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Urban granularities—a data structure for cognitively ergonomic route directions

**Alexander Klippel · Stefan Hansen ·
Kai-Florian Richter · Stephan Winter**

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Abstract This paper addresses a data structure specification for route directions that incorporates essential aspects of cognitive information processing. Specifically, we characterize levels of granularity in route directions as the result of the hierarchical organization of urban spatial knowledge. We discuss changes of granularity in route directions that result from combining elementary route information into higher-order elements (so called spatial chunking). We provide a framework that captures the pertinent aspects of spatial chunking. The framework is based on established principles used—from a cognitive perspective—for changing the granularity in route directions. The data structure we specify based on this framework allows us to bridge the gap between results from behavioral cognitive science studies and requirements of information systems. We discuss the theoretical underpinning of the core elements of the data structure and provide examples for its application.

Keywords Route directions · Spatial structure · Granularity · Spatial chunking

A. Klippel (✉)
Department of Geography, GeoVISTA Center, Penn State,
State College PA, USA
e-mail: klippel@psu.edu

S. Hansen
CRC Spatial Information, The University of Melbourne,
Melbourne, Australia

S. Hansen
LISAsoft, Pyrmont, Australia

K.-F. Richter
Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition,
Universität Bremen, Bremen, Germany

S. Winter
Department of Geomatics, The University of Melbourne,
Melbourne, Australia

1 Introduction

Cognitive processes that abstract from rich environmental information are an essential part of human information processing [6], [14]. 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). Our work focuses on urban environments, specifically on how information on routes in such environments can be structured by information systems in ways that 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 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 among these levels. This issue will dominate the discussions throughout this paper. Generally, the following approaches to route information can be distinguished: (a) those that take a complete route as input and optimize route directions for this particular route [9], [28], [44]; (b) those that optimize the route choice based on cognitive aspects, for example, to ease the description of the route or to reduce the likelyhood of getting lost [5], [13], [20]; (c) those that differentiate between parts of the environment that are known to the wayfinder and parts that are unknown. The idea here 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 [22], [41], [46], [47], [49], [53].

All of these approaches deal with different levels of granularity in route directions. The contribution of this paper is therefore twofold: on one hand, our characterization of route knowledge will provide a framework for specifying a data structure for *cognitively ergonomic route directions* [26], that is, route directions adapted to the cognitive capacities of human wayfinders. The focus is placed on changing the granularity in route directions. On the other hand, the presented data structure allows for specifying several alternatives to reduce the amount of information in route directions. We will discuss how the data structure can interact with existing approaches to route information to determine the most adequate level of granularity with respect to cognitive ergonomics. One overall goal of our work is to define a data structure that 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 therefore 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 2. We then discuss chunking as a process to change the granularity in route knowledge and present different chunking mechanisms in Section 3. This is followed by an introduction to the urban knowledge data structure (UKDS) in Section 4 that captures these chunking mechanisms. An example of how UKDS captures these chunking mechanisms is provided in Section 4.5. Finally, Section 5 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. [21, p. 435]

The hierarchical organization of spatial information and the ability to flexibly change between different levels of granularity are key characteristics of the cognitive organization of spatial knowledge [14], [21], [29], [52]. 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 [33], [52]. 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 systems design, providing a user with too much detail violates many findings in cognitive science as discussed such as 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. [6, p. 64]

For built environments, Kevin Lynch [33] introduced a new viewpoint to architecture with his pioneering work on imageability. Instead of looking at cities architecturally, Lynch made an effort to explain cities as they are perceived and structured by their inhabitants. He proposed the concept of *imageability* to characterize 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 that are 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. Lynch differentiates between five basic elements: paths, edges, districts, nodes, and landmarks.

Structuring route knowledge by taking into account environmental features can potentially provide a coarser perspective on the required wayfinding action than simple turn-by-turn directions [32], [35], [44]. This is easier to cognize and often sufficient for successful wayfinding. Additionally, not only is the amount of information that has to be memorized and understood reduced, but the information additionally is 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) [40]. 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 possesses 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 [23], [50]).

This is especially the case if the user is familiar with the environment, i.e., when a traveller has experienced a specific environment before [7], [30], [31], [41], [51]. 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 her/his new position).[1] This may be made possible by zoom-in operations, i.e., by accessing a more detailed level of the hierarchy, or by (mental) inference processes. Such inferences extract information from the instruction to determine which action is to be performed in cases where this information is not explicitly specified. For example, from *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* can be inferred [36], [48].

Different parts of the route may require different levels of granularity. The approach by Dale and coworkers [8], [9] divides the route into three parts: a detailed beginning, a highly summarized middle part, and a more detailed ending (cf. also [22]). A comparable tri-partion can be found in early work on linguistic aspects of route directions by [24], [57]. The rationale behind this partition is that the origin and the destination of a route are special. 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 (1) getting on a main street from your current location, then (2) staying on that street for a considerable part of a route, and finally navigating through smaller streets of the neighborhood that your destination is located in. This distinction is also present in the work by Agrawala and Stolte [1] who generate route maps with varying scales depending on the frequency of changes in direction. Similarly in behavioral research, Michon and Denis [37] 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 tri-partition, Dale and coworkers employ different methods of segmenting a route: landmarks are used to structure specific route parts (see also Section 3); paths, primarily based on the road status hierarchy identify the middle part; path length and turn typology (e.g., T-intersections) refine this approach [9]. These methods are well suited to structure routes such that they result in the tri-partition (especially when relying on road status hierarchy).

[1] This distinction is reflected by differentiating *on-line*—route directions given while an agent is traveling—and *in advance* route directions—route directions given prior to the actual travel [16], [44]. A classification of different route direction styles is provided by [27].

3 Chunking and segmenting: processes to change the granularity in route knowledge

The basic unit—the *primitive*—in our approach is a decision point with an associated action identified as being pertinent by behavioral research [2], [10]. A route is a sequence of such decision point/action pairs.

Abstracting from individual decision points leads to higher-order route direction elements, HORDE [28]. We term this abstraction process *spatial chunking* [27]. In the context of this article the primary focus is placed on how the chunking of primitives into larger units (chunks) changes the level of granularity in route directions and thereby mimics cognitive processes of abstracting from details to reduce the amount of information necessary to follow a route. Alternatively, chunking may be employed in cases where parts of the route are unknown or only partially known. This plays a subordinate role in this paper; however, we will discuss it where appropriate.

In the following section, we will introduce different ways to segment a known route, i.e., to chunk consecutive decision points into HORDE. The chunking principles we discuss reflect human conceptualizations of specific spatial situations; their applicability depend on environmental information that is available and the route–following actions to be performed. We will start with an example that will be used throughout the paper to illustrate chunking principles and the application of the data structure that we will introduce in Section 4.

3.1 An illustrative example

Since the aim of this section is to illustrate different ways of segmenting routes, we chose a deliberately complex artificial example, as shown in Fig. 1. In particular, this route provides the possibility of applying alternative strategies to structuring a route description.

The chosen route can be verbalized by the following directions, which already apply several chunking procedures that we will explain in detail below. The numbers after each verbalization correspond to the numbering of each decision point (and chunked decision points, respectively) as displayed in Fig. 1:

- Start (1).
- Turn right at the T-intersection (2).
- Turn left at the next intersection (3).
- Go through the park (4–5) and turn right at the landmark (6).
- Turn twice left (7–8).
- Follow the rail tracks until you reach a roundabout. There you take the first exit (9–12).
- At the next roundabout take the first exit (13–15).
- Turn right at the end of the road (16–17).
- Turn left at the landmark (18–19).
- Turn right at the T-intersection (20).
- At the second roundabout take the third exit (21–25).
- End (26).

As can be seen when tracing these instructions in Fig. 1, consecutive decision points are chunked into a single route instruction in different ways. In the following, we will look at chunking principles more systematically by enriching the example

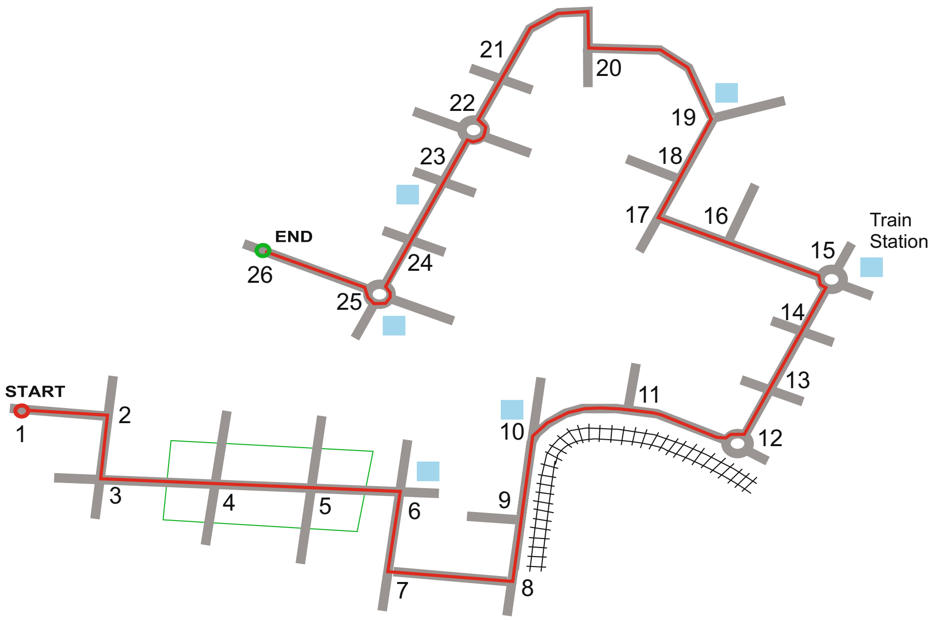

Fig. 1 An example route used to illustrate the implemented automatic chunking procedures. The decision points are *numbered* (*1–26*). The potential chunks are referred to by the decision points they contain (in the text), for example 4–6: *turn right at the landmark*

with approaches discussed in the literature; Section 3.9 summarizes our findings and places them into a more general framework of chunking, i.e. granularity changes.

3.2 Numerical chunking

Numerical chunking characterizes the chunking of decision points by counting them and summarizing them as a single instruction. Mostly, this is based on nodes in street networks [33].

Example: *Turn left at the second intersection.* (chunk 18–19 Fig. 1)
Example: *Turn twice left.* (chunk 7–8)
Example: *Turn right at the third intersection.* (chunk 4–6 Fig. 1, as one possibility)

It is also conceivable to have second order numerical chunks on the basis of salient elements in the environment, such as roundabouts or landmarks (e.g., McDonalds).

Example: *At the second roundabout take the third exit.* (chunk 21–25 Fig. 1)

3.3 Chunking based on structural features

Salient structural characteristics of intersections and environmental elements allow for identifying these locations uniquely with respect to a specific route. Mark [36] discussed this aspect in the context of inferring the navigational complexity of intersections from their structural qualities. Duckham and Kulik [13] 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 enforce a change in the movement 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 reflected in the physical structures of the road. Other examples are visually salient areas (districts) or visually salient channels (see Fig. 1).

Example: *Turn right at the T-intersection.* (chunk 16–17 and 20 Fig. 1)
Example: *At the next roundabout* (*following the train tracks*) *take the first exit.* (chunk 9–12)
Example: *Turn right just before the Botanical Garden.* (example not present in Fig. 1)
Example: *Turn right just before the river.*

3.4 Local chunking based on point-like landmarks along the route

Landmarks located along the route can be used to chunk specific parts of a route. Such landmarks are considered point-like if they are located at a specific spot along the route, for example, an intersection, and are only functionally relevant for this one spot. When 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 [45]).

Example: *Turn left at the landmark.* (e.g., chunk 18–19 Fig. 1)
Example: *Turn right at the Shell gas station.*

3.5 Local chunking based on linear landmarks along the route

Linear landmarks are landmarks that spread along the route, such as a river or railway tracks. They may be functionally relevant for more than one decision point. 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. Linear landmarks that directly influence decision points can be used to chunk route knowledge for as long as they are present along the route. Based on classifications found in the literature [9], [44] we differentiate the following three cases:

- Linear landmarks close to the route. Example: *Follow the rail tracks.* (*chunk 9–12 Fig.* 1)
- Virtually linear landmarks. Example: *Follow the markers.*
- The street level hierarchy. Example: *Take Princess Highway.*

In route directions, a wayfinder additionally needs to know until which point a linear landmark can guide the movement pattern, i.e., how long a linear landmark (a landmark that can be referred to as *along landmark*) is to be followed.

Example: *Follow the rail tracks until you reach a roundabout.* (chunk 9–12 Fig. 1)
Example: *Follow the tracks until they end.*

3.6 Local chunking based on area-like landmarks along the route

Area-like landmarks are similar to linear landmarks in that they spread along the route and may be functionally relevant for more than one decision point. However, conceptually they have clear area-like characteristics. We distinguish two alternatives. In the first, an area-like landmark 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. *Go through the park.* (chunk 4–5 Fig. 1)

3.7 Global chunking based on point-like landmarks

A similar situation as mentioned above occurs where a route does not always have to be fully specified. Consider the following case: the landmarks at the end of chunk 13–15 (i.e. decision point 15, where additionally a roundabout is present, see Fig. 1) is a well known train station. When providing a route direction such as *drive to the train station and from there...*, one might have a specific route in mind, but this is not a prerequisite. Recently, several approaches based on, what we term *super-chunks*, have emerged [41], [49], [53]. In these approaches, a landmark chunks part of the route while the route is underspecified. Tomko and Winter [53], [54] aim for identifying the environmental elements to be referenced in a route direction task for knowledgeable wayfinders by analyzing the given hierarchy of spatial information. Patel and collaborators [41] combine the analysis of movement patterns with the possibility of providing personalized information.

Example: *Go to the train station.* (see landmark at decision point 15 Fig. 1)

3.8 Global chunking based on area-like landmarks

In this case, an area-like landmark covers part of the environment that directly related to the route. An example would be the downtown area of a city [39]: *Drive downtown, at the corner ...* Area-like landmarks potentially allow for chunking 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 [54], or the wayfinder may need to traverse them somehow finding her own route to reach the next segment of the way to take [42]. 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 (see examples below), in the latter they serve as environmental features that can be exploited to guide the wayfinder toward 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*

3.9 Summary: principles of chunking

The chunking principles presented above can be summarized as belonging to two main categories. Within these two general categories, further distinctions can be made.

1. Part of a route is chunked and the involved decision point/action pairs are explicit in both the representation of the route and a potential route instruction. We can distinguish two cases:
   - The number of chunked elements is explicitly referred to (*turn right at the second intersection*).
   - A chunk of turning actions has been assigned a specific name reflecting a specific turning concept (e.g., *p-turn* or *hook turn*). Although not explicitly referred to, the individual turning actions that are characteristic for these concepts are still inferable.
2. Organization principles that chunk route parts such that individual decision point/action pairs are no longer identifiable. Here, we can additionally distinguish whether we assume that wayfinders are on a specific route and we need to keep them on this route, or if we assume that wayfinders are able to find their way to the next specified place on their 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. 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 element 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 tracks* or *through the park* (see Fig. 1). 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 [44].

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 general chunking principles have to be incorporated into a data structure. One aspect important to keep in mind is that we do not aim at mimicking human route directions as such; 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 than people normally have about their environment. At the same time, we can present route information such that it eases human cognitive processing (see Section 2). Some of the discussed principles are straightforward to implement while others depend on available information, either on individual cognitive processes or on the environmental data available.

4 An urban knowledge data structure

As demonstrated above, chunking is an important and omnipresent principle in organizing spatial knowledge that eases conceptualizing, memorizing, and communicating route information. Incorporating chunking into navigational assistance systems is an important step for the generation of cognitively ergonomic route directions. On the one hand, this requires algorithms that sensibly combine elementary wayfinding actions, i.e., chunk according to the principles presented in the last section. On the other hand, a data structure is needed that captures the relevant information and enables chunking in the first place. We developed such a data structure for turn-by-turn directions that we term *urban knowledge data structure* (UKDS).[2] UKDS is based on the well established OGC OpenLS standard, which we illustrate in Section 4.2 after discussing the prerequisites of UKDS. Section 4.3 presents the general architecture of UKDS; in Section 4.4 we outline its implementation. After discussing UKDS in the light of our example route (see Fig. 1) in Section 4.5, Section 5 relates the data structure to chunking approaches in the literature.

4.1 UKDS prerequisites

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

- The different kinds of urban structures 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 [19] for more details on representing point-like, linear-like, and area-like 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 because the same mechanisms as for

[2] The complete specification of this data structure is available as a technical report [18].

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 have extended XLS, a XML schema defined in the OpenLS specification provided by the Open Geospatial Consortium (OGC) [34]. OpenLS defines the 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) schema which define access to the core services on 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.

In addition to the five core services, there exists a sixth service, the Navigation Service [4]. It is based on the Route Service, but additionally provides the client with all information necessary to generate more elaborate route directions. 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 General architecture of the data structure

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-component that enables chunking; Section 4.4 further illustrates this part and Section 4.5 presents some examples of specifying instructions in UKDS. The data structure is fully documented and specified in a technical report available for download [18].[3] The schema consists of 1,200 lines of code, and hence, we refer to that report and abstain from presenting any detailed code snippets here.

The basic element of the data structure is termed *maneuver*. It is a tuple representing a route segment and the decision point to which the route segment is leading. A route, then, is a list of maneuvers; special maneuvers are defined for the start and end of a route. 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 will introduce different chunking methods implemented in UKDS that are used to further structure this basic route representation.

4.4 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. Consequently, this results in a hierarchy of chunk levels. Each chunk contains a so–called *ChunkingElement*, which provides the information required to identify the extent of the encoded type of chunk. For each of the chunking methods detailed below a specific *ChunkingElement* is defined that stores the required information; these types are derived from *AbstractChunkingElementType*.

4.4.1 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 left twice* or *turn right at the third intersection*. Additionally, landmarks may be used as in *at the second roundabout, take the third exit* or *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. Chunking equal turns (e.g., *turn left twice*) is covered by *NumericalChunkingTurnType*, instructions such as "turn right at the third intersection" by *NumericalChunkingStraightType*. These differ in that the former stores the number of equal turns ('left' or 'right'), while the latter counts the passed intersections until the intersection at which to turn will be reached (i.e., the number of 'going straight' before the turn). Counting roundabouts and landmarks is implemented differently, as is explained next.

[3] http://www.sfbtr8.uni-bremen.de/papers/SFB_TR_8_Rep_012-10_2006.pdf

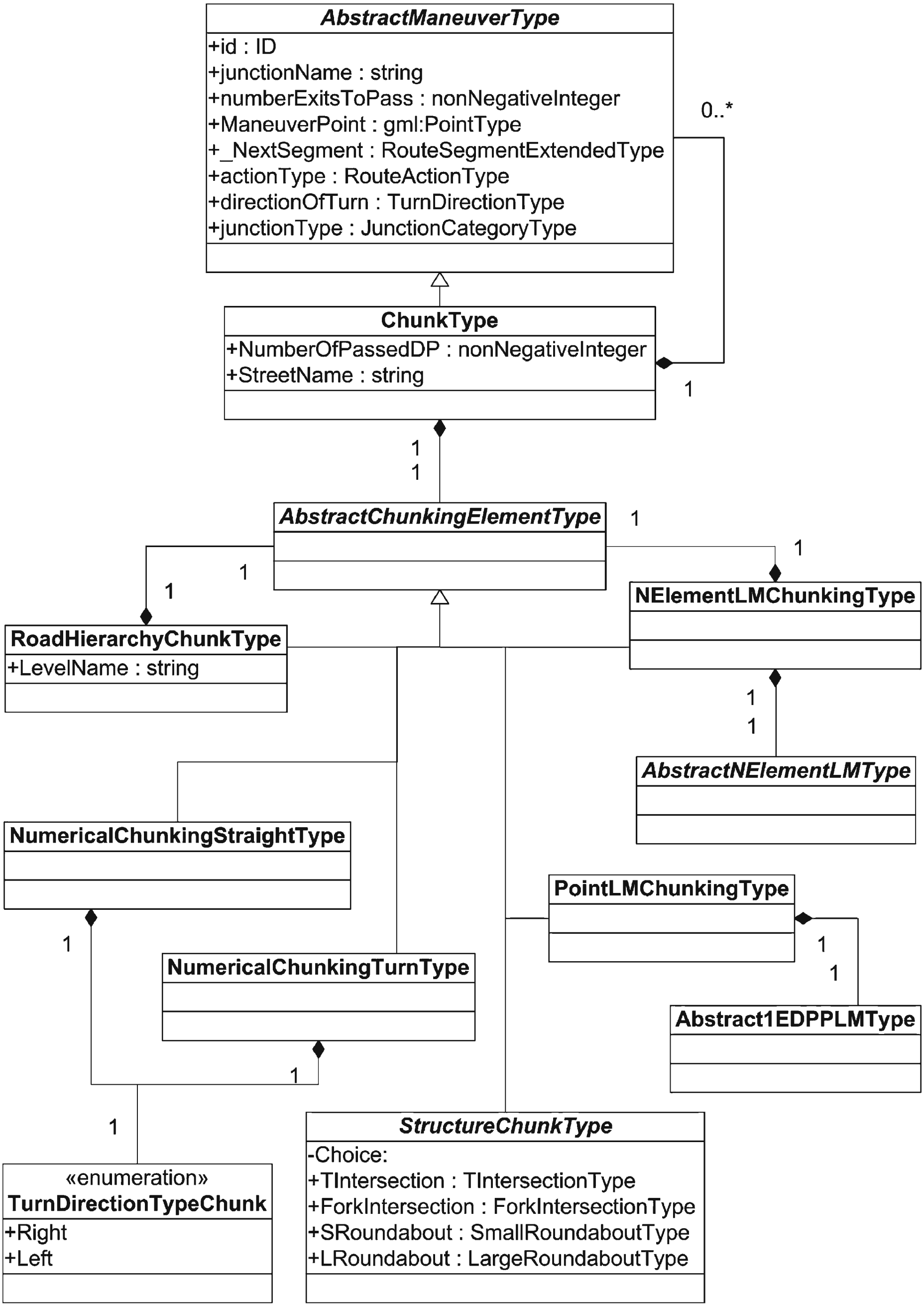

Fig. 2 UML-diagram of the UKDS-part that enables chunking

4.4.2 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. *StructureChunkType* covers this kind of chunking. 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.

4.4.3 Point-like landmarks

In chunking based on point-like landmarks, the end of the chunk is defined by a point-like landmark; the maneuvers up to this landmark need to represent going straight. This is similar to structural chunking. Hence, *PointLMChunkingType* stores an element 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).

4.4.4 Linear landmarks

A *ChunkingElement* for the use of linear landmarks contains an element describing the linear landmark (*NElementMChunkingType*). However, the linear landmark might not be sufficient to identify the end of the chunk (cf. [44], see Section 3.5). Therefore, an optional *ChunkingElement* for a point-like landmark is provided. This landmark may be used to indicate the end of the chunk.

Also, the street level hierarchy may be used for this kind of chunking as discussed in Section 3.5. This is covered by *RoadHierarchyChunkType*, which stores the name of the current level in the hierarchy and an element to indicate the end of the chunk.

4.5 Examples of using UKDS

In the following, we will refer back to the example presented in Section 3.1 (see also Fig. 1).

4.5.1 Specifying chunks in UKDS

In the following example, we list a UKDS specification for one of the instructions used in the example, namely *turn right at the T-intersection*. The listing is meant to illustrate the basic principles previously described. Space limitations do not allow for explaining every XML-element used in these specifications. Again, the report containing the complete data structure specification also contains extended examples of its application [18].

Listing 1 UKDS specification of a right turn at a T-intersection.

```
<xls:ChunkedManeuver xsi:type="xls:XManeuverType" actionType="Turn" id="dp1"
     directionOfTurn="Right" junctionType="Intersection">
    <xls:JunctionCategory xsi:type="xls:TIntersectionType" TurnDirection="right">
        <xls:RouteBranch>
            <xls:Angle uom="degree">90</xls:Angle>
        </xls:RouteBranch>
        <xls:NoRouteBranch>
            <xls:Angle uom="degree">270</xls:Angle>
        </xls:NoRouteBranch>
    </xls:JunctionCategory>
    <xls:Landmark xsi:type="xls:StructureLMType">
        <xls:Description xsi:type="xls:LMDescriptionExampleType"></
            xls:Description>
        <xls:Intersection xsi:type="xls:TIntersectionType" TurnDirection="right">
            <xls:RouteBranch>
                <xls:Angle uom="degree">90</xls:Angle>
            </xls:RouteBranch>
            <xls:NoRouteBranch>
                <xls:Angle uom="degree">270</xls:Angle>
            </xls:NoRouteBranch>
        </xls:Intersection>
    </xls:Landmark>
    <xls:PreviousSegment>
        <xls:Distance value="10"></xls:Distance>
        <xls:TravelTime>P1Y2M3DT10H30M12.3S</xls:TravelTime>
    </xls:PreviousSegment>
</xls:ChunkedManeuver>
```

4.5.2 Alternative chunking strategies

The example route of Fig. 1 allows for employing a great variety of chunking principles. It even offers different alternatives for some of the chunks. In the following, we discuss three of these alternatives: the segment that leads through the park (chunk 4–5), the segment along the rail tracks (chunk 9–12), the segment just before the last roundabout (chunk 21–25). Note that the UKDS provides chunks in a data structure and is not concerned directly 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 5).

Through the park After the second intersection along the route the traveler has to follow the road without turning while passing two decision points (4 and 5); at the third decision point, a right turn has to be performed. The two decision points where no turn is required are located within an area-like 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 area-like landmark** for identifying the last decision point as well as for reassuring the traveler while passing decision points without turning. The resulting verbalized chunk could 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 could 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 could read:

  Turn right at the landmark.

Follow the rail tracks The rail tracks (chunk 9–12 Fig. 1) can be used as linear landmark to chunk part of the route. The only roundabout on this part of the route allows for identifying the end of the chunk; it leads to a direction that is easy to follow and that bears no decision points where the traveler is likely to leave the route. This direction may be verbalized as *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 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 uses single instruction for each decision point instead of chunking them.

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 (chunk 21–25 Fig. 1) 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.

Thus, possible instructions are: *At the second roundabout, take the third exit*, *Take the third exit at the second roundabout, after you passed a landmark*, or *Take the third exit at the roundabout where the landmark is*.

5 Integrating chunking into automatic generation of route directions

The goal of this paper is to define 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 the wayfinding choreme theory [28] and context-specific route directions [44], as a possibility to define the best possible level of granularity for a specific route.

5.1 Theory of wayfinding choremes

The wayfinding choreme theory addresses the conceptualization and formal modeling of route knowledge [28]. Comparable to the primitive (in the sense of being foundational, not atomic) in the UKDS, i.e. the *maneuver*, the wayfinding choreme theory builds on cognitive conceptual primitives that structure route knowledge for wayfinding and route directions. This approach is inspired by the toolbox idea for route directions introduced by Tversky and Lee [55], [56]. The term wayfinding choreme is derived from the work of the French geographer Brunet [3] who proposed a limited set of abstract models for structuring geographic phenomena; these models are termed *choremes*. The term is a made up word combining the root of the Greek expression for space, *chor*, and the linguistic suffix, *-eme*.

From the literature on route directions and wayfinding [11], [32] we know that decision points, whether with or without a direction change, are the pertinent part of route knowledge. Taking up the theme from the beginning of the article, we can observe from the way in which humans employ directional knowledge that we do not conceptualize every potential direction that our bodies could turn to. That is, we do not consider infinitely precise directional information. For most situations, qualitative information about directions is sufficient—in the sense of a fairly small number of equivalence classes. We were able to show that the prototypical number for directions used at decision points is seven [25].[4] The wayfinding choreme theory builds on this set of conceptual primitives which could be linguistically characterized as: *left*, *right*, and *straight*, and can be rendered more precise into *sharp left*, *sharp right*, *bear left* and *bear right*. In a more formal notation we can write this as: wc_l, wc_r, wc_s and wc_{sl}, wc_{sr}, wc_{bl}, wc_{br}, respectively. These seven basic wayfinding choremes can be annotated further to capture aspects of the environment, such as landmarks (*turn left at the landmark*, wc_l^l) or salient intersections (*turn right at the T-intersection*, wc_r^t). The route represented in Fig. 1 would be characterized as follows in wayfinding choreme notation.

$$wc_r^t wc_l ws_s^a ws_s^a wc_r^l wc_l wc_l wc_s^l wc_b r^l wc_s^l wc_l^r wc_s wc_s wc_l^r wc_s wc_r^t$$
$$wc_s wc_l^l wc_r^t wc_s wc_s^r wc_s wc_s wc_r^r$$

[4]This observation holds for most intersections. Special cases such as highway exits or roundabouts where directions can be given in form or ordering information, e.g., *third exit* require an extension.

To formally handle transitions between different levels of granularity two concepts can be applied. First, the grouping of primitive elements into chunks, or *higher order route direction elements* (HORDE), is characterized as the wayfinding choreme route grammar (WCRG) [28], which is formally defined as a tuple (N, T, P, S). 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, and S is the start symbol. The grammar allows the specification of possible groupings of wayfinding choremes. 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 [49] 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 different degrees of familiarity).

Second, to actually process a route into specific route parts, term rewriting rules can be applied [12]. This technique processes a route-string that is defined using the formal grammar and identifies 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 route 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 even coarser levels of granularity, i.e. part of another chunk. For example, along the given route two roundabouts are encountered with a *straight* at the first roundabout (see Fig. 1, decision point 22) and a *right turn* at the second roundabout (see Fig. 1, decision point 25). 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*.

In the notation of term rewriting rules this procedure can be specified as follows (this example is simplified, for more details see [28]). The term rewriting rule for the first roundabout asserts that all decision points of the type *straight*, i.e., wc_s, that precede a decision point that is a roundabout, in this case wc_s^r, are transferred (rewritten) into a chunk, ra_s, a roundabout where the performed action is to go straight. Assume here that the number of wc_s is not restricted (i.e., $n \in \mathcal{N}$).

$$(nwc_s)wc_s^r \longrightarrow ra_s \tag{1}$$

The second roundabout would serve the same purpose as a landmark and all decision points with a *straight* movement pattern, wc_s, are subsumed into a new chunk:

$$(nwc_s)wc_r^r \longrightarrow ra_r \tag{2}$$

A third term rewriting rule would then be employed to further coarsen the granularity. In this example, the already existing chunks that were created on the basis of the roundabouts can be rewritten into an even coarser chunk, which can be verbalized as *turn right at the second roundabout*.

$$ra_s ra_r \longrightarrow ra_r^2 \tag{3}$$

This is only a short demonstration of how the wayfinding choreme theory can be employed to change the granularity of route information based on findings from behavioral studies on how cognitive agents structure route knowledge. The interesting aspect in the context of the present article is that a wayfinding choreme corresponds to the AbstractManeuver in the UKDS. While wayfinding choremes allow for modeling route knowledge conceptually, UKDS handles the technical requirements for current navigation services.

5.2 Context-specific route directions

Richter and Klippel [44] introduced a computational process for generating route directions. The process is termed GUARD, which stands for Generation of Unambiguous, Adapted Route Directions [43]. 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*.

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 [6], or the cognitive load theory [17], [38]). Further optimization strategies are conceivable, which could be induced by individual characteristics of a wayfinder (e.g., his familiarity with the environment [41], [47]), 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 discussed previously. It is important to note that pairing decision points with actions is similar to the approach of defining basic actions as *maneuvers*. Thus, it is possible to employ the presented data structure to incorporate a plethora of chunking principles in GUARD. Since GUARD allows for the implementation of different optimization strategies, this can be used to, for example, adapt instructions to the familiarity of a wayfinder with an environment (cf. also [46]).

5.3 Combining optimization and data structure

The proposed data structure provides all the information needed for chunking; in addition, 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 in a straightforward manner 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. [44]). 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 [5]) may be realized by preferring chunks based on point-like landmarks along a route over chunks employing other principles.

6 Conclusions and outlook

The aim of this article is to lay the foundation 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 offered for a data structure that explicitly allows for incorporating urban knowledge in a similar way as a cognitive agent would apply it. 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 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 briefly discussed one of the earliest taxonomies of these structures, the elements of Lynch [33]. Based on this initial taxonomy, we developed a detailed specification for the most pertinent structuring principles. The goal is to create a framework that provides flexibility with respect to the level of granularity with which 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 are used in this data standard. The close relation to this existing data standard allows 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 approaches 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 [15]. 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.

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Alexander Klippel is an Assistant Professor in GISCience at Penn State's GeoVISTA Center, Department of Geography. His research interest focusing on topics bridging formal and cognitive characterizations of spatio-temporal phenomena.

Stefan Hansen holds a Master's in Computer Science from the University of Bremen, Germany. For his thesis he did joint research with the Cooperative Research Center for Spatial Information (CRCSI), then joined the project for developing a proto-type implementation of the research work together with the project partner LISAsoft Pty Ltd. He is now employed by LISAsoft.

Kai-Florian Richter received a diploma in computer science at Universität Hamburg and a Ph.D. in Computer Science at Universität Bremen where he is currently a postdoctoral researcher. He is concerned with automatic wayfinding assistance; his work focuses on characterizing and representing wayfinding situations such that cognitively ergonomic descriptions can be automatically generated, and on questions of how to automatically identify and extract information from the environment that can be used to describe actions in space.

Dr. Stephan Winter is lecturing Geographic Information Science at the University of Melbourne, Australia. His research interests are focused on spatial cognitive engineering, in particular computational models of orientation, wayfinding and navigation.