Urban Granularities – A Data Structure for Cognitively Ergonomic Route Directions

Alexander Klippel[a]*, Stefan Hansen[b,c], Kai-Florian Richter[d], Stephan Winter[e]

[a] Department of Geography, GeoVISTA Center, Penn State, PA, USA

[b] CRC Spatial Information, The University of Melbourne, Australia

[c] LISAsoft, Australia

[d] Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition Universität Bremen, Germany

[e] Department of Geomatics, The University of Melbourne, Australia

Abstract

This paper addresses the specification of a data structure for route directions that incorporates essential aspects of cognitive information processing. Specifically, we characterize levels of urban granularity and the hierarchical organization of spatial knowledge. We discuss changes of granularity in route directions that result from combining elementary route information to higher-order elements (so called chunking).

*Corresponding author: Alexander Klippel. Department of Geography, GeoVISTA Center, Penn State, PA, USA. Email: klippel@psu.edu

We provide a framework that captures the pertinent aspects of this chunking. The framework is based on established principles to change the granularity in route directions as discussed in the literature. Based on the resulting classification of chunking principles, we specify a data structure bridging the gap between results from behavioral cognitive science and requirements of information systems. It is defined as an XLS schema that extends the OGC's OpenLS specification of a Navigation Service. We present the core elements of the data structure and provide examples for its application.

Keywords: Route directions, spatial structure, granularity, spatial chunking

1 Introduction

Cognitive processes that abstract from rich environmental information are an essential part of human information processing. This ability ensures that humans are functioning in their environments. Not astonishingly, the topic has attracted researchers from different fields (providing a characterization for all of them would be prohibitive). In our work, we focus on urban environments; more specifically on how information on routes in such environments can be structured by information systems in ways that they reflect and support human cognitive processes, such as following a route, finding one's way, or acquainting oneself with a city. How urban structures influence cognitive processes and how they can be exploited in communicating route information needs to be formally characterized in order to apply these principles in information systems. There is need for a data structure that is able to bridge the gap between high-level cognitive processes and the low-level data that is available through various databases or online recordings such as GPS.

A crucial aspect in dealing with spatial information is to successfully cope with different levels of granularity and changes between these levels. This aspect will dominate the discussions throughout this paper. Generally, the following approaches to route information can be distinguished: one type of approaches takes a given route as input and tries to optimize the route directions provided [8, 36, 22]. Another type of approaches tries to optimize cognitive aspects by choosing a route that complies to certain criteria [11, 4, 17]. Yet another type differentiates between parts of the environment being known to the wayfinder and parts being unknown. The idea is to provide only coarse information for the known parts, i.e., to abstract from a concrete route and only announce (intermediate) destinations, while being detailed in the unknown parts, i.e., giving turn-by-turn instructions there [33, 19, 34, 38, 43, 39].

The contribution of this paper is twofold: on the one hand, our characterization provides a framework for specifying a data structure for cognitively ergonomic route directions. On the other hand, the presented data structure allows for specifying several alternatives to reduce the amount of information in route directions. The data structure cannot only be used to realize the design of information systems but also for exchanging information in mobile client-server architectures. In defining this data structure, we rely on existing open standards.

The remainder of this paper is structured as follows: to provide some background, we start with an excursion into spatial information organization and a discussion of elements that structure the knowledge of a city. In Section 3, we then discuss chunking as a process to change the granularity in route knowledge and present different chunking mechanisms. This is followed by an introduction of the Urban Knowledge Data Structure in Section 4 that captures these chunking mechanisms, and an example of its application in Section 5. Section 6, finally, discusses different approaches to cognitively ergonomic route directions in light of the work presented in this paper.

2 A Short Excursion into Spatial Information Organization

> "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." [18, p. 435]

The hierarchical organization of spatial information and the ability to flexibly change between different levels of granularity are a key characteristic for the cognitive organization of spatial knowledge [18, 23, 42]. Considering urban environments, hierarchical structures may result from categorizing parts of the environment into units (like districts, see below) or grouping several consecutive wayfinding actions, such as turns at intersections. Such structuring of spatial information reflects not only cognitive conceptualization processes but also the organization of route knowledge in a cognitively ergonomic way. From the perspective of information system design, providing a user with too much detail violates findings of cognitive science as discussed, for example, in Clark's *007 Principle*:

> "In general, evolved creatures will neither store nor process information in costly ways when they can use the structure of the environment and their operations upon it as a convenient stand-in for the information-processing operations concerned. That is, know only as much as you need to know to get the job done." [5, p. 64]

Structuring route knowledge by taking into account environmental features potentially allows for providing a coarser perspective on the required wayfinding action than simple turn-by-turn directions [36, 26]. This is easier to cognize and often sufficient for successful wayfinding. Additionally, not only the amount of information that has to be memorized and understood is reduced, but the information is additionally structured in a way that is easy to perceive, for example, by using salient landmarks and structures (compared to often hard to read street signs) [32]. The importance of structuring environmental information for route following is pointed out by Allen [2] who discusses the importance of the general knowledge of environmental structures and spatial terminology that a wayfinder possess and that is activated (or primed) when route directions are remembered or followed. Verbal route directions, in this constructivist account of understanding route directions, are the input for a linearly ordered representation that in general corresponds to the perceptual experiences of a traveler along a path (see also [20, 40]).

This is especially the case if the user is familiar with the environment, i.e., when a traveller has experienced a specific environment before [25, 24, 6, 33, 41]. In navigation systems, however, the subsumed information should still be made accessible in case a user needs more detailed information (or, as discussions on positioning technologies show, the user may want to re-query a new route from his new position)[1]. This may either be possible by zoom-in

[1] This distinction is reflected by differentiating *on-line*—route directions given while an

operations, i.e., by accessing the next, more detailed level of the hierarchy, or by (mental) inference processes. Such inferences, for example, extract from an instruction, such as *turn left at the end of the road*, information on which action to perform at all intersections before the road's end, namely to continue *straight* [29].

Preliminaries: Lynch's Elements

For built environments, Kevin Lynch [27] introduced a new viewpoint to architecture with his pioneering work on imageability. 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, nevertheless, 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. Lynch differentiates between five basic elements: paths, edges, districts, nodes, and landmarks.

agent is traveling—and *in advance* route directions—route directions given prior to the actual travel [13, 36]. A classification of different route direction styles is provided by [21].

- *Paths*: For Lynch, paths are the most predominant elements used for organizing a city environment. They are physical objects in the environment that connect places. Other environmental elements are arranged along them. Examples for paths are streets, walkways, transit lines, canals, and railroads. Paths constitute the basis for what is widely discussed as route knowledge.

- *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 area-like components Lynch introduced. They are areas that contain elements that share common features. A distinction can be made between what is inside a district and what is outside.

- *Nodes*: Nodes are more than simply intersections of roads. Nodes are important strategic places. They comprise intersections, 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. Landmarks and nodes 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.

3 Chunking and Segmenting: Processes to Change the Granularity in Route Knowledge

Based on the principles of processing and structuring urban knowledge the following sections will develop a theoretical model capturing these principles. First the discussion deepens general aspects of chunking route knowledge. Subsequently, specific chunking strategies are specified that will directly serve as input for the data structure discussed in Section 4.

The basic unit—the *primitive*—in our approach is a decision point with its associated action as identified as most critical by behavioral research [9, 2]. [2] Abstracting from individual decision points leads to higher-order route direction elements [22]. We term this abstraction process *spatial chunk-*

[2]But, it is important to keep in mind that the ontological status of individual decision points can vary according to different levels of granularity.

ing [21]. In the context of this article this term comprises two perspectives with respect to different levels of granularity: the chunking of primitives into larger units and the identification of large chunks present in the environment (or as part of the spatial knowledge a cognitive agent possesses). It is important to keep in mind that the elements in one chunk are not always predetermined. Especially in the case of route directions for knowledgeable city dwellers parts of the route can be reached on ways not explicitly specified [33, 39, 43]. The general distinction with respect to the resulting chunk and the elements involved in chunking are discussed in the following. A general overview is provided first and then chunking principles are discussed individually.

1. Part of a route is chunked and the involved elements are explicitly present. We can distinguish two cases:

    - The number of chunked elements is explicitly referred to, for example, *turn right at the second intersection*.
    - A chunk of turning actions has been assigned a specific name reflecting a specific turning concept, such as *p-turn* or *hook turn*. Although not explicitly referred to, the individual turning actions that are characteristic for these concepts are still inferable.

2. Other organization principles chunk route parts such that individual decision points are no longer identifiable. Here, we can distinguish

whether we assume that the wayfinder is on a specific route and we need to keep her on this route, or if we assume that the wayfinder is able to find her way to the next specified place on her own. There are several variations:

- The chunk is focused on its end point. This means that the feature determining the endpoint of a chunk is salient enough to make the specification of additional decisions between start and end of the chunk superfluous. There are several facets of this type of chunk. We discuss them in the following section with respect to the elements identified by Lynch [27]. Additionally we distinguish between global and local landmarks. This corresponds to the distinction made above between the specification of a specific route (local) and specifying an element on the way to the destination but without requiring a user to reach this elements on a specific route (global).
- A landmark allows for structuring parts of a specific route directly, i.e., the landmark is of linear or area-like character. In this case a succession of decision points is identifiable due to the presence of the same landmark. Examples are *follow the river* or *around the park*. These landmarks can also be only virtually linear. For example, markers along a specific route, such as signs to the airport, function according to this principle (this works

even if the airport is not the final destination) [36].

As our goal is to provide a formal characterization of route knowledge that allows for communicating information on how to reach a destination (even if a specific route is not known), these principles have to be incorporated into a respective data structure. One aspect is important to keep in mind: we do not aim at mimicking human route directions; especially, as experiments show that many people give bad route directions. In contrast, we focus on cognitive structuring principles that allow for organizing route and environmental knowledge on levels of different granularity. This approach has great appeal as we potentially have more information available in spatial databases as people normally have about their environment and automatic systems do not forget to provide important information. At the same time we can present route information such that it eases human cognitive processing.

Some of the discussed principles are straightforward to implement while others depend on available information, either on individual cognitive processes or on the data available. The previous sections established the general framework for chunking and indicated the different levels of granularity which may be integrated into a formal specification. This section summarizes principles that have been discussed in the literature on a more detailed level. These principles are integrated in the data structure that we will develop in Section 4.

3.1 Numerical Chunking

Numerical chunking characterizes the chunking of decision points by counting them and summarizing them as a single digit. Mostly, these are nodes in Lynch's terminology. It is, however, conceivable to have second order numerical chunks on the basis of salient elements in the environment, such as roundabouts or landmarks such as McDonalds (see Figure 1).

Example: *Turn right at the third intersection.*

Example: *Turn right at the second {roundabout, McDonalds}.*

3.2 Chunking Based on Structural Features

Salient structural characteristics of intersections and environmental elements allow for identifying these actions uniquely with respect to a specific route. Mark [29] discussed this aspect in the context of inferring the navigational complexity of intersections from their structural qualities. Duckham and Kulik [11] used his approach to calculate a route with the least descriptional complexity. Within the context of a specific route, intersections can be highly salient features, especially when they require or enforce a change in the moving pattern or even block it. T-intersections are a dominant example. Reaching the end of the street, the current movement (going straight) is blocked. Such boundaries are most likely reflected in the physical structures of the road. However, they may also be present conceptually as other elements might fulfill the same function. Examples are visually salient areas (districts) or visually salient channels (see Figure 1).

Example: *Turn right at the end of the street.*

Example: *Turn right just before the Botanical Garden.*

Example: *Turn right just before the river.*

3.3 Local Chunking Based on Point-like Landmarks along the Route

Point-like landmarks along a route can be used to chunk specific parts of a route. Using such a landmark, explicitly mentioning actions to be taken in-between start and end of the chunk is redundant. The principle is the same as discussed for chunking based on structural features, although the location of a landmark at an intersection may need to be further specified, which might be difficult (see [37]).

Example: *Turn right at the Shell gas station.*

3.4 Local Chunking Based on Linear Landmarks along the Route

Linear landmarks that directly influence decision points can be used to chunk route knowledge for the time they are present along the route. Based on classifications found in the literature [36, 8] we differentiate the following three cases:

- Linear landmarks close to the route. Example: *Follow the river.*

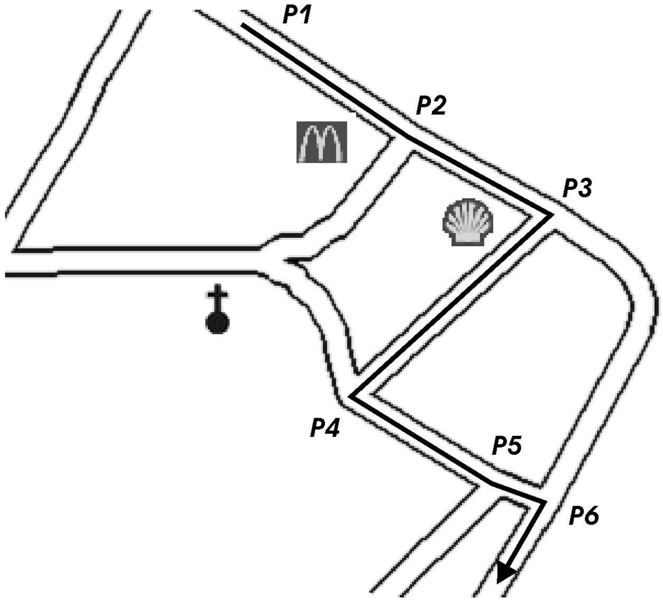

Figure 1: This figure (from [21]) exemplifies different chunking principles: P1 is the starting position. The required decision at decision point P2 can be integrated into a chunk that is terminating at P3 in two ways: either numerical *turn right at the second intersection* or by using the shell gas station as a landmark *turn right after the shell gas station.* P5 can be integrated into a chunk by using the salient T-intersection, P6, *turn right at the end of the road.*

- Virtually linear landmarks. Example: *Follow the markers.*
- The street level hierarchy. Example: *Take Princess Highway.*

Note that a linear landmark is not necessarily linear in terms of its geometric characteristics, but in terms of its conceptualization and its influence on organizing route knowledge. Also note that in route directions, a wayfinder additionally needs to know until which point a linear landmark is co-present with a route, i.e., how long a linear landmark is to be followed.

Example: *Follow the river until the gas station.*

Example: *Follow the tracks until they end.*

3.5 Local Chunking Based on Area-Like Landmarks along the Route

We distinguish two alternatives. The first one functions like a linear landmark that is present at consecutive decision points. This means that the action to be performed can be determined due to the presence of an area-like landmark at several decision points. The second alternative explicitly uses the area-like character of the landmark. It requires the traveler to traverse the landmark.

Example. *Around the park.*

Example. *Through the CBD.*

3.6 Global Chunking Based on Point-Like Landmarks

In this case, the landmark chunks part of the route while the route is underspecified. This approach is followed, for example, by Tomko and Winter [43, 44]. In their approach, they aim for identifying the environmental elements to be referenced in a route direction task for knowlegdeable wayfinders by analyzing the given hierarchy of spatial information. Another approach is discussed by [33]. They combine the analysis of movement patterns with the possibility to provide personalized information. The differences in these approaches listed here illustrate well the general distinction between different approaches to route information we made in the beginning.

Example: *Get to the train station.*

3.7 Global Chunking Based on Area-Like Landmarks

An area-like landmark covers (a considerable) part of the environment that needs to be crossed while moving from origin to destination. Area-like landmarks allow for chunking potentially large parts of the route without the need of announcing intermediate decision points. They may be nested in order to provide information on the destination in decreasing levels of granularity [44], or the wayfinder needs to traverse them somehow finding her own route to reach the next segment of the way to take [34]. In the former case, the area-like landmarks function as intermediate places to reach (with decreasing granularity and extension) on the way to the destination, in the latter they serve as environmental features that can be exploited to guide the wayfinder towards her destination.

Example: *Get to Manhattan; that is in New York City, New York State*

Example: *Get {past, around, to the other side of} the park*

4 An Urban Knowledge Data Structure

Chunking is an important principle in organizing spatial knowledge that eases its conceptualization, memorizing, and communication. Incorporating this principle in computational assistance systems requires algorithms that sensibly combine elementary wayfinding actions on the one hand and a data structure that captures the relevant information and enables chunking in the first place on the other hand. We developed such a data structure for turn-by-turn directions [15] that we term here *Urban Knowledge Data Structure* (UKDS). UKDS is based on a well established open standard, namely OGC's OpenLS which we illustrate in Section 4.2. After discussing and example in Section 5, Section 6 relates the data structure to chunking approaches found in the literature.

4.1 UKDS Prerequisites

A data structure capturing all information relevant for chunking has several prerequisites:

- The different kinds of urban structure that may be exploited for spatial chunking need to be representable and addressable. Different kinds of landmarks (point-like, linear, area-like), different types of salient intersections (e.g., T-intersections, roundabouts), and the street level hierarchy need to be present in the data structure (see [16] for more details on representing landmarks in OpenLS).

- Elementary route direction elements need to be represented. These need to capture the necessary attributes and elements to describe the required actions. For spatial chunking, these elements need to be combinable, i.e., it is also necessary to offer attributes and elements which relate the elements to each other.
- The data structure needs to contain all the information about each subsumed element and needs to provide means to access this more detailed information, i.e., enable switching between granularity levels.
- Computationally, it is desirable to treat higher order route segments the same way as elementary route direction elements. This way, generating second order route direction elements is straightforward as the same mechanisms as for first order route direction elements can be used. Chunks on different levels of granularity can be combined into one segment. For example, an elementary route direction can be chunked together with an instruction that already subsumes several other elementary route directions.

4.2 UKDS and OpenLS

The Urban Knowledge Data Structure is specified as an XML schema. More precisely, we extend XLS, a XML schema defined in the OpenLS specification that is provided by the Open Geospatial Consortium (OGC) [28]. OpenLS defines the so called GeoMobility Server (GMS), an open platform for location–based services and its core services (directory service, gateway service, location utility service, presentation service, route service). It consists of a set of specifications of interfaces and (XML)schemas which define access to the core services of such a server and the abstract data types used in the documents exchanged between server and client. OpenLS primarily specifies the interaction between client and server (request and response schemas) and the format in which the transferred data is encoded. The documents defined in the request are encoded in XLS.

Next to the five core services there exists a sixth service, the Navigation Service [3]. It is based on the Route Service, but additionally allows providing the client with all information necessary to generate more elaborate route directions. In that, it does not transfer pre-generated route directions, but provides all information needed to generate such directions on the client. This way, clients can adapt the presentation of route information according to their abilities without the server needing to know any details about the client.

The OpenLS data structure used for encoding the data for generating route directions basically consists of a sequence of instructions. Each describes the action a wayfinder has to perform at a decision point combined with the information about the next route segment. The original data structure used in OpenLS is not able to store all information that is needed in order to generate cognitively ergonomic route directions. For example, while there exists the possibility to integrate landmarks in the instructions, this can only be done in a very simple form that is insufficient to capture all possible functions of landmarks in route directions. As will be further elaborated in the next section, spatial chunking is also not possible with the basic OpenLS specification.

4.3 UKDS Definition

To enable the usage of chunking in OpenLS according to the principles discussed in Section 3, several changes in the design of the data structure, i.e., the *XLS*–schema, have to be made. Subsuming a sequence of directions in one single instruction has to be enabled to allow for spatial chunking. It is also necessary to offer attributes and elements which relate the single instructions to each other in order to build up a hierarchy of route direction elements. In the following, we briefly introduce the main concepts used to realize spatial chunking in *XLS*. Figure 2 provides an overview on the UKDS-part that enables chunking; a detailed description of the data structure (including the XML schema itself) can be found in [15].

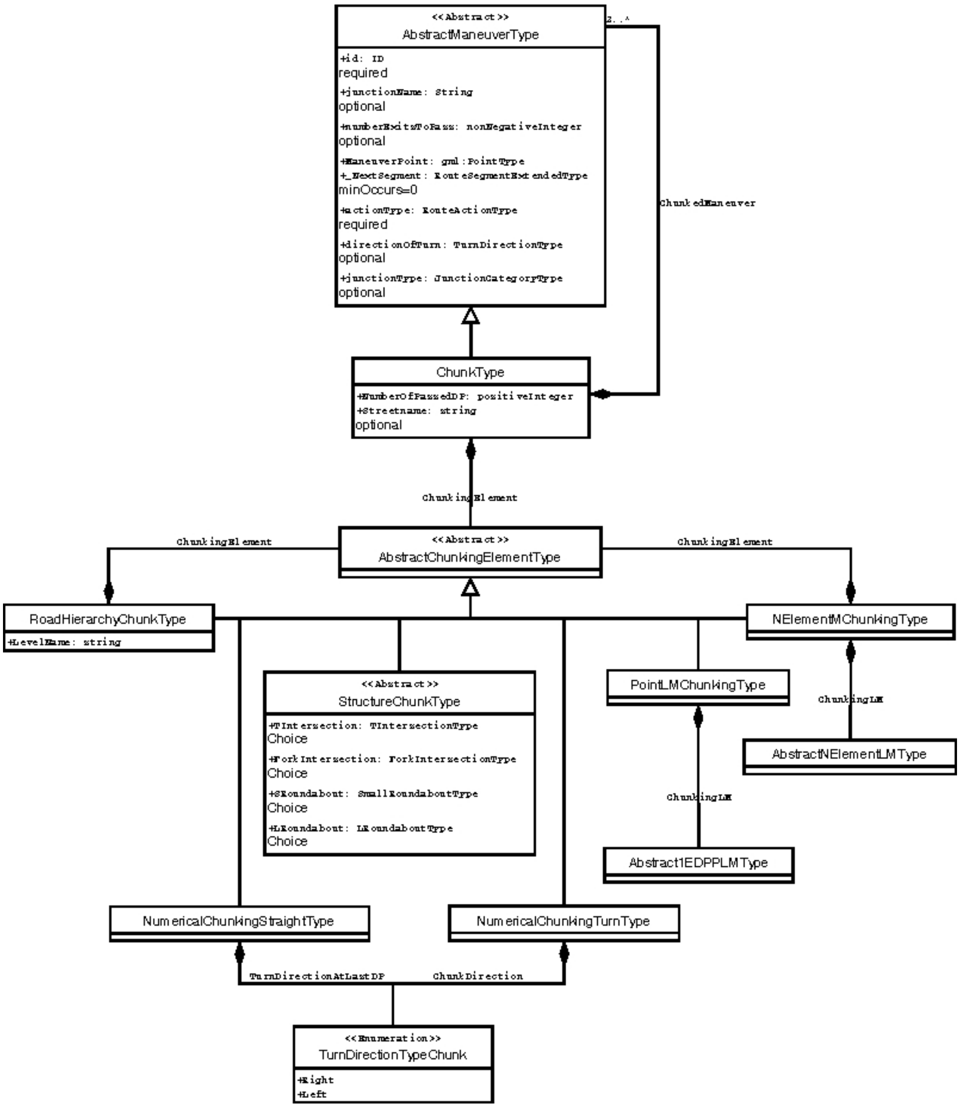

Figure 2: UML-diagram of the UKDS-part that enables chunking.

4.4 General Architecture of the Data Structure

The basic element of the data structure is termed *maneuver*. It is a tuple representing a route segment and the decision point the segment is leading to. A route, then, is a list of maneuvers; for start and end of a route special maneuvers are defined.

Without applying chunking, a route would consist of a start element providing information for the wayfinder's orientation at the beginning of the route, a maneuver element for each decision point along the route, and an element providing information for identifying the destination of the route. In the remainder of this section, we introduce different chunking methods implemented in UKDS that are used to further structure this basic route representation.

4.5 Implementation of Chunking Principles

In UKDS, a chunk is represented as an element containing a list of the chunked maneuvers. The data type representing chunks is derived from the same type as the maneuver type, namely from *AbstractManeuver* (see Fig. 2). This allows for combining atomic elements (maneuvers) and higher-order elements (chunks) in any desired way. Also, this way a chunk may subsume other chunks as well. Consequently, this results in a hierarchy of chunk levels. Each chunk contains a so–called *ChunkingElement*, which provides the information required to identify the extend of the encoded type of chunk.

For each of the chunking methods detailed below a specific *ChunkingElement* is defined that stores the required information.

4.5.1 Numerical Chunking

Numerical chunking can be performed in different ways; these differ mainly with respect to the element that determines the counting. Typically, a turning action denotes the end of a chunk, as in “turn right at the third intersection,” but, for example, also landmarks may be used as in “turn right at the second 7/11.” Since such elements are conceptually different, for each of these elements a separate class is defined.

A basic *ChunkingElement* for numerical chunking contains a counter to hold the number of subsumed elements and the element determining the end of the chunk itself. In some cases this last element is not required, for example, when a generic element without specific characteristics, such as a left turn, is used. Counting roundabouts and landmarks is implemented differently, as is explained next.

4.5.2 Structural Features

Structural features play an important role in the cognitively ergonomic description of a route, especially in chunking. If a salient structure is used for chunking, all the subsumed maneuvers must represent going straight. No other chunks or turns may be part of such chunks. Since this is the case, the subsumed elements need only be represented implicitly: the only information actually stored is an element representing the structural feature, for example, a T-intersection.

A special case, however, are roundabouts, since they can also be used as elements in numerical chunking. Accordingly, a *ChunkingElement* specific for roundabouts is derived from the general element used for structural chunking.

4.5.3 Point-like Landmarks

In chunking based on point-like landmarks, the end of the chunk is defined by this landmark; the maneuvers up to this landmark need to represent going straight. This is similar to structural chunking. Hence, the *ChunkingElement* contains an elment describing the landmark used for chunking. Additionally, a counter stores how many landmarks of the same type are passed before reaching this landmark—to enable numerical chunking based on landmarks (see above).

4.5.4 Linear Landmarks

A *ChunkingElement* for the use of linear landmarks contains an element describing the linear landmark. However, the linear landmark might not be sufficient to identify the end of the chunk (cf. [36]); therefore, an optional *ChunkingElement* for a point-like landmark is provided. This landmark may

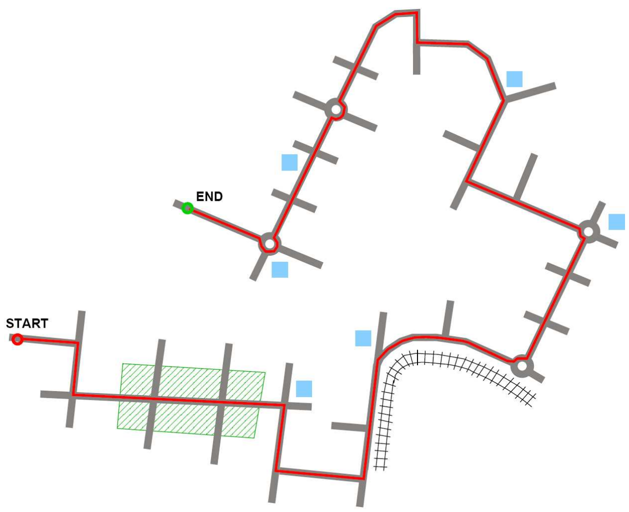

Figure 3: An example route used to illustrate the implemented automatic chunking procedures.

be used to indicate the end of the chunk.

5 Example

The Urban Knowledge Data Structure is implemented in a demonstrator, and runs on data of real street networks. In this paper, however, the focus is on illustrating the potential of the procedures of automatic chunking, and hence, we have chosen an artificial example: a route in a deliberately complex environment (Figure 3). In particular, this route covers various possibilities of applying alternative strategies to structure a route description.

The chosen route can be verbalized by the following directions, which already apply several chunking procedures:

- Start.
- Turn right at the T-intersection.
- Turn left at the next intersection.
- Go straight through the park and turn right at the landmark.
- Turn twice left.
- Follow the rail tracks until you reach a roundabout. There you take the first exit.
- At the next roundabout take the first exit.
- Turn right at the end of the road.
- Turn left at the landmark.
- Turn right at the T-intersection.
- At the second roundabout take the third exit.
- End.

In the following, we focus on three parts of the route in order to describe how alternative strategies of chunking can be applied and how they effect the results of an automatic directions generator implementing them. These cover the part through the park, the part along the rail tracks, and the part at the last roundabout.

5.1 Through the Park

After the second intersection along the route the traveler has to follow the road without turning while passing two decision points; at the third, a right turn has to be performed. The two decision points where no turn is required are located within an areal landmark, a park. The third decision point is identified by a point-like landmark. This constellation offers three major possibilities to build a chunk covering all three intersections:

- **Using the areal landmark** for identifying the last decision point as well as for reassuring the traveler while passing decision points without turning. The resulting verbalized chunk would read:
  - *Go straight through the park and turn right after you left the park.*
- **Using numerical chunking** to describe how to follow the chunk. Since the turn is already at the third intersection, it is easy for the traveler to pick the right decision point for turning by counting the intersections. The resulting verbalized chunk would read:
  - *Turn right at the third intersection.*
- **Using the point-like landmark** to determine the end of the chunk. If there is a salient and unambiguously identifiable landmark available this is always a good option to use. The resulting verbalized chunk would read:

– *Turn right at the landmark.*

Note that the UKDS provides chunks in a data structure and is not concerned with their verbalization. We present the chunks here in a verbalized manner only for readability. Note also that systems using the UKDS need to choose preferred chunks where alternatives are possible (see Section 6).

5.2 Follow the Rail Tracks

The rail tracks can be used as linear landmark to chunk part of the route. The only roundabout on this part allows for identifying the end of the chunk; it leads to a direction that is easy to follow and bears no decision points where the traveler is likely to leave the route. This direction could look like:

- *Follow the rail track until you reach a roundabout. There you take the first exit.*

The characteristics of the linear landmark also allows for building up a hierarchy, with the above suggested direction on the top level. This top level could be split up into two subsequent directions on the next lower hierarchical level:

- *Turn right at the second intersection / at the landmark.*
- *Take the first exit at the roundabout.*

The first direction at this layer, *turn right*, uses a point-like landmark in its alternative form, and the second direction refers to the same roundabout as the top layer direction. Both directions build chunks over intersections that do not require a turn. Hence, theoretically a third, and lowest hierarchical level can be provided, which does no longer contain any chunking, but single instructions for each decision point.

5.3 At the Last Roundabout

A good example of numerical chunking can be found shortly before the route reaches its destination. Before turning the last time at a roundabout the traveler passes four other decision points without changing direction. While going straight through the four intersections before the final roundabout, the traveler passes another roundabout and a landmark. At the end of the chunk another landmark is located, which is a possible alternative candidate for identifying the end of the chunk. Therefore, apart from the second roundabout and the turn that has to be performed at this roundabout, there are three other elements that can be integrated in an instruction. These are:

- **The first roundabout**, which has to be mentioned; otherwise the second roundabout could not be identified unambiguously. It is sufficient to talk about a *second* roundabout.

- **The landmark at the third decision point**, which can be used in the instruction describing the chunk to reassure the traveler. Its use is not mandatory.

- **The landmark at the fifth decision point**—the second roundabout—

can be used in the same way as the second roundabout itself to identify the last intersection of the chunk. However, the roundabout has to be mentioned since it is required to describe the turn direction properly. Mentioning the roundabout is already a strong element to identify the decision point for the next turn. Therefore, mentioning the landmark is optional.

The implementation of UKDS searches for a chunk consisting of elements that are easily identified, unambiguously describing how to follow the route, and as short as possible. Hence, the selected verbalized structure is:

- *At the second roundabout take the third exit.*

6 How Chunks can be Used in Route Directions

The goal of this paper is to advice a data structure that is as flexible as possible in incorporating a plethora of different chunking alternatives employed by natural cognitive agents. Therefore, we defined a conceptual framework of granularities of urban knowledge as a guideline for the proposed UKDS. In the previous sections we have detailed this data structure for hierarchically organizing urban knowledge to be employed in route directions.

In this section, we connect the UKDS to existing approaches that implement different chunking principles. We will especially focus on context-specific route directions [36], but also discuss other approaches, such as the wayfinding choreme theory [22], as a possibility to advise the best possible level of granularity for a specific route.

6.1 Context-Specific Route Directions

Richter and Klippel [36] introduced a computational process for generating route directions. The process is termed GUARD, which stands for Generation of Unambiguous, Adapted Route Directions [35]. This reflects that the process generates directions that unambiguously identify each route–segment and that adapt to a route's properties and environmental characteristics, i.e., to the given environmental context. Accordingly, the route directions generated by GUARD are termed *context-specific route directions*.

Especially, the process integrates different environmental features, such as rivers (linear landmarks), salient buildings (point-like landmarks), and T-intersections (structural features), as referable elements in route directions. Generation of route directions is realized as an optimization process. The result of an optimization clearly depends on the applied optimization criterion: in route directions, a straightforward choice is to reduce the number of instructions necessary to guide an agent from an origin to a destination. This approach is in congruence with several theoretical frameworks in cognitive science (e.g., the 007 principle [5], or the cognitive load theory [31, 14]). Further optimization strategies are conceivable, which could be induced by individual characteristics of a wayfinder (e.g., his familiarity with the environment [33, 38]), or by the wayfinder's mode of travel (e.g., a cyclist or a pedestrian).

The basic elements in GUARD are pairs of decision points and actions. This idea is related to the wayfinding choreme theory that will be discussed next. It is important to note that pairing decision points with actions is similar to the approach of defining basic actions as *maneuvers*. This similarity makes it possible to couple two aspects: first, the definition of a flexible data structure which incorporates a plethora of chunking principles allowing for changes in the granularity of route directions; second, the implementation of different optimization strategies that, for example, may adapt to the familiarity of the wayfinder with an environment. We will discuss this aspect in some more detail after introducing the wayfinding choremes theory.

6.2 Theory of Wayfinding Choremes

The core of the wayfinding choreme theory deals with the conceptualization of route knowledge and the formal modeling thereof [22]. To formally handle transitions between different levels of granularity two concepts are applied. First, the grouping of primitive elements into chunks, or higher order route direction elements, is characterized as a formal grammar. This way possible groupings are specified. These groupings can be local route parts, such as *turn right at the second intersection*, or they can be globally specified to chunk known parts of the route (see Srinivas and Hirtle [39] for a detailed description on how wayfinding choremes can be used to model a wayfinder's familiarity and the change in levels of granularity accompanied with this). Second, to actually process a route into specific route parts, term rewriting rules are applied [10]. This technique allows processing a route-string that is defined using the formal grammar and identifying those parts of a route first that are deemed most important. For example, T-intersections are generally thought of as valuable means to change the level of granularity. Hence, those parts that are terminated by a T-intersection will be looked for first. Practically this means that the rule for identifying a T-intersection will be executed first. The wayfinding choremes that are chunked by this procedure are not available for further chunking. The resulting chunk, however, can be part of coarser levels of granularity. For example, along a given route two roundabouts are encountered with a *straight* at the first roundabout and a *right turn* at the second roundabout. Roundabouts are salient features along a route and classify as structural features usable as landmarks. A first iteration would identify two distinct chunks in the route: *straight at the first roundabout* and *right at the second roundabout*. A second iteration applying further rules would, however, identify these two consecutive chunks and group them to an even coarser chunk: *right at the second roundabout*.

6.3 Combining Optimization and Data Structure

The proposed data structure provides all the information needed for chunking; it is structured such that it well supports the implementation of chunking algorithms working on it. These chunks may be multi-level, i.e., as explained in Section 4.1 we can generate higher-level route direction elements by combining already chunked route information into new chunks.

The data structure also straightforwardly supports generating route directions based on optimization (as in GUARD). The proposed optimization criterion of reducing the number of instructions corresponds to generating directions with as few chunks as possible. Accordingly, based on the data represented in UKDS, in generating route directions those chunks are preferred that cover a significant part of the route (cf. [36]). It is also possible to use other optimization criteria. For example, aiming for directions that guide a wayfinder along a sequence of point-like landmarks (as it is done in the landmark-spider approach [4]) may be realized by preferring chunks based on point-like landmarks along a route over chunks employing other principles.

6.4 CORAL

Different parts of the route may require different levels of granularity. The approach by Dale and coworkers [7, 8] employs a general three-partition of the route: a detailed beginning, a highly summarized middle part, and a more detailed ending (cf. also [19]). The rationale behind this partition is that the beginning of a route, i.e., getting on the right track starting from the origin, and the end of a route, i.e., actually getting to your destination while already being near it, often involves several frequent changes in movement, while the middle part often requires only a few. In urban environments, typically this involves getting on a main street from your current location, then staying on that street for a considerable part of a route, and to the end of the route navigating through smaller streets of the neighborhood that your destination is located in. This distinction is also present in the work by [1] who generate route maps with varying scale depending on the frequency of movement changes. Correspondingly in behavioral research, Michon and Denis [30] found that people giving route directions refer more frequently to landmarks at the beginning and end of a route than in the middle part.

To achieve this three-partition, Dale and coworkers employ different methods of chunking: they rely on landmark-based chunking (see Section 3) which does not necessarily result in route chunks corresponding to the partition. Path-based chunking, however, is based on road status hierarchy, path length, and turn typology (e.g., T-intersections) [8] and directly relies on the structure of the urban street-network. This approach is well suited to chunk routes such that they result in the three-partition (especially when relying on road status hierarchy).

7 Conclusions and Outlook

The aim of this article is to lay the foundations for a data structure that a) allows for specifying cognitively ergonomic route directions, b) is based on existing data standards, and c) links in with approaches to calculate routes or generate route directions. To achieve this aim a framework has been detailed for a data structure that explicitly allows for incorporating urban knowledge in a way that a cognitive agent would apply it or would find it beneficial in the task of understanding and following route directions. We limited the scope of this article to two fundamental aspects of cognitive spatial information processing: the creation of hierarchical knowledge structures and the ability to operate and use different levels of granularity. A central aspect of this approach is the assumption, discussed by Allen [2] as a constructivist approach to route directions, that the (verbal/written) input information is integrated into existing knowledge structures to specify a situation model. These knowledge structures are the result of continuous interaction with the environment and the abstraction from individual instances to general spatial knowledge structuring principles. We exemplarily discussed one of the earliest taxonomies of these structures, the elements of Lynch [27]. Based on this initial taxonomy we developed a detailed specification for the most pertinent structuring principles with the goal to create a framework that comprises flexibility with respect to the level of granularity with which environments, more precisely, information necessary for the generation of route directions, can be specified. The data structure, termed UKDS, is inspired by the OpenLS data standard and extends and complements the main data types that have been detailed in this data standard. The close relation to this existing data standard will allow for a wide application of this work and will help to solve interoperability problems. The data types of the OpenLS specification have the additional advantage that they correspond to other existing formal specifications that allow for specifying which route parts are actually used in giving route directions. This combination is fruitful as it covers the two main aspects necessary for cognitively ergonomic route directions: specifying data in an easy to use but comprehensive framework and applying algorithms to tailor route directions to specific situations (including personal preferences).

This work features in several current research efforts and, in more general terms, is a springboard for elaborating various aspects of specifications that capture the cognitive processing of spatial information in built environments relevant for the specification of an agent's movements. One prominent example is the use of the data structure in specifying linguistic descriptions thereof and, then, employing these in mining large corpora such as the web [12]. These research efforts add to filling the data structure with environmental information that can be used for creating cognitively ergonomic route directions relying on environmentally salient structures.

Acknowledgements

This work has been supported by the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition, which is funded by the Deutsche Forschungsgemeinschaft (DFG), by the Cooperative Research Centre for Spatial Information, whose activities are funded by the Australian Commonwealth's Cooperative Research Centres Programme, and by Lisasoft, Australia. OpenLS is a trademark of the Open Geospatial Consortium.

References

[1] M. Agrawala and C. Stolte. Rendering effective route maps: Improving usability through generalization. In *SIGGRAPH 2001*, Los Angeles, California, USA, 2001.

[2] G.L. Allen. Principles and practices for communicating route knowledge. *Applied Cognitive Psychology*, 14(4):333–359, 2000.

[3] T. Bychowski. OpenGIS location services (OpenLS): Part 6 – navigation service. Technical report, Open GIS Consortium Inc., 2003. OGC Implementation Specification 03-007r1 (Version 0.5.0).

[4] D. Caduff and S. Timpf. The landmark spider: Representing landmark knowledge for wayfinding tasks. In T. Barkowsky, C. Freksa, M. Hegarty, and R. Lowe, editors, *Reasoning with mental and external diagrams: computational modeling and spatial assistance - Papers*

from the 2005 AAAI Spring Symposium, pages 30–35, Menlo Park, CA, 2005.

[5] A. Clark. *Microcognition: Philosophy, Cognitive Science, and Parallel Distributed Processing.* MIT Press, Cambridge, MA, 1989.

[6] E. H. Cornell, C. D. Heth, and D. M. Alberts. Place recognition and wayfinding by children and adults. *Memory and Cognition*, 22:633–643, 1994.

[7] R. Dale, S. Geldof, and J.-P. Prost. Coral: Using natural language generation for navigational assistance. In M. Oudshoorn, editor, *Proceedings of the 26th Australasian Computer Science Conference (ACSC2003)*, Adelaide, Australia, 2003.

[8] R. Dale, S. Geldof, and J.-P. Prost. Using natural language generation in automatic route description. *Journal of Research and Practice in Information Technology*, 37(1):89–105, 2005.

[9] M. P. Daniel and M. Denis. Spatial descriptions as navigational aids: A cognitive analysis of route directions. *Kognitionswissenschaft*, 7(1):45–52, 1998.

[10] N. Dershowitz. A taste of rewrite systems. In P. E. Layer, editor, *Functional Programming, Concurrency, Simulation and Automated Reason-*

ing: International Lecture Series 1991-1992, pages 199–228. Springer, Berlin, 1993.

[11] M. Duckham and L. Kulik. "Simplest" paths: Automated route selection for navigation. In W. Kuhn, M. Worboys, and S. Timpf, editors, *Spatial Information Theory. Foundations of Geographic Information Science*, pages 169–185. Springer, Berlin, 2003. LNCS 2825.

[12] A. Furlan, T. Baldwin, and A. Klippel. Landmark classification for route description generation. In *Proceedings of the Fourth ACL-SIGSEM Workshop on Prepositions, Prague, Czech Republic*, pages 9–16, 2007.

[13] C. Habel. Incremental generation of multimodal route instructions. In *Natural Language Generation in Spoken and Written Dialogue*, Palo Alto, CA, 2003. AAAI Spring Symposium 2003.

[14] G. S. Halford, W. H. Wilson, and S. Phillips. Processing capacity defined by relational complexity: Implications for comparative, developmental, and cognitive psychology. *Behavioral and Brain Sciences*, 21(6):803–865, 1998.

[15] S. Hansen, A. Klippel, and K.-F. Richter. Cognitive OpenLS specification. Technical report 012-10/2006, SFB/TR 8 Spatial Cognition, Universität Bremen, 2006.

[16] S. Hansen, K.-F. Richter, and A. Klippel. Landmarks in OpenLS — a data structure for cognitive ergonomic route directions. In M. Raubal, H. Miller, A. U. Frank, and M. F. Goodchild, editors, *Geographic Information Science - Fourth International Conference, GIScience 2006*, LNCS 4197, pages 128–144, Berlin, 2006. Springer.

[17] S. Haque, L. Kulik, and A. Klippel. Algorithms for reliable navigation and wayfinding. In T. Barkowsky, M. Knauff, G. Ligozat, and D.R. Montello, editors, *Spatial Cognition V - Reasoning, Action, Interaction*, LNAI 4387. Springer, Berlin, to appear.

[18] J. R. Hobbs. Granularity. In A.K. Joshi, editor, *Proceedings of 9th International Joint Conference on Artificial Intelligence*, pages 432–435. Morgan Kaufmann, San Francisco, 1985.

[19] K. Höök. *An Approach to a Route Guidance Interface.* Licentiate thesis, Dept. of Computer and System Sciences, Stockholm University, 1991.

[20] P. N. Johnson-Laird. *Mental models.* Harvard University Press, Cambridge, MA, 1983.

[21] A. Klippel, H. Tappe, and C. Habel. Pictorial representations of routes: Chunking route segments during comprehension. In C. Freksa, W. Brauer, C. Habel, and K. F. Wender, editors, *Spatial Cognition III – Routes and Navigation, Human Memory and Learning, Spatial Rep-*

resentation and Spatial Learning, pages 11–33. Springer, Berlin, 2003. LNAI 2685.

[22] A. Klippel, H. Tappe, L. Kulik, and P. U. Lee. Wayfinding choremes - a language for modeling conceptual route knowledge. *Journal of Visual Languages and Computing*, 16(4):311–329, 2005.

[23] B. Kuipers. The spatial semantic hierarchy. *Artificial Intelligence*, 119(1-2):191–233, 2000.

[24] B. Kuipers and T. S. Levitt. Navigation and mapping in large scale space. *AI Magazine*, 9(2):25–43, 1988.

[25] D. Leiser and A. Zilbershatz. The traveller: A computatonal model of spatial network learning. *Environment and Behavior*, 21(4):435–463, 1989.

[26] K. L. Lovelace, M. Hegarty, and D. R. Montello. Elements of good route directions in familiar and unfamiliar environments. In C. Freksa and D. M. Mark, editors, *Spatial Information Theory. Cognitive and Computational Foundations of Geopraphic Information Science*, pages 65–82, Berlin, August 1999. International Conference COSIT, Springer. LNCS 1661.

[27] K. Lynch. *The image of the city.* MIT Press, Cambridge, 1960.

[28] M. Mabrouk. OpenGIS location services (OpenLS): Core services. Tech-

nical report, Open GIS Consortium Inc., 2005. OGC Implementation Specification 05-016 Version 1.1.

[29] D. M. Mark. Automated route selection for navigation. *IEEE Aerospace and Electronic Systems Magazine*, 1:2–5, 1986.

[30] P.-E. Michon and M. Denis. When and why are visual landmarks used in giving directions? In D. R. Montello, editor, *Spatial Information Theory - Cognitive and Computational Foundations of Geopraphic Information Science*, LNCS 2205, pages 400–414, Berlin, 2001. International Conference COSIT, Springer.

[31] G.A. Miller. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63:81–97, 1956.

[32] E. L. Newman, J. B. Caplan, M. P. Kirschen, I. O. Koroley, R. Sekuler, and M. J. Kahana. Learning your way around town: How virtual taxicab drivers learn to use both layout and landmark information. *Cognition*, 104:231–253, 2007.

[33] K. Patel, M. Y. Chen, I. Smith, and J. A. Landay. Personalizing routes. In *UIST '06: Proceedings of the 19th annual ACM symposium on User interface software and technology*, pages 187–190, New York, NY, USA, 2006. ACM Press.

[34] K.-F. Richter. “Cross the river and then follow the tracks”: Overview information on the way to take. In Georg Gartner, editor, *Location Based Services & Telecartography - Proceedings of the Symposium 2005*, Geowissenschaftliche Mitteilungen, pages 191–195. TU Vienna, 2005.

[35] K.-F. Richter. A uniform handling of different landmark types in route directions. In S. Winter, M. Duckham, L. Kulik, and B. Kuipers, editors, *Spatial Information Theory*, LNCS 4736, pages 373–389, Berlin, 2007. Springer. International Conference COSIT.

[36] K.-F. Richter and A. Klippel. A model for context-specific route directions. In C. Freksa, M. Knauff, B. Krieg-Brückner, B. Nebel, and T. Barkowsky, editors, *Spatial Cognition IV. Reasoning, Action, Interaction: International Conference Spatial Cognition 2004*, LNAI 3343, pages 58–78, Berlin, 2005. Springer.

[37] K.-F. Richter and A. Klippel. Before or after: Prepositions in spatially constrained systems. In T. Barkowsky, M. Knauff, G. Ligozat, and D.R. Montello, editors, *Spatial Cognition V - Reasoning, Action, Interaction*, LNAI 4387, pages 453–469, Berlin, to appear. Springer.

[38] F. Schmid and K.-F. Richter. Extracting places from location data streams. In *UbiGIS 2006 - Second International Workshop on Ubiquitous Geographical Information Services*, 2006. Workshop at GIScience 2006.

[39] S. Srinivas and S. C. Hirtle. Knowledge based schematization of route directions. In T. Barkowsky, M. Knauff, G. Ligozat, and D.R. Montello, editors, *Spatial Cognition V - Reasoning, Action, Interaction*, LNAI 4387, Berlin, to appear. Springer.

[40] H. A. Taylor and B. Tversky. Spatial mental models derived from survey and route descriptions. *Journal of Memory and Language*, 31:261–292, 1992.

[41] P. W. Thorndyke and B. Hayes-Roth. Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, 14:560–589, 1982.

[42] S. Timpf and W. Kuhn. Granularity transformations for routes. In C. Freksa, W. Brauer, C. Habel, and K. F. Wender, editors, *Spatial Cognition III – Routes and Navigation, Human Memory and Learning, Spatial Representation and Spatial Learning*, pages 77–88. Springer, Berlin, 2003. LNAI 2685.

[43] M. Tomko and S. Winter. Identification of the initial entity in granular route directions. In Andreas Riedl, Wolfgang Kainz, and Gregory A. Elmes, editors, *Progress in Spatial Data Handling. 12th International Symposium on Spatial Data Handling*, pages 43–60, Berlin, 2006. Springer.

[44] M. Tomko and S. Winter. Recursive construction of granular route directions. *Journal of Spatial Science*, 51(1):101–115, 2006.