forthcomming 2005, Journal of Visual Languages and Computing (JVLC), prefinal draft, pls quote original

Wayfinding Choremes – A Language for Modeling Conceptual Route Knowledge

Alexander Klippel

Cooperative Research Centre for Spatial Information,
Department of Geomatics, University of Melbourne, Australia

Heike Tappe

Linguistics Department
University of KwaZulu-Natal, Durban, South Africa

Lars Kulik

Department of Computer Science and Software Engineering
The University of Melbourne,Victoria 3010, Australia

Paul U. Lee

San Jose State University / NASA Ames Research Center,
Moffett Field, CA, USA

Address for correspondence:

Dr. Alexander Klippel
Collaborative Research Centre for Spatial Information
Department of Geomatics
University of Melbourne
VIC 3010 Australia

Phone: +61 3 83449186
Fax: +61 3 93495185
email: aklippel@unimelb.edu.au

Abstract. The emergent interest in ontological and conceptual approaches to modeling route information results from new information technologies as well as from a multidisciplinary interest in spatial cognition. Linguistics investigates verbal route directions; cartography carries out research on route maps and on the information needs of map users; and computer science develops formal representations of routes with the aim to build new wayfinding applications. In concert with geomatics, ontologies of spatial domain knowledge are assembled while sensing technologies for location-aware wayfinding aids are developed simultaneously (e.g. cell phones, GPS-enabled devices or PDAs). These joint multidisciplinary efforts have enhanced cognitive approaches for route directions.

In this article we propose an interdisciplinary approach to modeling route information, the *wayfinding choreme theory*. *Wayfinding choremes* are mental conceptualizations of functional wayfinding and route direction elements. With the wayfinding choreme theory we propose a formal treatment of (mental) conceptual route knowledge that is based on qualitative calculi and refined by behavioral experimental research. This contribution has three parts: First, we introduce the theory of wayfinding choremes. Second, we present *term rewriting rules* that are grounded in cognitive principles and can tailor route directions to different user requirements. Third, we exemplify various application scenarios for this approach.

1 Introduction

Within the past three decades the conceptualization of route knowledge in human and artificial navigators has become a central topic of research. The design of new information technologies that account for the application of conceptual knowledge is undertaken by applying formal conceptual and ontological approaches to route information (e.g. [15,33,44,47]) in concert with an increasing scientific interest in spatial cognition [21,23,38,49]. *Cognitive adequacy*[1] is becoming more important in the design of wayfinding assistance systems. The term *cognitive adequacy* has been used in two ways [43]: (1) to characterize an external representation—i.e. a representation outside the human mind—that is homomorphous to, or at least shares aspects with, an internal cognitive knowledge representation; (2) to identify external representations that support or enhances cognitive processes to aid knowledge acquisition and problem solving.

Cognitive adequacy in the first sense may foster cognitive adequacy in its second sense. This relation holds for certain domains such as route directions [19,45]. Hence, research on how people mentally conceptualize route information might—and should—be taken as input for formal conceptual and ontological models that in turn guide the design of route directions provided by artificial systems like in-car-navigation devices or handheld navigation aids.

The benefits of a formal characterization of route knowledge that is guided by insights of cognitive science research are the following: First, it allows for a *cognitive ontological approach*, resulting in, for example, the theoretical foundation of user-centered approaches incorporating location awareness and location conceptualization.

Second, the development of suitable visual languages for geographic knowledge is enhanced, in particular the design of (computer-generated) maps guided by cognitive considerations. Third, the modeling of contextualized and personalized wayfinding assistance desired by recent navigation approaches (e.g., [22,52]) becomes feasible.

In this article we combine multidisciplinary research in an interdisciplinary approach that guides the formal treatment of mental conceptual route knowledge on the basis of qualitative calculi refined by behavioral experimental research. The work is based on the theory of *wayfinding choremes* [30]. The wayfinding choremes are a representation vocabulary that characterizes route knowledge and that is based on mental conceptualizations of directions at decision points. In this sense the wayfinding choreme theory can be used for a route knowledge ontology (cf. [10]). In Guarino's [25] terminology such an ontology might primarily be characterized as a *domain ontology*. In detail, we propose the following ontology of wayfinding choremes to describe route knowledge: The primitives are wayfinding choremes that represent mental concepts of turning and non-turning actions at decision points (see section 2). Decision points are functionally relevant points along a route, such as street intersections, that require a decision which direction to take. Within our terminology, not taking a turn is also considered a decision (see section 2). In lieu of current approaches (e.g., [3]) our primitives are orthogonal to the distinction of SPAN and SNAP, they capture the conceptualization of turning actions at decision points. The rationale for this approach is grounded in recent discussions of events [8,28]. The conceptualization of events is compared to conceptualization of objects [51]. Following [40,41], [51] convincingly argue that events can be treated analogous to objects, which seems to be appropriate especially for actions in constraint structures like city street networks. In the nutshell, reference to events resembles reference to material entities, e.g. concrete objects: "It reflects our linguistic practice in talking about events and objects in the same ways; for example, we use quantification, definite and indefinite descriptions, count-expressions and proper names similarly in both cases." ([4]: 329).

Wayfinding choremes can be classified according to the basic distinction of turning actions (see section 2.2). Wayfinding choremes are also mereologically related to different kinds of chunks (called HORDE for *Higher Order Route Direction Elements*, see section 3) that exist in the conceptualization of route knowledge. The route in its entirety is the top-level category in our ontology. It is characterized by its origin, its destination, and the (possibly chunked) wayfinding choremes connecting the origin and the destination.

The same route can be organized in a number of ways by applying different mental conceptualizations that take into account, for instance, personal preferences (see section 3.4). This does not change the *formal conceptualization* within our route knowledge ontology but, in contrast, offers different descriptions for a given route on the basis of the same set of wayfinding choremes. For a more detailed discussion regarding conceptualization (and ontology) see [24].

Similar to [33] approach to an ontological assessment of activities in geographic space we regard language as a window to cognition. In addition, we integrate methods from psychology to elicit conceptual knowledge into our approach (cf. [32]). Our work emphasizes an important entry in the list of ontologically differentiated activities identified by Kuhn—turning concepts. The assumptions in our and in Kuhn's approach are similar: the interaction with the world shapes the (mental) conceptualizations of it. The focus and the methodological refinement of our approach allow for its integration into information systems and thus provide the basis for a high-level cognitive framework.

In this article we center our attention on chunking principles of wayfinding choremes to discuss cognitively adequate route directions. An example: The route direction *turn left at the third intersection* is more appropriate than the repetitive instruction *pass the next intersection, pass the next intersection, turn left at the next intersection*.

The efficiency of the wayfinding choreme approach originates in two essential characteristics (1) a small set of primitives is the basis for a variety of complex structures (HORDE), (2) the rules that generate HORDE can be adapted to different requirements, ranging from canonical cases to individual preferences. In combination, these two properties enable both, general as well as personalized cognitively adequate navigation assistance.

We represent route knowledge in terms of the *wayfinding choreme route grammar* (WCRG) [30]. This grammar—like any formal grammar—is a modality-independent representation that provides the basis for modality specific externalizations such as graphical and verbal route directions or gestures. This conception of the WCRG is supported by empirical evidence according to which abstract mental representations underlie various forms of externalizations (e.g., [29,46]).

Whereas the WCRG specifies valid expressions, i.e. the set of potential routes and route parts, the chunking of wayfinding choremes into complex expressions (HORDE) is handled by *term rewriting rules* (cf. [14]). Without term rewriting, our route directions would be very simplistic, consisting of simple strings of wayfinding choremes. Term rewriting rules allow us to combine the primitive elements into larger units such that route information efficiently be communicated and processed.

2 The Wayfinding Choreme Theory

The notion of wayfinding choremes as introduced in [30] is motivated by the French geographer Brunet [5,6] who proposed a limited set of abstract models of geographic phenomena, which he termed *choremes*. *Choreme* is a made-up word taken from the root of the Greek expression for space, *chor-*, and the suffix *–eme*. By this combination Brunet indicated his goal: the creation of a language for space. He in fact devised a language for maps and map design on a conceptual level, also known as *metacartography* [39]. In analogy, wayfinding choremes are defined as a limited set of mental conceptualizations of primitive functional wayfinding and route direction elements.

2.1 General Characteristics of Wayfinding Choremes

Following the Chomskian differentiation [9] between Internal and External language (I- and E-language), two types of wayfinding choremes are distinguished: I–wayfinding choremes and E–wayfinding choremes.

I–wayfinding choremes are abstract mental concepts underlying route directions and wayfinding in all possible modalities; they are modality neutral. In contrast, E–wayfinding choremes are modality specific external representations of I–wayfinding choremes that are used in different modalities, for example, in the graphical or verbal modality.[2] I-wayfinding choremes are accessible via their externalizations. However, E-wayfinding choremes are not homomorphous to I-wayfinding choremes: E-wayfinding choremes in different modalities vary from one another. Graphical externalizations are by their very nature spatially specific because their instantiation requires fixing all configurational parameters such as the orientation of the branches of an intersection and the angles between them.[3] In this sense every graphical externalization of an I-wayfinding choreme instantiates exactly one of the various visualization possibilities. Verbal E-wayfinding choremes, however, are spatially underspecified. Due to their propositional format they are themselves abstractions over a variety of spatial configurations.

Wayfinding choremes are functional primitives of direction (turning) concepts at decision points and conceptualize actions, i.e., which direction to take at an intersection, rather than structures, i.e. the spatial layout (or the conceptualization thereof) into which the action is embedded. The actions that have to be carried out or conceptualized in wayfinding and route directions demarcate functionally relevant parts of the underlying structure.

A small set of wayfinding choremes (see section 2.2) suffices to characterize most routes, route directions, and wayfinding actions. They can be combined to higher order route direction elements (HORDE). This chunking of wayfinding choremes to HORDE is explained in section 3.

2.2 The Set of Wayfinding Choremes

Following models of qualitative spatial reasoning [27,11] we assume an 8-sector model from which an 8-direction model can be derived by determining the bisecting lines of each sector. This model is a simplification that needs to be refined further as people may tend to use more than 8 sectors and sectors may not be equally sized (cf. [38,32]). However, for formal simplicity we confine ourselves to an 8-direction model here. It is also the case that a more refined model that integrates more sectors and that leads to a higher number of wayfinding choremes will not change the general approach taken in the wayfinding choreme theory.

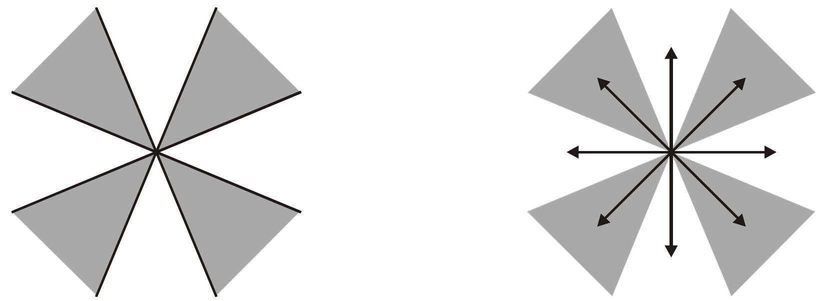

Figure 1. The 8-sector model (left part) and the derived 8-direction model (right part).

In an 8-direction model each sector is represented by 45° increments for prototypical directions (see Fig. 1). In a route direction context, however, people generally do not conceptualize possible directions as vectors that originate from the center of a decision point, i.e. the point that corresponds to the location where the branches of the intersection meet. Rather, one route segment—the one that a navigator is on—is singled out as the *reference direction.* On entering the intersection, the reference direction branch is combined with the subsequent branch, namely the branch that coincides with the direction to be chosen next (see Fig. 2). That people use these prototypical 45° directions has been confirmed in behavioral experiments [30].

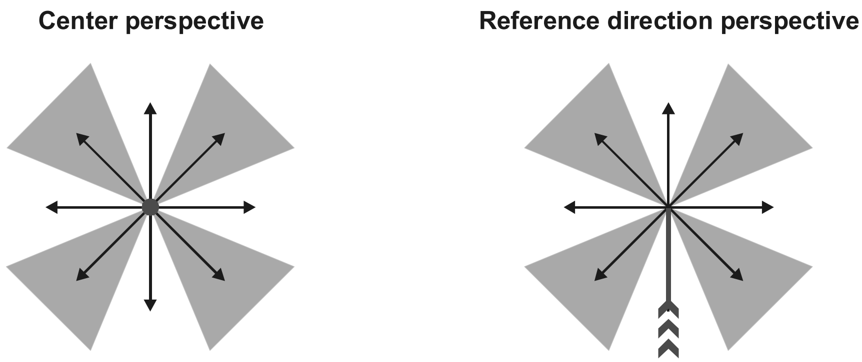

Figure 2. Seven potential directions based on an 8-direction model for a route direction context.

Seven directions are available for conceptualizing goal-oriented actions (i.e. turning or going straight). The reference direction perspective delineates the functionally relevant parts of the spatial configuration and therefore it is congruent with both the functional perspective of wayfinding choreme theory and a body of behavioral findings (e.g., [13,36]). In particular, our approach is based on the finding that decision points are the most vital elements of routes and route directions (e.g., [1,12]). The fundamental distinction between structure and function further enhances the prominence of decision points in that they play a pertinent role in the segmentation of the route a as goal-directed behavior.

Moreover, the wayfinding choreme theory models the canonical situations that the reference direction itself—i.e. turn around and go back—is less likely to be chosen as a possible continuation of the route than any of the other branches. Therefore, the reference direction perspective leads to a modification of established direction models used in the AI community (cf. [18,27]), where the concept BACK is treated on a par with the other direction concepts at a decision point. Yet, for goal-oriented movements turning back actions play a secondary role. Consequently, we do not include the special case of the concept BACK into the characterization at this point.

In sum, wayfinding choremes are extracted from the (7+1)-direction model based on the reference direction perspective: Seven potential directions conceptualized in combination with the reference direction result in seven wayfinding choremes: wc_{sr}, wc_r, wc_{hr}, wc_s, wc_{hl}, wc_l, wc_{sl} (see Fig. 3). Their (pseudo-) linguistic externalizations are *sharp right*, *right*, *half right*, *straight*, *half left*, *left*, *sharp left.*

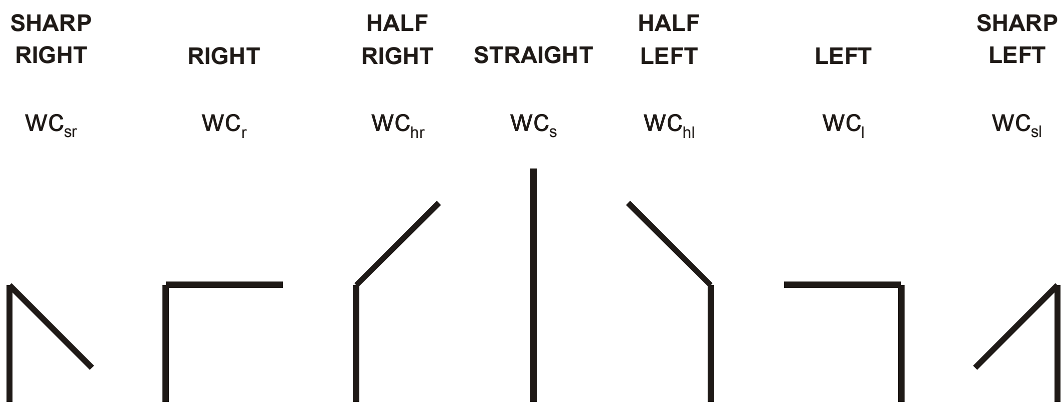

Figure 3. The seven wayfinding choremes: their conceptualization as linguistic externalization (top), the grammatical notation used (middle), and their graphical externalization (bottom).

Subsequently, the seven wayfinding choremes are organized in hierarchical categories according to findings from behavioral experimental work (e.g., [17]). The first major differentiation discerns between *turning concepts*—wayfinding choremes that are associated with a change of direction—and *non-turning concepts*—wayfinding choremes that do not involve a direction change. The first category comprises two subcategories: *standard turns* and *modified turns*. Standard turns are represented by the choremes RIGHT (wc_r) and LEFT (wc_l). Modified turns signify a modification of a standard turn: SHARP or HALF; the corresponding wayfinding choremes are SHARP RIGHT (wc_{sr}), HALF RIGHT (wc_{hr}), HALF LEFT (wc_{hl}), and SHARP LEFT (wc_{sl}). All six turning wayfinding choremes assume decision points at which a direction change takes place, also abbreviated as (DP+). The class of non-turning wayfinding choremes comprises the wayfinding choreme STRAIGHT, wc_s, which plays a crucial role for the chunking of wayfinding choremes (Section 3). STRAIGHT does not need a direction change at decision points, abbreviated as (DP-). The hierarchical categories of wayfinding choremes and their respective abbreviations are:

- Turning concepts

  Standard **T**urning **C**oncept (<STC>),
  Modified **T**urning **C**oncept (<MTC>),

- Non turning concepts

  Non-**T**urning **C**oncept (<NTC>).

- Special concepts

  BACK (no orientation change wrt. the underlying spatial structure but complete direction change)

Table 1 provides a categorization of the turning and non-turning wayfinding choremes (note that both standard turns and STRAIGHT are standard actions and thus appear in the same column).

Table 1. Three categories of standard and modified wayfinding choremes

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

These categorizations are accounted for in the wayfinding choreme route grammar WCRG; wayfinding choremes constitute the terminals for the category <DecisionPoint>.

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

In this way, valid combinations of wayfinding choremes are provided (cf. [30]). However, a grammar only states which combinations of wayfinding choremes are valid, whereas term rewriting rules generate higher order route direction elements (HORDE).

3 Combining Wayfinding Choremes (HORDE): Term Rewriting

HORDE denotes the functional (rather than the structural) chunking of wayfinding choremes: HORDE are *route elements* defined from the perspective of route direction and wayfinding tasks rather than *path elements* defined by the physical and spatial characteristics of the spatial configuration (*the path*). In contrast to the structural perspective, the functional perspective has the advantage of focusing the characterization of routes on the information that is essential for the task at hand.

In this section, we detail how wayfinding choremes can be chunked to higher order route direction elements using term rewriting rules. Term rewriting rules allow us to specify *canonical cases*—structuring route information on a general basis—and to model *personalized rules*—reflecting individual cognitive styles in accordance with different contexts. In addition, we show how, for example, turning restrictions can be handled efficiently by the wayfinding choreme approach.

In general, a formal language is determined by its strings over a finite alphabet. The rules to generate well-defined words in a language can be defined by a grammar, in our case the WCRG as introduced and explicated in [30]. For the WCRG the set of wayfinding choremes constitute the grammar's finite alphabet. Formally, a route is described by its corresponding route string R of wayfinding choremes, for example,

$$R := wc_s wc_s wc_r wc_s wc_{sr} wc_r wc_{sl} wc_s wc_{hr} wc_s wc_s wc_r$$

From the route string R HORDE can be identified as substrings. For instance, the conceptualization of a spatial configuration corresponding to the natural language expression *turn right at the third intersection* is a concatenation of the following three wayfinding choremes: $wc_s wc_s wc_r$. Whereas valid combinations of wayfinding choremes are specified by the WCRG, their chunking to HORDE is modeled by *term rewriting* [14].

This method has recently been introduced as an efficient tool for modeling terrain silhouettes as linear structures by employing a limited set of shape primitives [34]. Assuming that linear entities can be characterized by a small number of primitives, term rewriting can be used for modeling route information. We proceed in two steps: First, we show how route information is processed by term rewriting in canonical situations (section 3.1), and, subsequently, we specify term rewriting rules to handle (a) additional HORDE (section 3.2) and (b) personalized wayfinding assistance (section 3.3).

3.1 Processing Canonical Route Information by Term Rewriting

Let R denote a string of wayfinding choremes representing a route. Each two wayfinding choremes that are not of the same type are functionally different, for example $wc_s \neq wc_r$; each two wayfinding choremes of the same type are functionally equivalent, for example $wc_s \approx wc_s$. To obtain HORDE from R, the string is processed sequentially, i.e. the rules defined below are processed in the order given. Each rule is repeatedly applied to the complete route string before the next rule is used.

The first set of rules handle the extraction of HORDE, in which functionally **d**ifferent **w**ayfinding **c**horemes are chunked, abbreviated here as **dwc** (see section 3.1.1). The second set of rules applies to the chunking of functionally **e**quivalent **w**ayfinding **c**horemes, **ewc** (section 3.1.2).

3.1.1 Chunking Functionally Different Wayfinding Choremes: The Influence of Structure and Routemarks on Chunking Route Information

We start with two clear-cut cases: a string of one or more STRAIGHT wayfinding choremes is followed by a TURNING wayfinding choreme (<STC>, or <MTC>) that is unmistakably identified either by a T-intersection whose alignment makes any further forward movement impossible or by a salient routemark (see Fig. 4) [31].

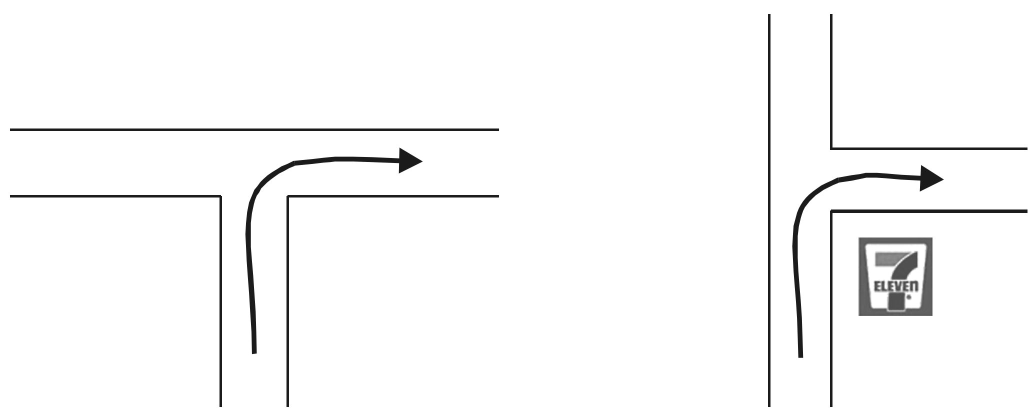

Figure 4. Unambiguous functional segmentation: TURNING wayfinding choreme with T-intersection or salient routemark.

Spatial situations of this kind bear the possibility to form large chunks. In their canonical treatment there is no restriction on the number of wc_s in a route term that may precede the unambiguously identified turning wayfinding choreme (cf. [37]).

The rule (D1) characterizes the case where a routemark is present at the turning wayfinding choreme: n denotes any natural number; tc comprises the two categories of turning wayfinding choremes, i.e. STC (Standard Turning Concepts) and MTC

(Modified Turning Concepts). Similarly, the rule (D2) applies to T-intersections. For T-intersections the turning concepts are restricted to the standard turning concepts, i.e. LEFT and RIGHT.

(D1) $\underbrace{(wc_s wc_s \cdots wc_s)}_{n-times} tc^{R+} \rightarrow dwc^{R+}$ $n \in \mathbb{N}$, $tc^{R+} \in$ {<STC^{R+}>, <MTC^{R+}>, Destination}

(D2) $\underbrace{(wc_s wc_s \cdots wc_s)}_{n-times} stc^{T} \rightarrow dwc^{T}$ $n \in \mathbb{N}$, $stc^{T} \in \{wc_r^T, wc_l^T\}$

If neither a routemark nor a T-intersection is present at a turning wayfinding choreme, further structuring of the route relies on alternate mechanisms. The easiest instances are those where only one or two wayfinding choremes of type STRAIGHT precede a turning wayfinding choreme and no additional information about the intersections is available. An example is the sequence of two wayfinding choremes STRAIGHT and a turning wayfinding choreme, which can be verbalized as *turn right at the third intersection*. The corresponding rules for 3 and 2 chunked primitives are given in (D3) and (D4).

(D3) $wc_s wc_s tc \rightarrow dwc^{3tc}$ tc ∈ {<NTC>, <MTC>}

(D4) $wc_s tc \rightarrow dwc^{2tc}$ tc ∈ {<NTC>, <MTC>}

Given the case that a sequence of more than two wayfinding choremes STRAIGHT is terminated by a turning wayfinding choreme and no additional information is available, it is possible to adopt further chunking principles. Since the corresponding rules—(D5) and (D6)—apply to functionally equivalent wayfinding choremes, they are detailed in section 3.1.2.

Chunking by routemarks depends on the properties of the routemark as such (e.g., [42,16]) as well as on functionally induced conceptualizations where the localization of routemarks is understood in relation to the orientation of the wayfinder [30], for example, *turn right after the post office* versus *turn right before the post office*.

3.1.2 Chunking Functionally Equivalent Wayfinding Choremes

The chunking of functionally **e**quivalent **w**ayfinding **c**horemes, abbreviated as **ewc,** enables further HORDE. The following rules are applied to a route string R after combinations using dwc rules are identified. (D5) specifies the rule to aggregate three times STRAIGHT into one chunk, (D6) the rule for two times STRAIGHT. Applying the rules in the correct order is necessary to obtain larger chunks.

(D5) $wc_s wc_s wc_s \rightarrow dwc^{3s}$

(D6) $wc_s wc_s \rightarrow dwc^{2s}$

In general, combinations of two or three functionally equivalent wayfinding choremes to a HORDE are allowed for as canonical cases. Combining several turning concepts in chunks corresponding to expressions such as *turn two times right*. The combination of modified turning concepts is, however, restricted to two identical turns immediately following each other. The order of their processing is given by the rules (E1) to (E8).

The combination of three (E1) and two (E2) subsequent right turns:

(E1) $wc_r wc_r wc_r \rightarrow ewc_r^3$

(E2) $wc_r wc_r \rightarrow ewc_r^2$

The combination of three (E3) and two (E4) subsequent left turns:

(E3) $wc_l wc_l wc_l \rightarrow ewc_l^3$

(E4) $wc_l wc_l \rightarrow ewc_l^2$

The combination of two sharp right (E5) and two sharp left (E6) turns:

(E5) $wc_{sr} wc_{sr} \rightarrow ewc_{sr}^2$

(E6) $wc_{sl} wc_{sl} \rightarrow ewc_{sl}^2$

The combination of two half right (E7) and two half left (E8) turns:

(E7) $wc_{hr} wc_{hr} \rightarrow ewc_{hr}^2$

(E8) $wc_{hl} wc_{hl} \rightarrow ewc_{hl}^2$

To illustrate these rules, we detail the procedure with an example illustrated in Fig. 5. The first step is to represent the route as a string of wayfinding choremes. This is accomplished by assigning to every decision point the corresponding wayfinding choreme according to the (7+1)-direction model. The route string R represents the route depicted in Fig. 6 using wayfinding choremes.

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

At first, rules (D1) and (D2) identify substrings of R. The substrings can be chunked due to additional information available at turning wayfinding choremes that are preceded by wc_s.

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

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

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

Finally, the rules (E1) to (E8) are applied. The result is a characterization of the route that is based on wayfinding choremes but simplifies the route description by using HORDE as much as possible:

$$R := \quad dwc^{3r}dwc^{T}dwc^{2r}dwc^{R+}ewc_{l}^{2}\,ewc_{r}^{2}\,dwc^{2l}$$

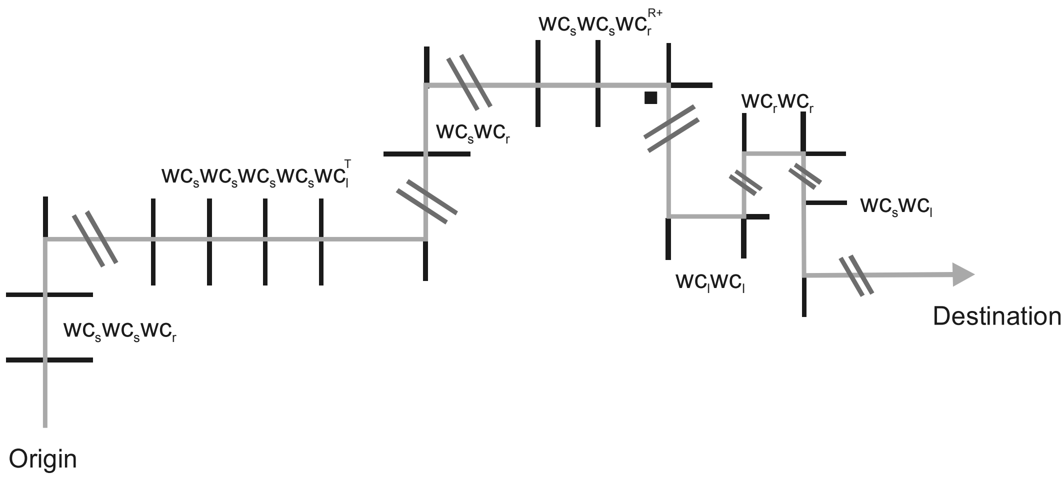

Figure 5. Example of a route characterized by chunks of wayfinding choremes

3.2 Refinement of HORDE

We show the potential of this approach by illustrating the integration of two special concepts that are illustrated in Fig. 6; they are to be understood as example cases for a variety of spatial situations: A so called P-TURN resulting from a turning restriction common in many cities, and the concept JOG ABOUT A BLOCK used in grid-shaped street networks in Northern America.

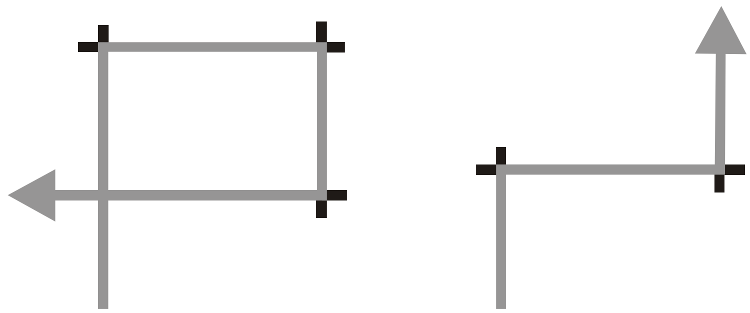

Figure 6. The concepts P-TURN and JOG ABOUT A BLOCK

A P-TURN is a spatial situation where a left turn is prohibited but an alternative is given by driving ‘around the block’. These situations are not easy to handle formally, for example, in graph notations. To solve this problem, [50] employs a dual graph approach that focuses on the linear structure of a route and allows for the specification of p-turns. Modeling p-turns within the wayfinding choreme approach is unproblematic: a wayfinding choreme STRAIGHT is followed by three wayfinding choremes RIGHT and another wayfinding choreme STRAIGHT, i.e. $wc_swc_rwc_rwc_rwc_s$. The resulting P-TURN concept (pt) is formally specified in rule (P1) and can be extracted automatically from a route string. For the term rewriting procedure, it is crucial when this rule is applied. To avoid conflicts with other HORDE, (P1) is processed as the first rule, i.e. before (D1).

(P1) $wc_swc_rwc_rwc_rwc_s \rightarrow pt$

The concept JOG ABOUT A BLOCK is not well defined. It can be used in conjunction with a turning direction, for example, *turn right and jog about a block* (see Fig. 6). In this case, the direction given reflects the conceptualization of a part of a route that could also be described as *make a right zigzag* or *go right and immediately left*. This example shows that it is not always easy to find a suitable and unambiguous externalization for a mental conceptualization. If we assume that *turn right and jog about a block* reflects a zigzag concept and if we furthermore assume that zigzag concepts are appropriate chunks, we can define rules for a LEFT ZIGZAG (Z1) and for a RIGHT ZIGZAG (Z2).

(Z1) $wc_l wc_r \rightarrow zz_l$

(Z2) $wc_r wc_l \rightarrow zz_r$

3.3 Effects of Situational Context and the Externalization Medium on Horde

The wayfinding choreme approach is a neutral representation formalism. It is important to recollect that although we made use of language examples to refer to conceptualizations, language is (a) just one possibility of externalizing mental conceptualizations, (b) different languages as well as different terms within one language may be employed for the same conceptualization.

Assuming that HORDE are valuable organizational elements in route directions the question arises in which way they should be externalized: is it more cognitively adequate to communicate them graphically or linguistically, for instance, in the case of in-car-navigation systems? Language instructions have the advantage that they do not demand the visual attention of a driver. In some situations, however, the complexity of the wayfinding decision may be the crucial factor. A turning action may be complicated to describe verbally, but may easily be depicted graphically due to the representational characteristics of the respective medium [19,26].

The wayfinding choreme approach supports different forms of externalization. Its underlying formal model can be taken, for example, as a basis to use different languages and different expressions. An analysis of verbal directions shows the variety with which people refer to the same turning actions, even though they are not asked explicitly to be inventive. The sectors of the formal direction model can thus be associated with quite different expressions (see Fig. 7).

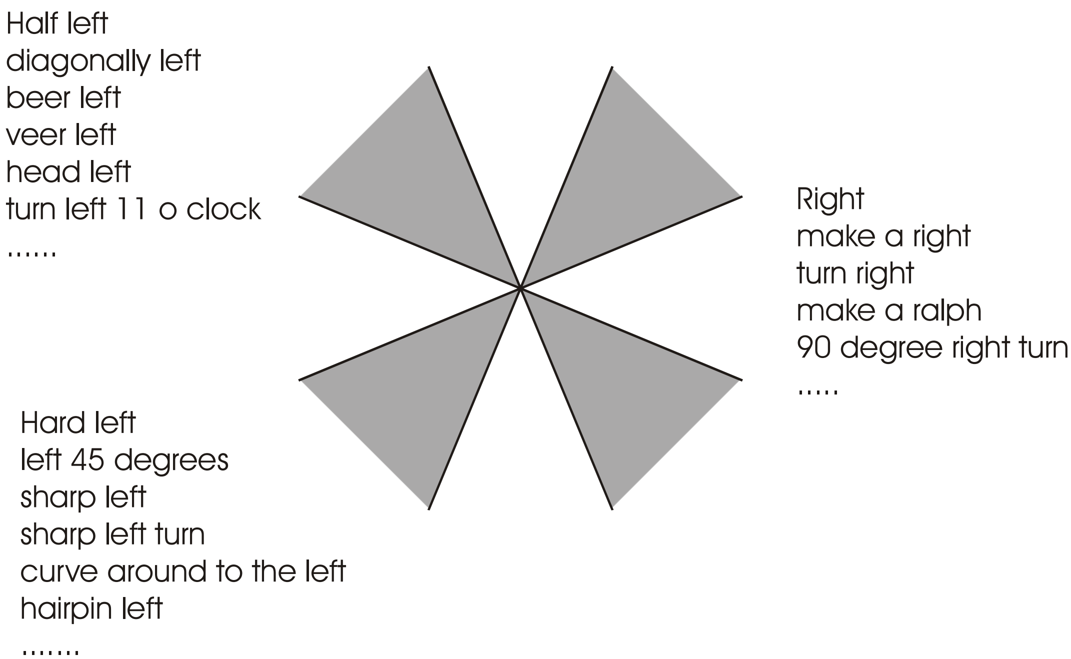

Figure 7. Different verbalizations applicable to sectors

The second aspect that has to be considered in the adaptation of the canonical rules of the wayfinding choreme theory concerns different parameters in encountered situations or contexts. The same user may need different directions depending on the situation she or he is in; among other factors this may relate to a user's familiarity with her or his current environment, the mode of transportation, or the structure of the decision points. In an unfamiliar environment users tend to need more confirmation along their way to overcome the feeling of being lost. The rule (D1), for example, may result in large chunks focusing on the identification of an intersection at which a turn is required and that is identified unambiguously by a routemark. In cases of unfamiliarity, it may be sensible to further structure the resulting chunk, for instance, by employing additional routemarks.

The conceptualization may also change in dependence of the mode of transportation, for instance, driving a car versus riding a bike, or even taking cars that drive at different speeds (cf. [48]) or the mode of presentation, for example, static or dynamic [35]. These conceptualizations can be modeled with the wayfinding choreme approach, too, resulting in smaller or larger chunks.

3.4 Personalized Wayfinding Assistance

Similar to the integration and specification of rules for particular spatial situation that allow for identifying and extracting HORDE, we can define rules based on personal styles or additional situational contexts. Personal style refers to conceptual preferences that people develop in interaction with their environments, for instance, the use of landmarks in route directions.[4] Other personal preferences may include that more right turns than left turns are allowed in one chunk, or that the number of wayfinding choremes of the type STRAIGHT in numerical chunking is restricted to a certain number.

Whereas the canonical cases previously discussed in section 3 allow for two STRAIGHT wayfinding choremes, some people may feel comfortable with five as they may have developed a strategy of phonological looping (allowing them to keep track of the intersections while moving along the straight segments). Instead of explicitly 'remembering' at each decision point how many decision points are left, they place the information in a phonological loop, and repeat the corresponding expressions to themselves. Starting with *turn right at the sixth intersection* they repeat it until they reach the next intersection where they change the expression to *turn right at the fifth intersection* and so on. This style has several drawbacks, among others that every decision point has to be unambiguously identified and that every interruption disturbing the phonological loop may result in loosing one's way. Nevertheless, some people may prefer it.

Term rewriting rules for these cases are similar to ones already presented; hence, we will not specify them individually here. It should be noted that either the existing (the basic) set of term rewriting rules has to be replaced or that the order of application has to be monitored. This leads to the discussion of two further cases of personal styles: first, the order in which a route string is processed and second, the question of different externalizations.

In the first case the order in which the term rewriting rules are applied will be changed. Consider rules (D3) and (E1); in the discussed example (D3) is applied before (E1). If this order is changed, a different set of HORDE could be identified for a given route string. This principle holds for most rules; the resulting sets of HORDE may contain more functionally equivalent wayfinding choremes than functionally different wayfinding choremes or greater number of small HORDE than large HORDE.

4 Conclusion and Outlook

We discussed an approach to route knowledge that identified conceptual primitives, so called wayfinding choremes. Wayfinding choremes are grounded in cognitive science research and reflect mental conceptualizations of turning actions at decision points. The characterization of routes based on these concepts of turning actions at decision points allows for modeling route knowledge with a small number of primitives. Further cognitive organization principles of route knowledge can be modeled by combining wayfinding choremes to higher order route direction elements, so called HORDE. Once a route is characterized by wayfinding choremes, i.e. as a route string, term rewriting rules are employed to extract HORDE. The term rewriting rules can be set up flexibly to model canonical cases of structuring route knowledge (identified, for example, in behavioral research), to reflect personal styles (e.g., a preference of numerical *turn left at the third intersection* over landmark chunking *turn left at the post office*), to cope with different situations or contexts, or to allow for new chunks that might become conventionalized in the conceptualization of our interaction with urban environments (e.g., p-turns in city street networks).

The advantages of the wayfinding choreme theory apply to various levels: Generally, the approach is efficient as a small number of primitives handle most spatial situations and cognitive styles. The wayfinding choremes are identified in behavioral studies and as such reflect cognitive (prototypical) representations of turning actions. The wayfinding choreme approach starts off as an abstract representation formalism that models route knowledge on a conceptual level, i.e. the level of I-wayfinding choremes. In this way one representation formalism is taken as a basis for different forms of externalizations (E-wayfinding choremes) that are instantiated in different representational modalities. Against this theoretical background, our approach fosters two procedures: first, a flexible instantiation of situation adapted route directions, and, second, a translation of one representational format into another such as the mapping between graphical and verbal route directions.

Several variations can be applied to the wayfinding choreme theory, some of which are currently under research. The study of prototypical representations of (graphical) wayfinding choremes confirmed an 8-sector model as a formal basis for the assignment of turning angles to their representation as wayfinding choremes. Although the prototypical direction representations are confirmed, the assumption of a homogenous sector model is questionable [38]. Therefore, other possibilities of modeling direction concepts may have to be developed, for example, the combination of sectors and axes [20].

Furthermore, a new line of behavioral experiments has been set up to reveal more about the formal model, which allows to represent the conceptualization of directions in city street networks. A combination of several research methods is employed to reveal conceptual structures; among others the grouping of directions at intersections and the conceptualization of turning actions in interaction with map-like and virtual reality (VR) environments. First results indicate that directions in street networks are most suitably represented by a combination of axes and sectors. The conceptualization of STRAIGHT, for example, is an axis and not a sector. The results also show that there is some variation between participants. Whereas some of them employ a fine-grained distinction of directions, others apply a coarse level of granularity resulting only in a basic distinction between LEFT and RIGHT.

These results again pose the question of how to model personalized styles in route directions and implement them in systems designed for navigation aid. One difficulty may be that people have a hard time identifying their personal style or that they may be unwilling to interact with the navigation system after some time of futile calibration attempts and thus miss the chance to find out which style suits them best. Research encompassing both aspects—canonical cases and personalized styles—therefore seems most promising: Generally, it allows for discovering default assumptions that will fit most users. Furthermore, the statistically most prominent deviations from the default can be identified and can then be used to discern a limited number of 'personal' styles. This way, an implementation narrow down the number of styles that a user might choose from, without being required to calibrate a truly personal style on the basis of a potentially infinite set of individual parameters and/or combinations thereof.

The question of different forms of externalizations may become a topic of research, as well, reflecting not only personalized styles but also situational contexts or offering alternatives to standard means of externalization. One of the most basic distinctions—graphic versus verbal—has recently been researched [7] and there are some ideas on how to apply different representational media in different situations. Other alternatives, for instance, using new expressions in the place of *right* for the concept RIGHT, are discussed in section 3.3 (see also Fig. 7).

5 Acknowledgements

This research was carried out while the first author was a member of the *Spatial Cognition Priority Program* and the SFB/TR 8 *Spatial Cognition: Reasoning, Action, Interaction* and the second author was a member in the priority program *Language Production: Information transfer by natural language*. Both authors gratefully acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG). This research was also supported by the National Imagery and Mapping Agency under grant number NMA201-01-1-2003. We thank three anonymous reviewers, Christian Freksa, Dan Montello, and Kai-Florian Richter for valuable comments.

6 References

[1] G.L. Allen, From knowledge to words to wayfinding: Issues in the production and comprehension of route directions, in: S.C. Hirtle, A.U. Frank (Eds.), Spatial Information Theory: A Theoretical Basis for GIS, Springer, Berlin 1997 (pp. 363-372).

[2] G.L. Allen, Gestures accompanying verbal route directions: Do they point to a new avenue for examining spatial representations?, Spatial Cognition and Computation (4) (2003) 259-268.

[3] T. Bittner, M. Donnelly, B. Smith, Endurants and perdurants in directly depicting ontologies, AI Communications (to appear).

[4] M. Brand. Identity conditions for events, American Philosophical Quarte*rly*, (14) (1977) 329–37.

[5] R. Brunet, La composition des modèles dans l'analyse spatiale, L'Espace Géographique (4) (1980) 253-265.

[6] R. Brunet, La carte, mode d'emploi, Fayard-Reclus, Paris, 1987.

[7] A. Butz, J. Baus, A. Krüger, M. Lohse, A hybrid indoor navigation system, in: International Conference on Intelligent User Interfaces, ACM Press, New York, 2001 (pp. 25-32).

[8] R. Casati & A.C. Varzi (Eds.), Events, Aldershot, England; Brookfield, Vt.: Dartmouth, 1996.

[9] N. Chomsky, Knowledge of Language: Its Nature, Origin and Use, Praeger, New York, 1986.

[10] B. Chandrasekaran, J.R. Josephson, V.R. Benjamins, What are ontologies, and why do we need them?, IEEE Intelligent Systems and Their Applications 14(1) (1999) 20-26.

[11] A.G. Cohn, S.M. Hazarika, Qualitative spatial representation and reasoning: an overview, Fundamenta Informaticae 46 (2001) 1-29.

[12] M. Denis, The description of routes: A cognitive approach to the production of spatial discourse, Cahiers de Psychologie Cognitive 16 (1997) 409-458.

[13] M. Denis, F. Pazzaglia, C. Cornoldi, L. Bertolo, Spatial discourse and navigation: An analysis of route directions in the city of Venice, Applied Cognitive Psychology 13 (1999) 145-174.

[14] N. Dershowitz, A taste of rewrite systems, in: P.E. Lauer (Ed.), Functional Programming, Concurrency, Simulation and Automated Reasoning: International Lecture Series 1991-1992, McMaster University, Hamilton, Ontario, Canada, Springer, Berlin, 1993 (pp. 199-228).

[15] M. Duckham, L. Kulik, “Simplest” paths: Automated route selection for navigation, in: W. Kuhn, M.F. Worboys, S. Timpf (Eds.), Spatial Information Theory: Foundations of Geographic Information Science, Springer, Berlin, 2003 (pp. 182-199).

[16] B. Elias, Extracting landmarks with data mining methods, in: W. Kuhn, M.F. Worboys, S. Timpf (Eds.), Spatial Information Theory: Foundations of Geographic Information Science, Springer, Berlin, 2003 (pp. 398-412).

[17] G.W. Evans, Environmental cognition, Psychological Bulletin 88 (1980) 259-287.

[18] C. Freksa, Qualitative spatial reasoning, in: D.M. Mark, A.U. Frank (Eds.), Cognitive and Linguistic Aspects of Geographic Space, Kluwer Academic Publishers, Dordrecht, 1991 (pp. 361-372).

[19] C. Freksa, Spatial aspects of task-specific wayfinding maps. A representation-theoretic perspective, in: J.S. Gero, B. Tversky (Eds.), *Visual and Spatial Reasoning in Design,* Key Centre of Design Computing and Cognition, Sydney, 1999 (pp. 15-32).

[20] C. Freksa, K. Zimmermann, On the utilization of spatial structures for cognitively plausible and efficient reasoning, in: Proceedings SMC92 1992 IEEE International Conference Systems Man and Cybernetics, Chicago, 1992 (pp. 261-266). Reprinted in F.D. Anger, H.W. Güsgen, J. v. Benthem (Eds.), Proceedings of the Workshop on Spatial and temporal reasoning, IJCAI93, Chambery, 1993 (pp. 61-66).

[21] C. Freksa, W. Brauer, C. Habel, K. Wender (Eds.), Spatial Cognition III. Routes and Navigation, Human Memory and Learning, Spatial Representation and Spatial Learning, Springer, Berlin, 2003.

[22] G. Gartner (Ed.), Location Based Services & Telecartography, Geowissenschaftliche Mitteilungen. Technische Universität Wien, Wien, 2004.

[23] R.G. Golledge, Human wayfinding and cognitive maps. In R.G. Golledge (Ed.), Wayfinding Behavior. Cognitive Mapping and Other Spatial Processes, John Hopkins University Press, Baltimore, 1999 (pp. 5-45).

[24] N. Guarino, Understanding, building and using ontologies, International Journal of Human-Computer Studies 46 (1997) 293-310.

[25] N. Guarino, Formal ontology and information systems in: N. Guarino (Ed.), Formal Ontology in Information Systems. Proceedings of FOIS'98, Trento, Italy, 6-8 June 1998, IOS Press, Amsterdam, 1998 (pp. 3-15).

[26] C. Habel, The representational commitment of maps, in: Foundations of Geographic Information Science, M. Goodchild, M. Worboys (Eds.) Taylor and Francis, London, 2003.

[27] D. Hernandez, Qualitative representation of spatial knowledge, Springer, Berlin 1994.

[28] J. Higginbotham, F. Pianesi & A. C. Varzi (Eds.), Speaking of Events. New York & Oxford: Oxford University Press, 2000.

[29] R. Jackendoff, The architecture of the language faculty. Cambridge, MA: MIT 1997.

[30] A. Klippel, Wayfinding Choremes – Conceptualizing Wayfinding and Route Direction Elements. University of Bremen, Bremen, 2003.

[31] Klippel, H. Tappe, C. Habel, Pictorial representations of routes: chunking route segments during comprehension, in: C. Freksa, W. Brauer, C. Habel, K.F. Wender (Eds.), Spatial Cognition III. Routes and Navigation, Human Memory and Learning, Spatial Representation and Spatial Learning, Springer, Berlin, 2003 (pp. 11-33).

[32] Klippel, C. Dewey, M. Knauff, K.-F. Richter, D.R. Montello, C. Freksa, E.A. Loeliger, Direction concepts in wayfinding assistance, in: J. Baus, C. Kray, R. Porzel (Eds.), Workshop on Artificial Intelligence in Mobile Systems 2004 (AIMS'04), Saarbrücken: SFB 378 Memo 84, 2004 (pp. 1-8).

[33] W. Kuhn, Ontologies in support of activities in geographical space, International Journal of Geographical Information Science 15(7) (2001) 613-631.

[34] L. Kulik, M.J. Egenhofer, Linearized terrain: Languages for silhouette representation, in: W. Kuhn, M.F. Worboys, S. Timpf (Eds.), Spatial Information Theory: Foundations of Geographic Information Science, Springer, Berlin, 2003 (pp. 128-145).

[35] P.U. Lee, A. Klippel, H. Tappe, The effect of motion in graphical user interfaces, in: A. Butz, A. Krüger, P. Olivier (Eds.), Smart Graphics. Third International Symposium, SG 2003, Heidelberg, Germany, July2-4, 2003, Proceedings, Springer, Berlin, 2003 (pp. 12-21).

[36] K.L. Lovelace, M. Hegarty, D.R. Montello, Elements of good route directions in familiar and unfamiliar environments, in: C. Freksa, D.M. Mark (Eds.), Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science, Springer, Berlin, 1999 (pp. 65-82).

[37] D.M. Mark, Automated route selection for navigation. IEEE Aerospace and Electronic Systems Magazine 1 (1986) 2-5.

[38] D.R. Montello, A.U. Frank, Modeling directional knowledge and reasoning in environmental space: Testing qualitative metrics. in: J. Portugali (Ed.), The Construction of Cognitive Maps, Kluwer Academic Publishers, Dordrecht, 1996 (pp. 321-344).

[39] F.J. Ormeling, Brunet and the revival of French geography and cartography, The Cartographic Journal 29 (1992) 20-24.

[40] W.V. Quine, Theorien und Dinge, Suhrkamp: Frankfurt a.M., 1985.

[41] W.V. Quine, Events and reification, in: R. Casati & A.C. Varzi (Eds.), Events, Aldershot, England; Brookfield, Vt.: Dartmouth, 1996 (pp. 107-116).

[42] M. Raubal, S. Winter, Enriching wayfinding instructions with local landmarks, in: M.J. Egenhofer, D.M. Mark (Eds.), Geographic Information Science - Second International Conference GIScience *2002*, Springer, Berlin, 2002 (pp. 243-259).

[43] G. Strube, The role of cognitive science in knowledge engineering, in: F. Schmalhofer, G. Strube, and T. Wetter (Eds.), Contemporary Knowledge Engineering and Cognition, Springer, Berlin, 1992 (pp. 161-174).

[44] S. Timpf, Ontologies of wayfinding, Networks and Spatial Economics 2 (2002) 9-33.

[45] Tversky, P.U. Lee, How space structures language. in: C. Freksa, C. Habel, K.F. Wender (Eds.), Spatial Cognition. An Interdisciplinary Approach to Representing and Processing Spatial Knowledge, Springer, Berlin, 1998 (pp. 157-175).

[46] Tversky, P.U. Lee, Pictorial and verbal tools for conveying routes. in: C. Freksa, D.M. Mark (Eds.), Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science, Springer, Berlin, 1999 (51-64).

[47] W. Wahlster, J. Baus, C. Kray, A. Krüger, REAL: ein ressourcenadaptierendes mobiles Navigationssystem. Informatik Forschung und Entwicklung, 16(4) (2001) 233-241.

[48] W. Wahlster, A. Blocher, J. Baus, E. Stopp, H. Speiser, Ressourcenadaptive Objektlokalisation: Sprachliche Raumbeschreibung unter Zeitdruck, Kognitionswissenschaft 7(3) (1998) 111-117.

[49] S. Werner, B. Krieg-Brückner, T. Herrmann, Modeling navigational knowledge by route graphs, in: C. Freksa, W. Brauer, C. Habel, K.F. Wender (Eds.), Spatial Cognition II. Integrating Abstract Theories, Empirical Studies, Formal Methods, and Practical Applications, Springer, Berlin, 2000 (pp. 295-316).

[50] S. Winter, Route specifications with a linear dual graph, in: D. Richardson, P. van Oosterom (Eds.), Advances in Spatial Data Handling, Springer, Berlin, 2002 (pp. 329-338).

[51] J.M. Zacks & B. Tversky, Event structure in perception and conception, Psychological Bulletin 127(1) (2001) 3-21.

[52] A. Zipf, K.-F. Richter, Using focus maps to ease map reading – Developing smart applications for mobile devices. KI Special Issue Spatial Cognition 02(4) (2002) 35-37.

[1] Some researchers differentiate between *cognitively adequate* and *cognitively plausible*. In the present paper we will not be concerned with this distinction, however, and will use cognitive adequacy as a cover term for both.

[2] These are at the same time the most canonical forms of externalization and the ones we are concerned with in the current paper. There are, however, other potential modalities for externalization, like gesture and locomotion, or, subordinate kinds within the graphical and the verbal modality, e.g. 3D-Graphics and sign language (e.g., [2]).

[3] This does not imply that graphical representations are veridical to the depicted real world spatial configuration. Rather we want to point out that the depiction of a spatial configuration encompasses more concreteness and thus more 'spatial commitment' than a typical verbal description of the same situation.

[4] If at some point sex differences are unmistakably identified our approach may be used to model male and female route directions. As this is still a topic of discussion we focus on individual differences that are often neglected in behavioral experiments.