial structure. Comparable to behavioral patterns, i.e. taking two branches of an intersection and leaving the other branches as they are, graphic E–wayfinding choremes are embedded in the structure that is provided by the corresponding branching point. This means that in opposition to abstract mental concepts and linguistic expressions that do not specify the spatial structure, this information is depicted with the graphic E–wayfinding choreme. The actual graphic instantiation resolves ambiguities, as different information sources can be used at the same time: a turning concept plus the ordering information of the branches. The combination of aspectualized information embedded in rich information sources has proven to be a natural and effective way of communication.

The veridicality of an intersection—number of branches, angle between branches—adds to the function of an intersection as a routemark. Prototypical intersections, i.e. those structurally prototypicalized, cannot accomplish this function well (see Figure 14). For example, if there is a wayfinding choreme with a corresponding linguistic expression *turn half right at the next intersection* this specification of a direction may be ambiguous if we assume an 8-sector model. More than one street may fit to the concept HALF RIGHT. By embedding the wayfinding choreme into the structure of the branching point the ordering information provided by the branches is accessible: Since the wayfinding choreme is ordered with respect to the other branches, ordering information disambiguates the situations (see Figure 67).

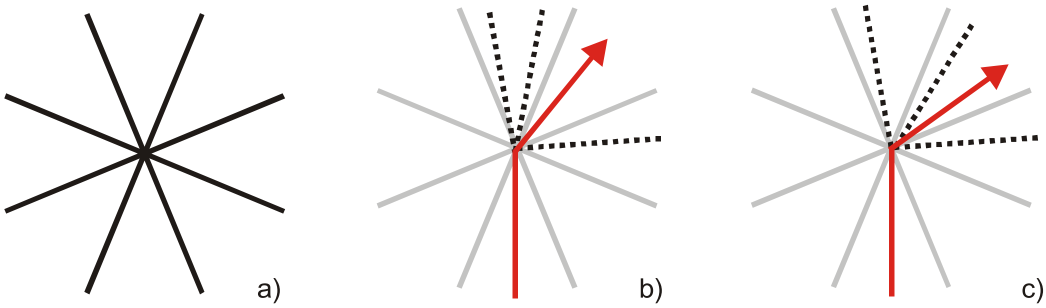

Figure 67. (a) is the homogenous 8-sector model that is taken as the basis for the wayfinding choreme model. The other parts of the figure, (b) and (c), illustrate spatial situations that may be ambiguous with respect to the wayfinding choreme approach. The dotted lines represent additional branches at an intersection.

The red lines in Figure 67 depict the intended route segments that corresponds to the concept HALF RIGHT. In example (b) the I–wayfinding choreme or a verbal E–wayfinding choreme—underspecified as they are—could result in problems on how to decide which branch to take. The branch left of the route segment to take (dotted lines) might also fit into the category HALF RIGHT. In contrast, there is no problem to communicate the action to perform by the corresponding graphical E–wayfinding choreme. The pictorial representation, due to its analogical character, provides this information without additional effort.

In figure (c) the problem gets somewhat trickier and cannot be resolved in every case. The wayfinding choreme can be assigned the same way as in (b) but theoretically several things could happen. Schematizing the path segment to take according to the given wayfinding choreme leads to a problem if the 45° direction is already occupied by another path segment. In the worst case scenario the ordering information could even reverse. This case does hardly occur in physical environments, as the configuration of streets is constrained by their width. Actually, problematic street configurations are often circumvented by roundabouts or places (see section 6.3.2.2 and Figure 73).

Summarizing, the model of wayfinding choremes comprises three levels with different advantages for the specification of route information and their communication. These levels are:

- The abstract conceptual level, i.e. the level of I – wayfinding choremes.

Two levels of externalizations, i.e. E–wayfinding choremes:

- Linguistic externalizations that are closest to I – wayfinding choremes. Here, flexibility is maintained but problems can arise due to the underspecified character of language.
- Graphic externalization that are bound to a two-dimensional representational medium and inherit the benefits and the constraints of an analogical representation.

> "This luxurious enrichment of even a simple piece of geographical information is due to the fact that a map is an iconic image, a graphic analogue, which shares certain visual properties of the object it represents." (Arnheim 1976, p. 5)

5.4.3 Obtaining Wayfinding Choreme Maps

Generally, I distinguish between wayfinding choremes employed for mobile wayfinding assistance or partial route information and wayfinding choremes for depicting complete route information, from origin to destination. The wayfinding choremes as such do not change but what changes are primarily the technical factors. In the following sections, I detail the procedure for mobile assistance and partial route information. In section 5.4.5 I describe the principal proposal for complete routes by taking the approach of Agrawala and Stolte (2000, 2001) as a motivation. The three cardinal steps for depicting route information by wayfinding choremes in a mobile assistance system are:

- focus on decision points,
- substitution of functional parts, and
- alignment of the representation.

5.4.3.1 Focus on Decision Points

As worked out within this thesis, decision points are the most vital parts of routes and route directions, respectively. Therefore, they play a major role in route directions—graphically and verbally. Within the category of decision points, those that require a change in direction of traveling are most pertinent.

For the depiction of route information in mobile devices, two general possibilities have to be taken into account: First, to depict every decision point explicitly. Second, to apply rules for chunking wayfinding choremes to HORDE. As these rules have been set up on a general basis, there are other influential factors that have not been examined yet, for instance, distance. Nevertheless, the presentation of route information pregrouped into sensible chunks is a next step to achieve cognitive adequacy. Here, I exemplarily focus on the depiction of information at two decision points combined into a chunk.

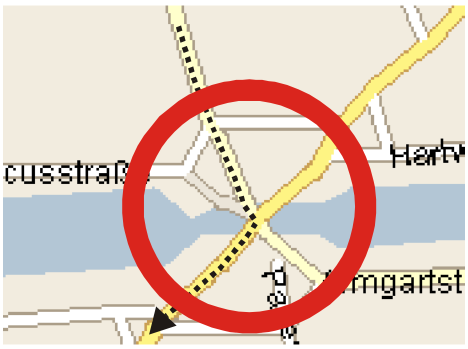

Figure 68. Focus on one decision point (www.mapblast.com, arrow and red circle added).

Figure 68 shows an example of a pictorial representation of a decision point along a route. This depiction is taken from a common internet service that provides map-based route information (www.mapblast.com). Depicted is an intersection in the city of Hamburg. For a route direction I will first focus on the relevant decision point. In the illustrated case the action to be performed is conceptualized as a HALF RIGHT turn.

5.4.3.2 Substituting Functional Parts by Wayfinding Choremes

As indicated in several figures (see Figure 32) there are functionally relevant parts of an intersection. These parts are the route segment an agent is on, or, when she is at the center of a decision point, the route segment where she has come from, and the route segment that she has to choose. These two parts build the basis for wayfinding choremes. A wayfinding choreme alone cannot always tell the whole story (see 5.4.1). Hence, it is embedded in the complete and veridical spatial situation at a decision point (see Figure 69). Only the functionally relevant parts of the intersection are substituted by the corresponding wayfinding choreme, i.e. wc_{hr}.

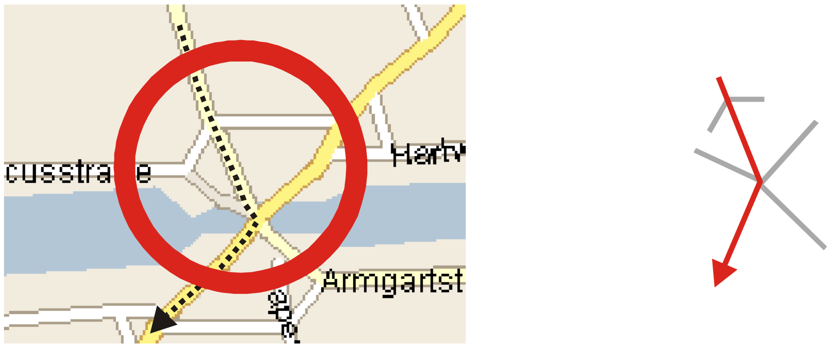

Figure 69. An example of replacing the functionally relevant parts of an intersection by an E–wayfinding choreme. The prototypical functional information at a decision point is regarded as the most pertinent information. This information is clearly communicated by the E–wayfinding choremes: $wc_s wc_{hr}$ (map: www.mapblast.com, arrow and red circle added).

Again, the two objectives for this approach are:

- The action that has to be performed at a decision point has to be communicated clearly. This is best accomplished by employing E–wayfinding choremes.
- Overschematization leads to wrong inferences (e.g., Berendt, Rauh, and Barkowsky, 1998). Therefore, an alternative strategy is chosen, i.e. a combination of veridical information (for recognition and pattern matching) and prototypical information (wayfinding choremes) for the communication of the required action.

Different to existing solutions and navigation systems, a wayfinding choreme based navigation assistance system focuses on the functional information for which prototypical graphical concepts can be determined (E–wayfinding choremes). The conceptualization of an action that takes place at an intersection demarcates branches that are emphasized, branches that are not functionally involved are deemphasized.

5.4.3.3 Aligning Wayfinding Chorematic Representations

There is converging evidence that in spatial orientation and decision making tasks—when all three instances of the interaction triangle are involved (see section 3.2.2)—the alignment of the representation with the represented world is a crucial factor for effectiveness, i.e. the speed of decision making. Most research in this field has been carried out on You-Are-Here-Maps. Starting with Levine (1982) who examined some general features of alignment and the placement of maps within the environment, there is ample experimental research confirming the hypothesis that alignment is indeed crucial for efficient spatial problem solving (e.g., Adeyemi, 1982; Levine, Marchon, and Hanley, 1984; Presson & Hazelrigg, 1984; O'Neill, 1999; Rossano & Warren, 1989; Shepard & Hurwitz, 1984).

According to this proposition it seems more than advisable to provide spatial information in map form such that information located in front of a wayfinder can be found at the top of the graphical representation. Especially in situations where no information on complete routes is provided, but piecemeal information on the next actions to perform, alignment is a crucial factor.

Figure 70. Aligning representations with the direction of travel (map: www.mapblast.com).

5.4.4 Summary

To sum up, the three basic steps to obtain wayfinding chorematic maps for parts of the route or for individual decision points are depicted in Figure 70. These steps comprise, first, the focus on the decision point in question. Second, the replacement of the functionally relevant parts of the intersection by the corresponding wayfinding choreme. All other branches are left unchanged. Finally, the wayfinding choreme map is aligned with the direction of travel.

5.4.5 Complete Route Information

Besides advising new visualization principles to the stepwise depiction of route information, wayfinding choremes can be employed in depicting complete routes in a sketch map like fashion. This approach modifies the proposal by Agrawala (2001) and Agrawala and Stolte (2000, 2001). They started with insights on mental conceptualizations of route information, especially the work by Tversky and Lee (1998, 1999). Due to technical constraints they decided to abandon a purely cognitive conceptual approach and adapted their model to technically easier solutions. The main aspect they kept from sketch maps is the reduction of visual clutter (see section 1.1.2.1).

The approach of wayfinding choremes bridges the gap between cognitive and technical solutions by focusing on functional aspects. It enables map design that sticks to results of cognitive experimental research. Figure 71 displays one example of how a map received from the LineDraw(c) algorithm—available via mapblast (www.mapblast.com)—would look like if wayfinding choremes were employed for visualizing direction information at decision points.

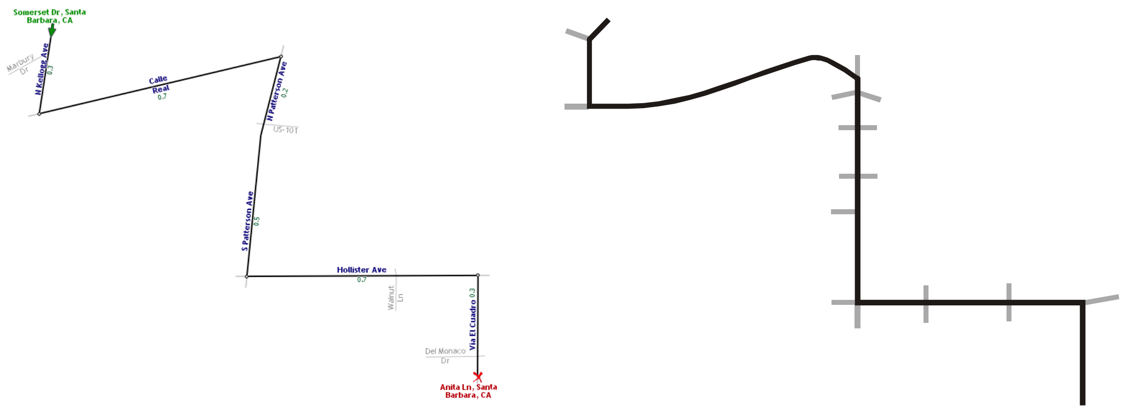

Figure 71. Wayfinding chorematic map depicting a complete route compared to an internet map (from Anita Lane (Santa Barbara) to Somerset Drive). The left part of the Figure is obtained from www.mapblast.com (now run by Microsoft(c) mappoint.msn.com with the LineDrive(SM) option, 22.05.2003).

The mapblast approach offers a straightforward solution for dealing with route segments between decision points. The decision points are simply connected. While this procedure technically eases the calculations necessary for the depiction, it also leads to distortions of the direction information at decision points. In contrast, the turning concepts at decision points are the most important information in the wayfinding choreme approach. Therefore, the route segments have to be adapted to the wayfinding choremes and not vice versa. This can be achieved, for example, by using the line simplification algorithm by Barkowsky et al. (2000) or by simply connecting the 'ends' of the wayfinding choremes by straight lines. Further differences between the two approaches are that in the wayfinding choreme model decision points (DP-) are only left out when the corresponding (DP+) is uniquely identifiable. This can be achieved by a routemark or a T-intersection (see section 5.1.2.3). Street names alone do not suffice (cf. Tom & Denis, 2003).

All's well that ends well.

6 Summary, Conclusion, and Outlook

In this work I have laid the foundation for the theory of wayfinding choremes—mental conceptualizations of primitive functional route direction and wayfinding elements. The final chapter presents a resume of the previous chapters and offers an outlook on future lines of research. Section 6.1 summarizes the core ideas and the research underlying the wayfinding choreme approach. Section 6.2 presents the results and the major findings: cognitive conceptual map construction, conceptualization of direction (turning) concepts, chunking of wayfinding choremes, route characterization, and the distinction between structure and function. Possible extensions of the wayfinding choreme theory, ongoing and future investigations are detailed in section 6.3.

6.1 Summary

The goal of this thesis was to develop a theory of wayfinding choremes. I defined wayfinding choremes as:

> **Mental conceptualizations of primitive functional wayfinding and route direction elements.**

They are a subcategory of abstract mental concepts that I defined as:

> Underspecified and above all task-specific knowledge structures, necessary for solving spatial problems, like wayfinding. An abstract mental concept is neither equal to a natural language expression nor to a specific mental image.

Humans are able to externalize their mental conceptualizations via different output channels. To demarcate the internal concepts from the external instantiations I introduced two terms:

> **I-wayfinding choremes** – mental conceptualizations of primitive functional wayfinding and route direction elements.
>
> **E-wayfinding choremes** – the graphical or verbal externalizations of mental conceptualizations of primitive functional wayfinding and route direction elements, i.e. the externalizations of I-wayfinding choremes.

The investigation of wayfinding and route directions is a multidisciplinary endeavor. One rationale behind this interest is that for the study of space from a cognitive point of view, wayfinding and route directions constitute a unique field of research. They are both objects of investigation and probes for the study of spatial cognition in general. They are a *window to cognition* for those seeking to reveal cognitive processes on organizing, representing, and processing spatial knowledge.

In the interest of space and in order to control for influencing parameters, the scope of the present investigation was restricted to an idealized cognizer who is navigating and wayfinding in a city street network environment. This was necessary because the characteristics of environments as well as the means of travel influence both approaches to cognitive adequacy: the modeling of cognitive processes on the one hand and cognitive human engineering on the other hand. The results of this work can be extended to the modeling of further spatial domains.

Based on behavioral experiments graphical instantiations of I–wayfinding choremes were individualized to allow for their direct application to map construction (see section 4.3.1). Further experiments have detailed their combinatorial possibilities and their interaction with routemarks (see section 4.3.2 and 4.3.3). Wayfinding choremes enable the aspectualization of spatial information from a cognitive science perspective; this means that they result from active processes that structure environmental information. This is reflected in the term *conceptual structuring processes* that I used in section 3.2.1 to denote active processes that organize the information between the world and the wayfinder and between the wayfinder and the map. The reasons that there are benefits to aspectualization (see section 1.1.2) explain the benefits of the wayfinding choreme theory:

- **Visual-perceptual considerations.** Graphic E–wayfinding choremes specify a method to depict route information. Brunet (1987) claimed that his choremes possess a 'Gestalt'. This holds for wayfinding choremes as well. The exact details of their visualization are subject to further research. In their present state, they fulfill requirements of good map design: readability, clarity, and completeness with respect to the task at hand.
- **Cognitive conceptual considerations.** The wayfinding choreme theory adds to the four advantages of aspectualization from the cognitive conceptual perspective. Wayfinding choremes reduce the abundance of information (seven primitives that can further be aspectualized by the chunking principles). They therefore reduce working memory load. Their integration (matching) with other information sources is achieved as they are embedded into veridical spatial structures, i.e. only the functionally relevant parts of an intersection are re-coded by a wayfinding choreme. Positive effects on the speed of decision making are expected.
- **Informatics and AI considerations.** As pointed out in section 2.3, AI and especially qualitative spatial reasoning research is concerned with the identification of conceptual spatial primitives. Wayfinding choremes are primitives and their applicability to characterize route information from a

cognitive perspective was shown in chapter 5. The elegance of the wayfinding choreme approach stems from the fact that only seven primitives are sufficient and that on their basis HORDE can be determined.

- **Technical considerations.** The technical advantages of the wayfinding choreme theory are related to the above mentioned benefits. Graphic E-wayfinding choremes have a clear shape. No matter how low the resolution of a display is, wayfinding choremes are applicable.

The wayfinding choreme theory is an important step towards the development of an approach to map making that I termed *cognitive conceptual*, i.e. abstract mental concepts of spatial situations guide the depiction of locational spatial information (see section 3.1).

In chapter 5 the model of the wayfinding choremes was described with its two major aspects. The formulation of the wayfinding choreme route grammar and the analysis of possibilities to employ wayfinding choremes in the depiction of route information. Wayfinding choremes offer the possibility for a high applicability within all sorts of visualizations that afford electronic displays in the place of paper, like for example PDAs. This is the case because they fulfill various prerequisites that have been defined for map-like screen display.

6.2 Results and Major Findings

6.2.1 Cognitive Conceptual Map Construction

Cognitive conceptual map construction relies on cognitive organization principles for choosing spatial relations depicted in a map. As the first researcher that can be credited for this approach, I identified Brunet. His approach aimed explicitly at using (abstract) conceptual models, such as *boundary, hierarchy,* or *area of influence*, for the construction of maps. Tversky (2000) would contradict this point of view as she claims that maps generally reveal mental conceptions of space. There is some truth in her claim, especially when we think of medieval time when the earth was believed to be flat and contemporary maps reflected this view. For modern maps that partially aim at a veridical representation of the world this does not hold. In my opinion, there is a difference between cognitive processes relevant for designing a map and the explicit aim to reflect cognitive concepts in a map. In the first case, the design of a map may reveal a great intellectual effort of a large group of map makers that rely on established technical and graphical standards. In the latter case, the intention is to establish a close correspondence between internal and external concepts. The rationale behind this aim is cognitive adequacy; both from the perspective of cognitive modeling and cognitive ergonomics.

Brunet's theory, chorematic modeling, laid the foundation for the identification and depiction of systematic patterns. First, these patterns can be reduced to a limited number of abstract models of spatial phenomena and, second, as he specified corresponding graphic models, they also can be used for the construction of maps. Even though he made no explicit connection to cognitive science research, several correspondences exist and might be worth further analyses (see sections 2.2.1 and 2.2.4).

Brunet's approach, however, is not applicable to automated map construction. His claim to develop a *language for maps* failed to spell out the interactions of the primitives (choremes). What is missing is a grammar that specifies valid combinations of choremes. I leave it open whether the wayfinding choreme approach can be extended to fill the range of Brunet's theory, i.e. for the entirety of geographic phenomena. I was able, however, to show that for a more restricted domain it is possible to ascertain conceptual spatial primitives (models) on the one hand and their graphic realization in a map on the other hand. Within this scope it is possible to aim at the automatic construction of maps. The important point here is: it shows that the combination of conceptual spatial primitives and graphic instantiations is possible. It broadens the use of maps as a means of modeling cognitive processes (cf. Berendt, Barkowsky et al., 1998).

6.2.2 Benefits of the Wayfinding Choreme Approach

The main advantage of the wayfinding choreme approach is that it provides a clear-cut description of routes in network structures. It takes in—at a minimum level of information—all that is vital to reach a destination from a preset origin. For example, the characterization of the route in Figure 65

$$wc_s wc_s wc_r wc_s wc_s wc_s wc_s wc_l^T \, wc_s wc_r wc_s wc_s wc_r^{R+} \, wc_l wc_l wc_r wc_r wc_s wc_l$$

Generally, this abstract description is transducable into graphical primitives without any need for adaptation. Additionally, the chunking principles detailed (see section 5.1.2) can be applied to this primary description. By employing this simplification the route information becomes simpler, shorter, and cognitively more adequate. The route string given above can be rewritten into

$$dwc^{3r} dwc^T dwc^{2r} dwc^{3r} ewc_l^2 \, ewc_r^2 \, dwc^{2l}$$

The wayfinding choreme model has the potential to transduce abstract mental concepts into graphical instantiations. Hence, within the particular framework for the depiction of route information (see section 5.4) the criteria of a cognitive conceptual approach suffice. From the viewpoint of conceptualizations of locational spatial information the work at hand offers the possibility to evaluate current navigation systems. As we will see in section (6.3.1), the wayfinding choreme model can be extended to integrate additional findings on wayfinding and wayfinding support by augmenting the initial set of wayfinding choremes.

6.2.3 Empirical Results for Wayfinding and Route Directions

I support the proposition by Tversky and Lee (1998, 1999) that pictorial and verbal route directions originate in common conceptual structures (common abstract mental concepts). I referred to these abstract mental concepts as I–wayfinding choremes. I–wayfinding choremes can be externalized by various output modalities and are then referred to as E–wayfinding choremes. Most pertinent to the work at hand are pictorial E–wayfinding choremes followed by verbal ones. Other possible externalizations (like sign language) were not further examined.

The crucial difference between the wayfinding choreme model and the proposal by Tversky and Lee lies in the functional perspective inherent in wayfinding choremes. The functional perspective stresses the conceptualization of actions performed during wayfinding and in the communication of route directions. This holds for both graphical and verbal E–wayfinding choremes. Substituting the graphical primitives in a pictorial toolkit by graphical E-wayfinding choremes strengthens the semantic correspondences to the corresponding verbal toolkit. Consequently, the transduction from verbal to pictorial spatial primitives and vice versa should become easier as they both originate in the same abstract mental concepts (I-wayfinding choremes).

The manifold research findings on organization principles underlying environmental and especially route knowledge (see sections 2.4 and 4.1) were enriched by the investigations on the chunking of route elements (see section 4.3.2). For the formation of wayfinding choreme chunks—that I termed HORDE, higher order route (direction) elements—the influencing factors were specified and grouped into three categories: numerical, landmark, and structure chunking. The fine-grained functioning of these structuring mechanisms awaits further investigation (see section 6.3.3.2).

Street names were excluded from the experimental settings because they often cause problems both in user-map and in user-environment interaction. A navigation by more easily identifiable environmental features seemed to be the best solution (e.g., because street signs are often hidden or otherwise unreadable). This procedure originated in my experiences as an experimental cartographer. This perspective is enhanced by results of Tom and Denis (2003). They showed that route following by street names is indeed inferior to route following by landmarks. I do not wish to imply that street names should be left out, only that better identifiable route elements should be preferred. This procedure is conceivable in modern navigation systems, i.e. street names are only shown on-demand or at critical places for a specific route.

6.2.4 The Wayfinding Choreme Route Grammar

The formal specification of wayfinding choremes as a route grammar (WCRG) was chosen for various reasons. First, the very approach of wayfinding choremes is inspired by linguistics in analogy to the original idea of Brunet. Second, a grammatical notation allows for the description of valid combinations (expressions). Early on, it became obvious that the wayfinding choremes are the primitives whereas the cognitive organization principles are operating over chunks at a coarser level of granularity (see also section 6.3.9). A grammatical notation can account for chunks of concepts as well. Third, grammatical notations encompass the possibility of interdisciplinary transparency. By their very nature they are part of the scientific fields in cognitive science, especially linguistics and informatics.

The grammar as such is not sufficient to characterize the process of *obtaining* higher order route direction elements from a route string. Therefore, another method, *term rewriting*, was applied to specify these rules. The rules are based on valid combinations (expressions) provided by the WCRG.

6.2.5 Function and Structure

The distinction between structural and functional aspects in the conceptualizations of spatial environments and spatial behavior has been proven to be an efficient method for revealing the genuine nature of mental conceptualizations of route direction and wayfinding elements. This thesis spelled out this distinction and defined structural and functional aspects of route directions and wayfinding:

> **Structure –** denotes the layout of elements physically present in the spatial environment relevant for route directions and wayfinding. This comprises, for example, the number of branches at an intersection and the angles between those branches.
>
> **Function –** denotes the conceptualization of actions that take place in spatial environments. The functional conceptualizations demarcate parts of the environment, i.e. those parts of the structure necessary for the specification of the action to be performed.

In the consequence, the conceptualization of an action at an intersection is distinguished as the wayfinding choreme, **not** the intersection, i.e. the spatial structure, as such. This has been shown in section 4.3.1. The underlying mechanism corresponds to the 007 principle defined by Clark (1989; see section 1.1.2.2): An organism is best off if it knows only what it needs to know. In the case of route directions and wayfinding, this means that the agent, first, needs to know that a decision is required, and second, what kind of decision (action) it is. The structure of branches that are not directly involved is of minor interest; they are deemphasized. The communication of knowledge along these lines is in accordance with Grice's conversational maxims (Grice, 1989). In the style of Kant he termed his maxims Quantity, Quality, Relation, and Manner. Here, I only detail his maxim of Quantity:

- Make your contributions as informative as is required (for the current purpose of exchange)
- Do not make your contribution more informative than is required.

I claim that the functional nature of wayfinding choremes fulfills these maxims. They specify that a decision is necessary and what kind of decision (action/turn) is required. Everything else is accessory and therefore deemphasized. Everything present in a map communicates, even if it is not meant to do so, by employing the characteristics of the representational medium. The selection of 'appropriate' aspects and their adequate visualization is thus the most demanding task for every map maker. To sum up the advantages of the functional perspective:

- For the functional approach a small number of conceptual spatial primitives (seven) suffices.
- The semantic correspondences between the pictorial and the verbal toolkit stated by Tversky and Lee (1999) are enhanced by the wayfinding choreme model. The predominance of structural aspects in the pictorial toolkit is eliminated.
- Stressing the functional perspective in pictorial route directions also makes it easier to translate between both forms of external representations.
- Wayfinding choremes are embedded in the spatial structure of intersections that is kept veridical with respect to the number of branches and the angles between them. The set of wayfinding choremes is depicted in Figure 54.

6.3 Future work

6.3.1 The Basis for Future Work

In the present state of development, the wayfinding choreme model has some limitations that await further advancements. These include the visual display of directional concepts on coarser levels of granularity, such as U-turns, loops, and some rare spatial configurations for which no natural language expression exists. Here the potential influence of such non-canonical contexts on the conceptualization requires more fine-grained analyses (see section 6.3.2.2). Against this background it is crucial to determine, whether and to what extent primary concepts like SHARP RIGHT are differently conceptualized when they are embedded into more complex spatial configurations (see section 6.3.3.3). Contextual effects also have to be verified for the chunking process to make sure that, among others, side roads and play streets are identified when the wayfinding choremes are chunked. One possibility to enhance identification in such cases is to employ redundancy, for example, to combine wayfinding choremes with routemarks.

Furthermore, the current set of wayfinding choremes is fitted to the two-dimensional plane structured by a city street network. It does not include directional concepts of upward and downward movement, for example, concepts like UNDER THE BRIDGE, or, UP THE HILL. Such concepts will have to be added to handle, for example, 3D environments such as hilly parks. Should the application domain of the model be broadened to include indoor navigation tasks, further concepts become necessary, for example, UP THE STAIRS or THROUGH THE HALL (see also section 6.3.2.2).

The methods used in the behavioral studies have to be refined as well. Sketch map drawings are regarded as a soft method compared to hard methods like reaction time studies. I used the drawings by participants in a very focused sense: to elicit turning concepts at intersections. In contrast to studies where complete sketch maps are required, the drawing abilities of the participants were not predominant. Nevertheless, the need arises for a study that allows for a finer grained analysis of the sectors associated with turning concepts than it is possible on the basis of drawings. This is necessary to refine the computational model that underlies the wayfinding choremes, i.e. a homogenous 8-sector model. An outlook of planned experiments is given in section 6.3.3.3.

Likewise, the analysis of language data requires great responsibility, especially in such complex areas as route directions. Again, I used the language data in study 2 (see section 4.3.2) in a very focused sense. Data points for chunking were integrated into the stimulus material and an identification of chunks was straight forward. The rationale behind the employment of maps as the source for route information was to allow for access to veridical information. Nevertheless, the chunking may be different for the interaction with real spatial environments. Outdoor or VR experiments are not planned at the moment but should be considered for extending the wayfinding choreme theory as well.

As is the case for all scientific work, the desired effect for the current model and the concepts I have put forward is that they inspire their verification and revision. Thus, the wayfinding choreme model may contribute to gaining insights into spatial primitives as described by Golledge.

> "The major shortcoming of research activity to date is that while specific components of spatial knowledge have been identified and more light has been thrown on types of spatial knowledge, it has not yet clearly been identified whether or not people in general are able to use the logic and inference needed to extend their naive spatial understanding into the 'expert' domain. As geographers, we assume everyone has the ability to do this, and we develop methods for assisting such a transition. But often we are not aware of the nature of the reasoning and inferential processes that are required in as 'simple' a matter as reading a map." (Golledge, 1992, p. 5)

6.3.2 Extending the Theory of Wayfinding Choremes

There are various possibilities for extending the wayfinding choreme theory. I discuss additional concepts and possibilities for the modification of wayfinding choremes (section 6.3.2.1); the relaxation of environmental constraints, and the influences of different means of transportation (section 6.3.2.2).

6.3.2.1 BACK and STRAIGHT Revisited

Both the BACK and the STRAIGHT concept bear the potential of adding greater flexibility to the wayfinding choreme theory. One aspect is that they allow for the conceptualization of movement in space that is not restricted to decision points. STRAIGHT and BACK can occur almost everywhere along the route. Their scope is therefore beyond the one aspired by the present work. The STRAIGHT concept is applicable to points of interest along the route in between two decision points, i.e. $routemark^0$, or any site that appears to be relevant. The BACK concept can be instantiated at every point along a route as well. The BACK concept and the extended use of the STRAIGHT concept have been excluded from the present version of the wayfinding choreme model. The rationale behind this decision was twofold. First, for the minimum characterization of route information that is **goal oriented**—in opposition to the characterization of a trajectory that describes someone's movement through space who may or may not have a goal, i.e. is strolling around—these two concepts are dispensable. Second, the elegance of the wayfinding choreme approach would have suffered as these two concepts introduce greater flexibility and combinatorial possibilities but their integration also leads to some problematic consequences. As actions at decision points are regarded as most pertinent to wayfinding and route directions it was reasonable to start the wayfinding choreme model on this basis.

The question arises, whether a BACK concept can occur without a preceding STRAIGHT concept, like in a combination of TURN RIGHT and BACK. Does this BACK concept imply that the agent turns around and is obliged to make a left turn? This example illustrates that the semantics of the BACK concept is not immediately evident. Furthermore, the BACK concept is not fixed to a certain location along the route. A concatenation of BACK concepts, $wc_bwc_bwc_bwc_bwc_bwc_b$, can signify 'anything' and only very generally characterizes the movement of an agent.

If the STRAIGHT concept can mean both, i.e. straight at an intersection and straight at any point along the route in between two decision points, the unambiguity criterion underlying the wayfinding choreme approach cannot be guaranteed anymore. A concatenation of $wc_swc_bwc_swc_bwc_swc_b$ can either mean the same as $wc_bwc_bwc_bwc_bwc_bwc_b$ or it can represent a situation, in which the agent has to pass a number of decision points and keeps straight on. In the consequence, the integration of the BACK concept would make it necessary to introduce an additional STRAIGHT concept signifying straight movement in between two decision points.

6.3.2.2 The Relaxation of Environmental and Travel Constraints

For the purposes of this thesis, I have restricted the scope of the wayfinding choreme model to actions at decision points in city street networks. I actually implicitly excluded some features that may occur in city street networks, for example, places (see also section 6.3.9). Additionally I assumed an idealized cognizer who is traveling by either bike or car. Therefore, possibilities for the further development of the wayfinding choreme model are evident as it presents the foundation for future work. First, I will discuss some additional kinds of decision points and sketch some ideas on how they may be integrated into the WCRG. Second, I turn to other travel means and consider possibilities for their treatment within the model.

Especially in big cities, the physical reality does not allow for classical intersections only. What is needed are roundabouts or places to manage the confluence path segments. Examples are many path segments that meet in one place—like the 12 path segments that merge at the Arc de Triomphe in Paris—or spacious path segments, or both. Additionally, roundabouts become more common at smaller intersections to prevent traffic jams. Two possibilities for their conceptualization are conceivable (despite the case that the 'exit' is named): The first holds for rather small roundabouts with three or four perpendicular branches. These are treated like 'ordinary' intersections. In Sweden (Steinhauer, pers. comm.[45]) traffic signs reflect this point of view, i.e. directions are specified from the center of the roundabout disregarding its circular structure. This is possible because the few (three or four) perpendicular branches make the spatial situation uncomplicated: STRAIGHT is an unambiguous concept at one of these roundabouts, even though a little detour is required.

For bigger roundabouts like the one around the Arc de Triomphe a different strategy is necessary. Prototypical turning concepts are of no use in such situations: often two or more branches can be covered by the same turning concept and by the time one has reached the correct branch anything could have happened to distract the agent from the original turning concept. The alternative is to treat every incoming branch as a single decision point. The third branch to take would thus correspond to AT THE THIRD DECISION POINT. The STRAIGHT concepts have to be relaxed somewhat as the branch that belongs to the roundabout is not necessarily straight but maybe rather HALF LEFT. This is a good example why it is important to consider the structure as well as the function: the conceptualization of an action (the functional perspective) can be influenced by the structure. Of course, there are situations that cannot be individualized anymore and interactivity takes over (see Figure 72 and Figure 73). Note how difficult it is to find an appropriate sign for this spatial situation. Our daily interaction with the environment does not prepare us well for conceptualizing such degrees of complexity.

[45] 07.06.2003

Figure 72. A sign that aims at preparing the traveler for the combination of roundabouts to come (http://www.strum.co.uk/wessex/brunpic.htm, 27.01.2003 (both pictures)).

Figure 73. A photograph of the real situation of combined roundabouts.

Wayfinding is a multimodal activity (Timpf, 2002). Often, one route comprises the use of different travel means or leads across different environments. According to the scope of this thesis (see section 1.2), I have focused on city street networks. Some possible extensions of the wayfinding choreme theory are the following.

Besides the fact that our body axes provide a general means for the conceptualization of direction information, each environment may add its own requirements that have to be accounted for. In less constraint movement-spaces, like halls (or deserts), specifications of concepts such as THROUGH are required. In differently constrained environments, for example, 3D settings, the following concepts need attention: UP, DOWN, THROUGH, UNDER. It is an open question whether it is possible to find prototypical graphical instantiations for these concepts.

An extension within the domain of street networks comprises, for example, highway systems. The conceptualization of turning actions at highway exits and highway crossing is not part of the wayfinding choreme theory, yet. This question is related to different levels of granularity which are discussed in section 6.3.9.

Different travel means require different actions and therefore different conceptualizations can be expected. What does it mean to switch trains either in long distant travel or in subway networks? How is an intersection conceptualized when we travel by foot, by bike, or by car? The literature provides some answers (e.g., Wahlster, Blocher, Baus, Stopp, and Speiser, 1998). Nevertheless, many questions await further research.

6.3.3 Future Experimental Work

6.3.3.1 Routemarks

In section 4.3.3 the importance of routemarks was stressed with special emphasis on routemarks at decision points. The significance of these routemarks is taken into account by employing a hybrid depiction of route information. For the sake of experimental distinctiveness, the positions of the routemarks were not varied and I have only integrated routemarks into the wayfinding choreme model that are passed before the change in direction occurs. Still, section 5.1.2.3 pointed out that routemarks at four way intersections may occupy different canonical positions. Further experiments are needed to reveal the different functions of routemarks at different locations with respect to an intersection; including, in a final step, the interrelations between routemarks and wayfinding choremes at non-prototypical intersections. Results from this line of investigation could expand approaches on automatically extracting and depicting routemarks (Elias & Sester, 2002; Raubal & Winter, 2002). Or they could be related to research on the conceptualization of actions according to different travel means (Wahlster et al., 1998).

6.3.3.2 HORDE

Impressively, the results of study 2 (section 4.3.2) show that participants rather chunk route direction elements than mention every decision point. Chunking occurs frequently even in the dynamic presentation mode although it rather suggests a step by step verbalization. These results add to various pieces of research on how participants organize route information. The general structuring means—numerical, landmark, and structure—will guide further investigations on the influence of environmental information on the conceptualization of chunks.

Further research is also needed on the specifications made in chapter 5. I have argued for various chunking principles guided by empirical evidence and canonical assumptions. In the next step these chunking principles should be empirically validated with involvement of further environmental information. Aspects that have not yet been considered within the characterization are the influence of distance, the kind of streets, the complexity of intersections. It is also an open question where the boundary lies between verbal concepts and those for which we do not have a single natural language expression. Some examples have already been discussed and their formalization was exemplarily detailed: The case of the turning restriction that could be referred to as a *p-turn*, or the combination of left and right turns resulting in expressions like *jog about a block*. The questions that need to be answered are twofold. First, what are appropriate concepts that adequately characterize these situations? Second, are these concepts unambiguously understood?

6.3.3.3 Assessing the Validity of the 8-Sector Model

For the modeling of the turning concepts, I have assumed a homogenous 8-sector model. In a first approximation this model fits the externalizations of the turning concepts at decision points, i.e. prototypical 45° increments (see section 4.3.1). The question arises whether the 8-sector model really is the basis for prototypical turning concepts, or whether, for example, the size of the sectors has to be adapted to specific properties of individual wayfinding choremes. It could be hypothesized that the standard turning concepts apply to a bigger sector than the modified turning concepts. It is also conceivable that the STRAIGHT concept is coupled to a narrower sector because even slight direction changes may have as a consequence that the STRAIGHT concept is abandoned. These considerations are inspired by Montello and Frank (1996), whose research indicates possible modifications for sector models. As described in section 4.1.1 Montello and Frank analyzed direction models on the basis of behavioral experimental data (Sadalla & Montello, 1989) by running Monte Carlo simulations. The results indicate that homogenous sectors do not model direction judgments of participants best. Consequently, Montello and Frank propose 8- or 10-sector models with different sized sectors (see Figure 36). Against this background, one of the follow up experiments aims at investigating the potential adaptation of sector models to the characteristics of wayfinding choremes.

For the further evaluation of the conceptualization of direction information at decision points I chose a *grouping paradigm*, which Knauff et al. (1997) consider the traditionally famous method to investigate conceptual knowledge in psychology. “The main idea of such tasks is that conceptual knowledge plays the central role in assessing the similarity of a given stimulus: Stimuli are assessed as similar if they are instances of the same concepts, or are assessed as dissimilar, if they are instances of different concepts.” (Knauff et al., 1997).

Especially for the interaction with visual stimuli it is important to differentiate between two general possibilities to group the stimulus material. First, the task could be to group the representations of direction changes at intersections, i.e. map parts. Second, the visual representations could be treated as representations, i.e. the participants are required to take them as representations of actual turning situations they have experienced. The second is more appropriate for the concretization of the wayfinding choreme theory because the main goal is to gain knowledge about the conceptualizations of participants.

There are various possibilities to create and classify the stimulus material. Here, I will only sketch the first two ideas on how more light may be shed on the conceptualization of direction concepts. In the first series of experiments, the turns are presented as increments of 5.625°. This results from an even partition of a full circle starting from bisection 45° sectors (45 - 22.5 - 11.25 - 5.625). In the consequence 63 turning concepts are obtained (the direct back concept is not distinguishable from the straight concept).

The concepts will be doubled (= 126) and integrated into the testing tool (see Figure 74). The doubling will prove whether the same visually presented turning concepts are grouped into the same categories. Depending on the results of this first experiment the further procedure will be specified. The employment of a finer granularity of turning concepts is conceivable, or the explicit definition of models, like the ones used in Montello and Frank (1996).

In follow up experiments the influence of additional branches should be elaborated. Are directions conceptualized the same way if additional branches are present? For these experiments three prototypical branch constellations will be added to the turning concepts; the ones that are prototypical for intersections, i.e. LEFT, RIGHT, and STRAIGHT. These are the first experiments on which results of further environmental factors will be tested.

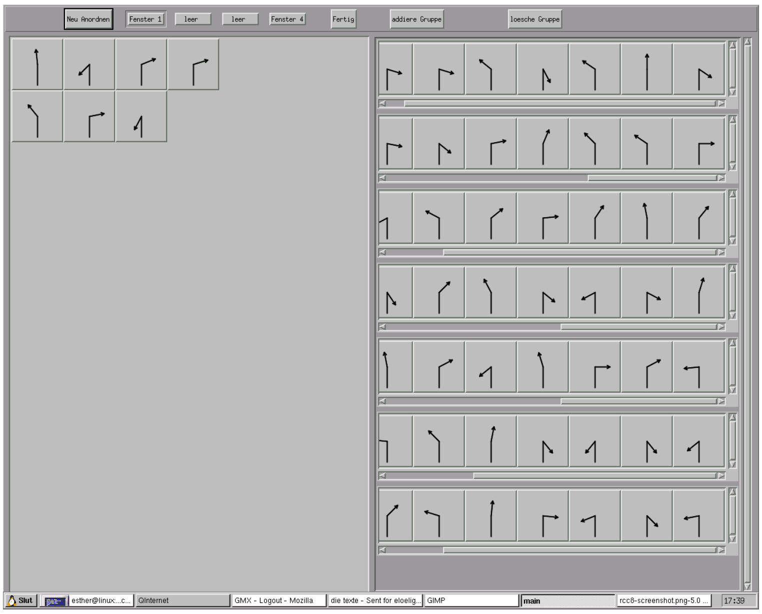

Figure 74. The testing tool for the grouping experiments.

6.3.3.4 Visually Representing Underspecified Concepts

There is a growing interest in representing underspecified (vague/qualitative) knowledge in maps (e.g., MacEachren, 1992; Davis & Keller, 1997; Berendt, Barkowsky et al., 1998; Klippel & Kulik, 2000; Cai, Wang, and MacEachren, 2003). The leading question is how to prevent information from being read off a map that is not intended to be read off (cf. Berendt, Barkowsky et al., 1998). MacEachren (1992) has suggested various techniques to convey vague information. However, as was already pointed out, it is the thematic information that is most relevant for cartographers and not the spatial locational information (see section 3.2.2). In their first article, Agrawala and Stolte (2000) suggested a rendering algorithm for a technical approach that transduces straight lines into more sketch map like lines. To my knowledge, this procedure has not yet been tested experimentally, i.e. the issue whether the depiction of straight lines encourages an interpretation that is too veridical remains unresolved. Subway maps are examples that adhere to a strict geometric layout. No one really believes that subway trains perform 90° turns, but does this hinder map readers to assume that the locations of the stations are correctly displayed?

The wayfinding choreme theory offers a twofold approach. While the surrounding spatial information is kept veridical, the turning concepts are prototypical. My model thus combines information relevant for the recognition of a spatial situation and the clear and straightforward communication of actions to be performed. This technique, besides the cognitive arguments provided in section 5.4, is also grounded in the cartographic tradition, where we find examples of maps in which topographic knowledge is provided as a background. It is planned to perform usability studies to verify the assumption the wayfinding choremes embedded in veridical but deemphasized spatial structure indeed ease map interpretation.

6.3.4 Assessing the Frequency of Wayfinding Choremes and Exceptions

One of the claims that I support is that humans acquire general concepts (schemata) through their interaction with the environment. Whereas this can be explained relatively well on an abstract level, like conceiving UP and DOWN as resulting from being subjected to gravity or conceptualizing PATH image schemata as results of experiencing connections, it is difficult on a more concrete level. Definitely, our body axes lay the foundation for the distinction of turning concepts at decision points as we apply an egocentric (relative) reference system. But can our body axes explain all the turning concepts? While this is an interesting question in its own right, it would be an appealing approach to evaluate city street networks with respect to the frequency of turning concepts and, maybe more importantly, to the frequency of HORDE. What is the likelihood of two SHARP RIGHT turning concepts to follow immediately one after the other? What is the likelihood of a sequence of three HALF RIGHT turning concepts? These questions can be answered even though it requires great empirical effort. It is the starting point to make further statements on the origin of turning concepts at decision points. The same could be asked for the frequencies of less elementary spatial configurations, for example, places, circuits, and the like. For this assessment the specification of parameters that describe spatial data is indispensable.

6.3.5 Static and Dynamic Presentation of Route Information

The debate about the advantages and disadvantages of animation to understand graphical representations has not yet come to a conclusion. Some researchers argue in favor of motion in graphic displays because it seizes user attention and might facilitate, for example, perceptual grouping (Bartram & Ware, 2001). It has also been suggested that motion enables the integration of multiple viewpoints (e.g., McCuiston, 1991). In contrast, other researchers claim that dynamically presented graphs hinder learning (e.g., Jones & Scaife, 1999), and even for events that are perceived dynamically, such as the weather, static images are preferred over dynamic presentations (Bogacz & Trafton, 2002). Furthermore, it has been pointed out that static and animated graphics might not be comparable in the first place (Narayanan & Hegarty, 2000; Tversky, Morrison, and Betrancourt, 2000). The main criticism here is that the information content of the different presentations is not the same.

As it is discussed by MacEachren (1995; cf. also 1986) people encounter various problems when they have to transform map knowledge into procedural knowledge. He states that dynamic presentations are good means to aid in this mapping process. As some of our own results suggest (not reported here), participants who have access to dynamically presented route information are more likely to use a route perspective than participants who are presented with static route information. The route perspective is reflected in the use of a variety of verbal cues (cf. Taylor and Tversky, 1992), one of which is the use of expressions for cardinal directions. Cardinal directions are an indication of a 'birds-eye-view' on a spatial configuration, i.e. a survey perspective. In the dynamic condition participants use cardinal expressions less often than in the static condition. In the US American and German verbal data this finding only holds for the English speaking participants because cardinal directions are particularly uncommon in German route directions. The analyses of other linguistic means that make it possible to determine the respective choice of perspective is in progress.

Another line of investigation we are pursuing is concerned with the possibilities that lie in the combination of dynamic and static presentation. First findings suggested that focusing on crucial route aspects, more precisely on routemarks, might be enhanced by the combination (see section 4.3.3). These results were further elaborated in follow up studies (Lee, Klippel, and Tappe, 2003). The presentation mode that combines a static display and a dynamic display of the actions to be performed, may unite the benefits of both types of displays. The static presentation allows users to organize the spatial information at hand more freely, applying principles acquired by everyday interaction with the environment, and it encourages a planning component. On the other hand, dynamically displayed information guides users along their way, and aids them to focus on the next action to perform within the city street networks. The combination of different presentation modes and the resulting memory improvement for vital information add to findings regarding the benefits of redundant information display (Hirtle, 2000). In summary, the findings obtained by Lee, Klippel, and Tappe (2003) demonstrate the need for selectively choosing the appropriate presentation mode for the task and encourage further research on the interaction of various information sources, especially their display by different modalities.

6.3.6 Route Choice and Route Complexity

> "The *legibility* of a route is the ease with which it can become known, or (in the environmental sense) the ease with which relevant cues or features needed to guide movement decisions can be organized into a coherent pattern. Legibility influences the rate at which an environment can be learned (Freundschuh 1991)." (Golledge, 1999b, p. 6)

The wayfinding choreme theory is originally not intended to determine which route to take nor to provide complexity measures for routes. Yet, the results obtained so far and the planned experiments can add to the understanding of route complexity and route choice. Several aspects of the wayfinding choreme theory may be of use. The first is the distinction between structure and function. Consider the case of T-intersections. Mark (1986) has worked on how T-intersections ease wayfinding as they disallow forward movement. *Walk to the end of the street* is probably one of the most fail-safe route direction elements. In this case, the T-intersection is oriented in such a way that it stops the forward movement. A T-intersection is not per se valuable, as it may be oriented in such a way that it permits forward as well as either left or right turns. It is therefore not the structure alone that is responsible for the complexity of an intersection but rather its interaction with the action that is performed (functional perspective). Likewise the action as such does not account for the complexity. It is important to have a clear understanding of what we are doing at decision points (cf. Richter & Klippel, 2002).

The second aspect is derived from the assumption that complexity is revealed by the ease with which actions in spatial structures can be conceptualized. This is evident, for example, by the degree of agreement I found for the SHARP turning concepts in study 1 (see section 4.3.1). I hypothesize that this reflects to a certain degree how difficult people judge SHARP turning concepts. Further evidence can be found in language data of the studies that has not been reported in this thesis. When participants verbalize standard intersections or 3-way intersections at which they keep straight on, utterances are produced fluently without much hesitations. In contrast, in study 2 participants had problems finding an adequate concept for the action required at the final, star-shaped intersection, which is relatively complex (see section 4.3.2, Figure 46). This was apparent in an increasing number of hesitations and self corrections across participants. Additionally, the diverse conceptualizations of this action are reflected in that participants used various utterances for its description, for example[46]:

[46] These are examples of utterances from the data collected in Santa Barbara (study 2, see section 4.3.2).

> “walk always straight down that and then you gonna reach a convergence of like, of seven different streets comming together in one point, you don't wanna not, you don't ?? wanna take the third one, ah, from the left, so not, so skip over the first one on the left, skip over the second one, take the third one, and you see a FedEx”
>
> “continue down straight, until you come to a, ah, six intersection road, and you will take the, you'll you will not go straight, you will go, left on the third, the third intersection and travel down that and reach your destination”
>
> “follow that street down through another, to a six-point intersection and continue on and pass the FedEx-Office on your left”
>
> “go straight for a while and then there is gonna be another big intersection, don't make the complete left, but veer left and you should see a FedEx building”
>
> “go down straight towards the FedEx and then stop”

The third aspect stems from the knowledge on chunking wayfinding choremes. This relates to the general question, how primitives can be grouped together in order to reduce the working memory load. A route may contain more decision points, but if the decision points can be grouped into less HORDE, it still may be easier. General chunking principles have been specified. Their application to and specification by spatial situations awaits further research.

6.3.7 Ontologies

Research on *ontologies* provides new insights into the cognitively adequate depiction of locational spatial relations. This is apparent when looking at a definition for ontologies given by Gruber (1993) which says that an ontology is an explicit specification of a conceptualization. The original reading of *conceptualization* in cognitive science is ‘the characterization of how human beings make sense of their environments by organizing and structuring the innumerable information to manageable pieces of information resulting in an abstract mental concepts’ (Tappe, pers. comm.[47]). Focusing on this understanding of conceptualization and relating it to questions of graphical representations—especially their locational spatial characteristics—the definition of an ontology given above can be rewritten to meet the purpose of this thesis:

> An ontology for pictorial route directions is a specification of basic graphical elements resulting from research on mental conceptual structuring processes and on abstract mental concepts.

In this sense wayfinding choremes establish an ontology for wayfinding and route directions both on an abstract conceptual level and on the level of graphical (verbal) externalizations (instantiations). As such, they add to endeavors which aim at the

[47] 02.11.2002

specification of wayfinding research from an ontological perspective (Kuhn, 2001; Timpf, 2002). Questions that have to be answered are: What is the ontological status of wayfinding choremes for different environments and further travel means? And, what ontological status can be assigned to HORDE?

6.3.8 RouteGraph Theory

In section 2.4.2 the basic concepts of the RouteGraph theory (Werner et al., 2000) were discussed and were demarcated from the terminology of the work at hand in section 3.3. The RouteGraph is one of the main frameworks within the SFB/TR 8 (SFB/TR 8, in prep). From a more formal perspective it can be characterized as an abstract data format. Thus, the RouteGraph formalism is flexible enough to specify wayfinding choremes. It is desirable to combine the two approaches as the cognitive conceptual basis of the wayfinding choreme approach and the specification possibilities of the RouteGraph theory can enhance the design of human-machine-interaction systems. The grammatical notation that has been employed within the current work has the opportunity of being highly transparent and allows for the structuring of abstract mental concepts.

One example illustrates both current problems and a future perspective[48]. I only discuss the first parts of a movement with one turn. Imagine, someone is in office MZH 8210. He leaves the room and heads towards the window in the corridor. Within the RouteGraph theory, this movement consists of two route segments; each route segment has five components with different values: Source, entry, course, exit, and target. For the two route segments in the example (see Figure 75) this means:

- Route segment 1
    - Source: room MZH 8210
    - Entry: turn to door
    - Course: walk through door
    - Exit: do nothing
    - Target: corridor heading towards elevator

- Route segment 2
    - Source: corridor heading towards elevator
    - Entry: turn right
    - Course: walk along corridor
    - Exit: stop at window
    - Target: T-crossing in front of window

[48] The example is taken from a talk by Klaus Lüttich, Tutzing 2003.

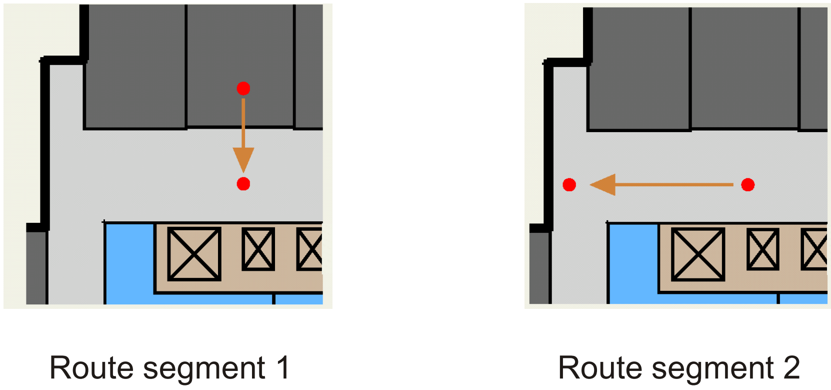

Figure 75. Example of two route segments within the RouteGraph specification.

Even though in its current state of development the wayfinding choreme theory is not meant to model wayfinding and route direction elements for indoor activities, this situation is akin to one that is regularly encountered at decision points within city street networks. The wayfinding choreme that corresponds to the two specifications of the RouteGraph theory given above is wc_r. The discrepancy between the two kinds of specifications is obvious. The divergence gets even bigger if the places (nodes) are also taken into account (see section 2.4.2). Furthermore, this example illustrates how important it is to establish an awareness of different conceptualizations especially for the interaction between human and artificial agents. The mapping of elements from and to the respective knowledge bases is a crucial future task.

Graph theory plays an important role in wayfinding assistance (e.g., Duckham & Kulik, 2003). Especially an approach by Winter (e.g., 2002b) is central in the present context as he has renewed the dual graph approach (Caldwell, 1961) that directly relates to the specification of wayfinding choremes and may be used for a formal treatment of the interaction between the wayfinding choreme and the RouteGraph theories. Informally speaking, a dual graph is a graph (line graph) within a graph (primal graph) that connects the edges of a calculated route ('path' in graph theory terminology) through a graph (see Figure 76). This has the advantage that one node—in case of the turning restriction—is not visited twice and no conflicts arise if two values are necessary. This additional graph could connect the courses of the route segments and assign a corresponding wayfinding choreme to its edges. In this way it might be possible to bridge the gap between the RouteGraph theory and the wayfinding choreme model.

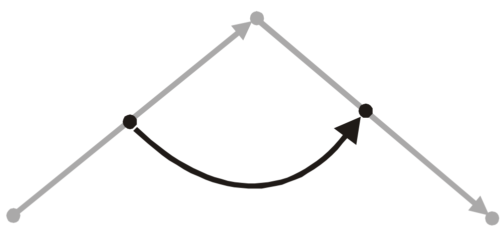

Figure 76. Dual graph approach. A primal graph (gray) and its line graph (black).

6.3.9 Granularity

> "It is that our knowledge consists of a global theory together with a large number of relatively simple, idealized, grain-dependent, local theories, interrelated by articulation axioms. In a complex situation, we abstract the crucial features from the environment, determining a granularity, and select the corresponding local theory." (Hobbs, 1985, p. 435)

Wayfinding and route directions take place on different levels of granularity. Characterizing human wayfinding behavior we can assume a hierarchy of wayfinding processes comparable to specifications made in robotics (e.g., Kuipers, 2000; Krieg-Brückner et al., 1998). For example, when we plan a trip in its entirety we operate on a different level of granularity compared to a situation that requires our (re)orientation at an intersection. Another possibility is the chunking of basic wayfinding and route direction elements into a higher order concept, HORDE. Consider, for example, the route direction fragment *in a westward direction at the highway exit Othmarschen*. Here it is necessary, of course, to leave the highway *before* one can head to the west. As the actions required to leave the highway follow a recurring pattern, they can be inferred and may therefore be omitted. This line of thought bears some similarities to work by Timpf (1992; cf. also Timpf, Volta, Pollock, Frank, and Egenhofer, 1992) on generalizing highway exits for differently scaled maps.

Chunking of route segments relates to effects of granularity changes that have been broadly discussed in the literature (e.g., Hobbs, 1985; Timpf et al., 1992; Frank & Timpf, 1994). The ideas on chunking presented in sections 5.1.2 may be seen as being concerned with different levels of granularity. So far I restricted the combinatorial possibilities of wayfinding choremes to one level of granularity (that is, under this view, wayfinding choremes and HORDE are at the same granularity, or, 'conceptual zoom' level). The necessary restriction to one level of granularity is a consequence of the chosen domain that consists of a city street network in which elementary behaviors constitute a route, like turning at decision points. The chunking of these primitive elements is at issue and not the general planning of a route. This means, that even though the chunking principles detailed result in non-elementary route segments, the number or at least the type of wayfinding choremes that are grouped into one chunk are still identifiable. In contrast, changing the level of granularity requires the instantiation of a completely new concept for a certain aggregation of actions.

Obviously, there are situations that can be characterized more adequately at such a coarser level of granularity. The treatment of habitual actions at highway exits discussed above is one example. Another case in point is suggested by Hirtle (2000) as *map gestures*. Map gestures are compared to gestures in route directions, for example, *the hotel is over there* plus 'gesture'. The gesture can subsume a variety of necessary actions. As an example Hirtle discusses the graphic route direction provided for COSIT 1999 in Stade (http://www.cosy.informatik.uni-bremen.de/events/cosit99/). Figure 77 depicts the map part that provides the information of how to get from the interurban train station (*S-bahn* station) *Landungsbrücken* in Hamburg to the nearby docks. The landing stage for the rapid ferry boat to Stade is located at dock 4. Like most interurban train stations, the station *Landungsbrücken* has more than one exit. Moreover, from each one of these exits there exist various options to reach the docks. On the one hand, this makes the situation complicated as different sequences of route direction elements have to be arranged. On the other hand, the situation is rather easy. Even though there are several possibilities, the destination is rather obvious (a classical all-roads-lead-to-Rome situation). Especially as the environment constrains the movement, which makes the spatial situation comparable to a huge T-intersection (see section 5.1.2.3). In this case, it is actually an edge in the terminology of Lynch (1960)—the waterfront—that terminates the general possibilities of movement in one direction. The arrow in Figure 77 therefore subsumes a whole set of possible actions and focuses one's attention by indicating the general direction that a wayfinder needs to take.

Figure 77. Example of a map gesture (Hirtle, 2000, modified).

This discussion shows that it is worthwhile to consider the initiation of wayfinding choremes that account for changes of granularity, for instance, wayfinding choremes on the level of map gestures. Such abstract wayfinding choremes, which I call *second order wayfinding choremes*, could be successfully externalized and employed for the depiction of situations that make detailed graphical display superfluous, as in the case of most highway exits, where the environment in combination with our world knowledge tightly constrains the range of possible behaviors. Wayfinding choremes at this level of granularity would no longer be transparent because their internal structure would no longer consist of an accessible combination of wayfinding choremes. Rather all wayfinding choremes that belong to one spatial situation would be replaced by a single wayfinding choreme. One drawback in these considerations is that abstract wayfinding choremes that roughly correspond to map gestures can probably not be characterized in analogy to their seven elementary counterparts, i.e. the original wayfinding choremes. As the wayfinding choreme model is based on mental conceptualizations and their prototypicality, the question arises whether there are homogenous mental conceptualizations akin to wayfinding choremes on a higher level of granularity that capture highly complex and yet environmentally constrained situations such as the ones just outlined. Even if the future investigations result in the insight that the wayfinding choreme model cannot be transferred to a coarser level of granularity, it is still worthwhile to systematically identify situations that might allow for the application of second order wayfinding choremes and focus on possibilities for their depiction.

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