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The Cognitive Reality of Schematic Maps[1]

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Abstract. In graphics and language, schematization is an important method to emphasize certain aspects and to deemphasize others. Different disciplines use schematization for different reasons. In cartography, graphic schematization is one aspect of map generalization. In contrast, cognitive science addresses schematization as a method to intentionally emphasize certain aspects of knowledge beyond technical necessity; therefore, the notion of *schematic map* is proposed to denote maps that employ schematization for cognitive representational reasons. This chapter discusses different views of schematization from cartography, linguistics, and artificial intelligence. Connections to qualitative reasoning in artificial intelligence are drawn. We address human spatial cognition and present examples of task-oriented representations. Finally, multimodality for conveying spatial knowledge and its application in schematic maps are discussed.

1 Introduction

Long before it was possible to create spatially veridical representations of geographic space, people created geographic maps based on their mental conceptualizations of their surroundings (e.g., Harley & Woodward, 1987). Although these maps were topographically inaccurate in terms of Euclidean metrics, they conveyed many details concerning aspects of the spatial environment that were important for the mapmakers. When cartography developed as a scientific discipline, one goal was to create spatially veridical maps. As this problem seems to be well understood and solvable for any specific requirements, the focus of interest in mapmaking has turned back towards cognitive issues that may have been the driving force for creating maps in the first place (e.g., Montello, 2002).

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[1] This chapter summarizes work done in the project *Spatial Structures in Aspect Maps* of the German Spatial Cognition Priority Program and the *MapSpace* project of SFB/TR 8 Spatial Cognition: Reasoning, Action, Interaction. References to literature therefore focus on publications from these projects. For more detailed references, please refer to these publications. Funding by the Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged. We want to thank two anonymous reviewers for their thoughtful comments that helped clarify the ideas presented.

In many situations, we are no longer interested in conveying the details of an environment to human map users with high precision such that the users can derive the information they need; instead, we now look for more abstract, cognitive ways to directly convey to the map user the information for solving certain tasks. This goal requires a formal characterization of kinds of spatial knowledge and an understanding of human spatial concepts and how they are used in spatial problem solving.

Cartographic developments, for example the invention of mathematical projections, have placed a set of formal rules between the conception of space and its representation. Map production is guided by technical and formal models (e.g., object ontologies) and a set of rules established within the cartographic community (e.g., Bertin, 1974; Dent, 1996). Some of the methods used for making spatially accurate maps and for making 'cognitively adequate' maps are rather similar. In particular, both targets require simplification of some sort. In this chapter, we look at *schematization*. We work towards an answer to the question whether schematization required for technical / graphical reasons are of the same type as schematizations introduced for cognitive reasons. We work out a more precise underpinning of the notion of schematization and we motivate the use of the term *schematic map* for a certain type of intentionally distorted maps.

2 Schematization and Generalization

Cartographic maps depict aspects of a geographic environment on a spatial scale much smaller than 1:1. To maintain good legibility of small geographic features, certain characteristics (e.g. the width of a road) must be exaggerated. As a consequence, the representation must be simplified to fit all important features onto the representational medium. Simplifications of this kind can be considered as *schematizations*, as certain aspects are summarized in these maps. For example, on a hiking map the width of the trails is not depicted to scale; their width is exaggerated. Therefore, not all curves of a serpentine might fit on the map. However, curviness of a trail is a very important feature that should not be eliminated by smoothing the curve; thus, on some hiking maps serpentines are depicted with fewer turns, falsifying the number of turns but maintaining the general character of the trail. The shape of the trail has been schematized due to spatial constraints on the map. As simplifications of this kind are generally applied to cartographic maps, cartographers rarely speak of *schematic maps*.

In areas outside cartography, the terms *schematization* and *schematic map* are used in the context of qualitative knowledge representation, qualitative spatial reasoning, design computing, and in cognitive science (e.g., Tversky & Lee, 1998). Lately, the term *schematic map* has been used in the context of spatial cognition to denote diagrammatic artefacts in order to bridge the gap between physical and conceptual structures (cf. Freksa, 1999). In the context of AI / cognitive robotics, the term is used to denote maps that are intentionally distorted beyond representational requirements to simplify shapes and structures or to make maps more readable (Freksa et al., 2000). Examples of *schematization* procedures and algorithms to convert topographic maps into *schematic maps* have been presented by Barkowsky et al. (2000).

So far, there has been no definition of *schematization* and *schematic map* in cartographic terms and some cartographers reject the notion of a special class of maps that is called schematic[2]. Although cartographic maps are highly schematic, it is not clear, (1) whether cartography considers 'schematic maps' as regular instances of one of the classical cartographic maps (and if so: what 'schematization' by cognitive principles means in cartographic terms) and (2) to what extent cognitive considerations and notions can be expressed in terms of classical cartographic language. We argue for using the term *schematic map* for a certain type of maps—those that are intentionally schematized beyond the requirements of the representational medium.

In the following, we will argue for the significance and relevance of schematization and schematic maps from a cognitive perspective of knowledge representation and reasoning. We will analyze the usage of the term *schematization* in the context of the cognitive science literature, especially in linguistics, cognitive psychology, and artificial intelligence. Stating the meaning of 'schematization' more precisely, particularly by juxtaposing it to generalization, we will be able to clarify the term *schematic map* and to work out its importance for cognitively adequate representations.

There are at least two meanings of the term *cognitively adequate* (Strube, 1992): (1) representations that resemble mental knowledge representation, and (2) representations that support cognitive processes. The argumentation for the importance of schematic maps draws on both meanings: the qualitative character of schematic maps makes them a unique tool for modelling cognitive knowledge representation. Additionally, a correspondence between internal and external representations can be assumed to support cognitive processes.

Authors often use 'schematization' when they refer to a reduction of information content. The term is restricted neither to a cognitive domain nor to a technical domain. In contrast to the term *generalization*, schematization does not correspond to a research area (e.g., Müller, Lagrange, and Weibel, 1995). On the level of natural language, it is difficult to demarcate schematization from related terms like idealization, abstraction, generalization, and conceptualization. The distinction we make is that schematization aims at cognitive adequacy in the first sense defined above and, therefore, intentionally distorts (aspectualises) a representation beyond technical constraints. This perspective will be explained in the course of this section.

Cognitive science, especially linguistics, looks at schematization from an information processing point of view, focusing on the relation between language and space, i.e. concepts—their corresponding spatial objects and/or spatial relations or even actions (events)—and their matching spatial expressions. Herskovits (1986) states: "[T]here is a fundamental or canonical view of the world, which in everyday life is taken as the world as it is. But language does not directly reflect that view. Idealizations, approximations, conceptualizations mediate between this canonical view and language" (p. 2). On this proposition, she proceeds defining schematization in two ways: "Systematic selection, idealization, approximation, and conceptualization are facets of schematization, a process that reduces a real physical scene, with all its richness of detail, to a **very sparse** and **sketchy** semantic content. For

[2] D. R. Montello and S. Fabrikant pointed out that especially thematic maps are (highly) schematic. In fact, naming a map schematic is regarded as a pleonasm (pers. comm. Dec 2003).

expressions such as 'The village is on the road to London,' this reduction is often said to involve applying some abstract spatial relation to simple geometric objects: points, lines, surfaces, or blobs" (Herskovits, 1998, p. 149; emphasis by the authors). In other words: "Schematization involves three distinguishable processes: abstraction, idealization, and selection" (p. 150).

Herskovits' work is grounded on ideas proposed by Talmy (1983) who defines schematization as "... a process that involves the systematic selection of certain aspects of a referent scene to represent the whole, while disregarding the remaining aspects" (p. 225). Yet, this definition does not capture schematization completely as it only focuses on the aspect of *pars pro toto*, i.e. a part standing for the whole.

One problem remains: The processes used to define schematization are not well-defined concepts themselves and, hence, cannot easily be operationalized. Selection, idealization, approximation, abstraction, and conceptualization give just an idea what schematization is but do not really define its contents or processes.

Another question that arises is whether and how these ideas can be transferred to the domain of graphic representations of our spatial environment or whether they are restricted to the relation between language and space. When we speak of *space* we refer to what Herskovits has termed the canonical view on space, i.e. the world as it is or as we perceived and described it if we employed gauges for precise measurement. If we look at some approaches in cognitive science taken in this area we find especially work by Tversky (1999), Tversky and Lee (1998; 1999), Freksa (1999), and Berendt et al. (1998).[3]

Tversky and Lee are concerned with prototypical graphical representations of space. Tversky (1999), for example, mentions the fact that drawings of human participants do reflect the results of a schematization and conceptualization process for a specific domain, and states in congruence with the view found in Herskovits' work: "[...] drawings reveal people's conceptions of things, not their perceptions of things" (p. 94). Tversky and Lee's (1998) understanding of drawings and their claim that both, sketch maps and language expressions, reveal something about people's conceptions about the world result in the term *'ceptions* they introduce. 'ceptions mirror human conceptions about the world no matter in what form of representation they are expressed.

Berendt et al. (1998) present a computational approach to schematization. They provide a framework for constructing schematic maps. The resulting maps represent the specific knowledge needed for a given task. The knowledge, called aspects, is extracted from existing knowledge prior to map construction. Accordingly, the resulting maps are *task-specific maps* (Freksa, 1999). Three different types of knowledge are distinguished in this approach: knowledge that needs to be represented unaltered, knowledge that can be distorted but needs to be represented, and knowledge that can be omitted. This distinction guides the map construction process (see Section 3).

Otherwise, in computer science, especially in artificial intelligence, the modelling of schematization processes is not a great research topic (or at least not an explicit one). Herskovits mentions this fact: "Work in artificial intelligence sometimes

[3] A discussion on the influence of maps on spatial cognition and on maps as reflecting cognitive principles can be found in Uttal (2000a; 2000b) and Tversky (2000).

mentions schematization, but I know of no computational model of the use of spatial expressions in which it plays a significant role. Yet, schematization cannot be overlooked in modeling human abilities; it is most certainly a key to understanding both the strengths and limitations of spatial language" (Herskovits 1998, p. 149). Whereas she refers to the domain of spatial language, the like can be stated for modelling in the graphical spatial domain. There is no consistent approach to model schematization. On the other hand, there are several approaches that could serve as building blocks for defining schematization for graphical representations (e.g., Berendt et al., 1998; Wahlster et al., 2001).

According to Bryant, Lanca, and Tversky (1995), the study of diagrams is one of these approaches: "Another way of dealing with space is by use of diagrams. This is an interesting case because diagrams are intermediate to language and physical environments. A diagram is representational, intended to convey spatial information about a place that is not physically present, just as in language. A diagram, however, is also a physical object having its own spatial properties, just as do real environments. The study of diagrams also has ecological justification because maps, sketches, pictures, and so on are commonly used to provide spatial information" (p. 536). Freksa (1999) supports and emphasizes this view: "Space can be realistically explored by operating on its representation" (p. 26). Note though, that this works for schematic maps only if we assume that the map-reader applies a conceptual level in the interpretation (see next section).

Schematization is also an important aspect in the area of wayfinding even if it is not named this way all the time: "[...] whereas full guidance instructions can have a negative impact upon wayfinding performance, less complex instructions that link landmarks to directions have the capacity to enhance wayfinding performance" (Jackson 1998, p. 1000).

Some of the remaining questions not answered yet include the following: Is schematization a process or the result of a process? Are concepts or conceptualizations the result of a schematization process? For the map domain this may be easier as we could claim that the result of a schematization process is a schematic map, which is a non-deniable fact, but what is the schematic map composed of? Another question that should be answered is: do we schematize spatial relations or do we schematize spatial objects? Do we schematize intersections or do we schematize angles between streets? The former corresponds to the toolkit approach by Tversky & Lee (1998, 1999), the latter is closer to 'classical' generalization in cartography. To pinpoint the distinction between map design that gradually adapts representations through simplification and map design that starts with identifying cognitive concepts and integrates them in depicting spatial knowledge rather than spatial information, we contrast the *data driven approach* with the *cognitive conceptual approach* (cf. Klippel, 2003a).

3 Maintaining Qualitative Information

Maps are regarded to be spatially veridical (Mark & Egenhofer, 1995). Additionally, the representational medium does not support underspecificity, i.e. it requires the instantiation of exactly one representation. As a consequence, maps are suited for representing spatial objects and relations schematically only to a limited extent (cf. Berendt, Rauh, Barkowsky, 1998; Habel, 2003). Hence, to avoid misinterpretation one has to make sure that people using the map recognize the type of map, i.e. that they can distinguish veridical and schematized content and interpret them correctly. This is a bigger problem in the graphic domain than in the linguistic domain as graphic representations are obliged to choose one possible interpretation, i.e. one graphical realization, and have to make sure that this interpretation is not regarded as a veridical representation of a canonical view of the world but as the result of a schematization process. MacEachren mentions that "Early railroad cartographers routinely straightened routes in an effort to convey an impression that their own route was the most direct" (MacEachren 1986, p. 18). To overcome this drawback of schematized representations, Agrawalla and Stolte (2001) used a rendering algorithm to give their 'map' the appearance of sketch maps to suggest spatial inaccuracy. Yet, there has been no systematic behavioural research on this question.

In the project *Spatial Structures in Aspect Maps* (Berendt et al., 1998), we took another approach. Following the distinction of knowledge into three different types as presented in the last section, the aspects to be depicted are ordered in a depictional precedence (cf. Barkowsky & Freksa, 1997). This precedence denotes the rank order of the knowledge to be represented, i.e. its importance for the task. Knowledge that needs to be represented unaltered is at the top of the order, followed by knowledge whose representation can be altered; at the end of the order is knowledge that can be represented highly distorted or even missing. This depictional precedence is used in the map construction process, for example, to decide on which knowledge can be distorted to solve (local) conflicts that result from space limitation in the depictional medium, i.e. the map. When reading a schematic map, the user's assumption about this depictional precedence, i.e. whether some information is depicted veridically or not, needs to match the actual depictional precedence used. Otherwise, map reading may lead to mis- or over-interpretation (Berendt, Rauh, et al., 1998), i.e. some information in the map is assumed to be represented veridically while it is not and, thus, invalid conclusions can be drawn.

Subway maps are a good example for the approach of depictional precedence. While the direction and distance relations between stations along a line can be distorted, for example, to fit a qualitative eight-sector direction model, and therefore cannot be read off the map literally, the ordering information between different subway lines needs to be preserved in order to keep the maps usable. This latter aspect can be seen to be veridical.

This is also a good example that certain spatial knowledge needs to be maintained while other knowledge can be altered or omitted. Altering or omitting objects is easier since these changes are more obvious to the map-reader than modifications in the depiction of spatial relations. Omitting a specific type of object in a map is easily understood; it is simply not present. On the other hand, ignoring distance relations in the construction of a map, for example, is much more problematic. Due to the characteristics of the representational medium, one can always read off the map distances between objects that, in this case, are purely accidental. Thus, spatial relations conveyed in a map need to be characterized in a way that allows for different levels of granularity. That is, the map should communicate which deviations from the precise relation can be considered qualitatively equal to the original one and at which point deviations actually start changing the relation in a way that leads to different inferences. In contrast to cartographic approaches, successfully applying this approach requires an explicit specification of the spatial knowledge needed: the kind of knowledge and its intended qualitative level needs to be given prior to actual map design in order to create the depictional precedence and to resolve design conflicts. For the characterization of spatial relations in schematic maps qualitative approaches can be taken into account (Schlieder, 1993; Barkowsky et al., 2000).

These considerations, for example schematizing local features of the knowledge while preserving its global ordering, led to the development of a schematization algorithm (Barkowsky et al., 2000). The algorithm is based on the method of discrete curve evolution (DCE) by Latecki and Lakämper (2000). Latecki and Lakämper use this method to simplify the shapes of objects as a preprocessing step for measuring shape similarity in image comparison. The process of discrete curve evolution runs on closed polygonal curves. It simplifies these curves in a stepwise manner by eliminating kinks; its main accomplishment is that it preserves the overall perceptual appearance of an object while ignoring features of minor importance. The main idea of DCE is to remove in each step the kink of an object that is least relevant to its overall shape. The effect of this algorithm is comparable to simplification of detail due to scale reduction in cartographic generalization.

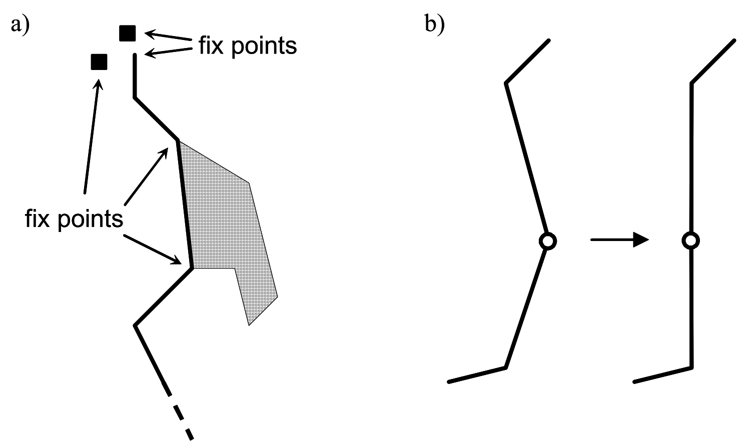

Figure 1. a) Examples of fix points: Single-point objects, endpoints of lines, and points shared by two or more objects are treated as fix points in the simplification process; b) Example of a simplification step: movable points on linear entities are projected back onto the entity after the simplification step

We adapted DCE to meet with the requirements of map schematization; in addition, we enhanced its functionality to account for design goals in map-making. DCE runs on closed polygonal curves, but entities in a map can be point-like, linear, or two-dimensional. While shape simplification as performed by DCE can be applied to linear and two-dimensional entities, their special properties and constraints and their relations need to be taken into account. As the relevance measure in DCE depends on pairs of line segments, no such measure can be computed for entities represented by single points or for the endpoints of linear entities. These points are excluded from the evolution process and are no longer considered. The points that belong to more than one entity, for example points on a shared boundary, need to be retained unchanged as well, as eliminating or displacing them violates topological information that needs to be preserved. These points are marked as fix points. Point-like entities that are located on linear entities are another special case; these distinguished entities need to be projected back to the linear entity when it is changed by the process of DCE. They are thus marked as movable points. All these cases are shown in Fig. 1. Just like in the original DCE process, a given threshold determines the degree of schematization.

The basic algorithm can be extended easily in different respects, one being the relevance measure. Other extensions include an additional factor that depends on the object at hand, for example, streets or rivers. The factor increases or decreases the relevance measure of an object's points. Therefore, this object will appear more or less simplified compared to others. In addition, a different cost function can be used that captures different aspects. The algorithm ensures that topological and various ordering relations are maintained. For example, a point-like object that is located left of a linear object will stay in this relation. On the other hand, panoramic ordering information as defined by Schlieder (1993) for point-like objects in the plane will not be kept on a general basis. Current lines of research elaborate the integration of qualitative distance concepts.

It is then possible to restrict the schematization such that certain minimal (or maximal) distances between objects remain preserved. By eliminating a kink from an entity, the distance of this entity to other entities is changed. This change in distance is not restricted as long as it does not violate any topological relation. Thus, the distance may get arbitrarily small and be no longer perceivable but the schematized map will still be a valid result of the algorithm's application. This can be avoided by introducing a minimal distance between objects and testing it before applying the changes. If the new distance is smaller than this threshold, the change is not performed. Likewise, this can be used to push entities away from each other if their distance is smaller than the threshold in the original map.

4 Aspects of Human Spatial Cognition

In this section we present two approaches to map design that reflect principles of human spatial cognition (wayfinding choremes and focus maps) and how these approaches can be combined (chorematic focus maps). Additionally, we discuss multimodality as a key feature of human communication about space and how it can be related to map design.

4.1 Wayfinding Choremes

Klippel (2003a) defines wayfinding choremes as mental conceptualizations of primitive functional wayfinding and route direction elements. Given their focus on functional aspects, i.e. the action that takes place in environmental structures, they reflect procedural knowledge, i.e. knowledge about how to interact with the world. In this sense wayfinding choremes are schemata and do not as such concern categorical knowledge about physical spatial objects (e.g., Neisser, 1976). Here the approach differs from toolkits (e.g., Tversky & Lee, 1998, 1999) and computational approaches (e.g., aspect maps). Wayfinding choremes can be externalized, for example, graphically or verbally. They are key elements of a formal grammar, which models route information on a conceptual level (Klippel, 2003a).

The wayfinding choreme theory got inspired by the idea of chorematic modelling, invented by the French geographer Brunet (e.g., 1987). Most pertinent for following a route is direction information at decision points on which the research efforts are placed. In Klippel (2003b) the empirical basis for wayfinding choremes is detailed. One major achievement is a clearer distinction between structural and functional elements of route information and how this distinction contributes to a better understanding of conceptualization processes. Most approaches concerned with the visualization of route information focus on *structural* aspects, i.e. they are concerned with the conceptualization or depiction of objects. In contrast, the wayfinding choreme theory aims at a *functional* characterization of route information, i.e. it focuses on actions that demarcate only parts of a physical spatial structure. The distinction is reflected in the following definitions (see also Fig. 2):

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

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

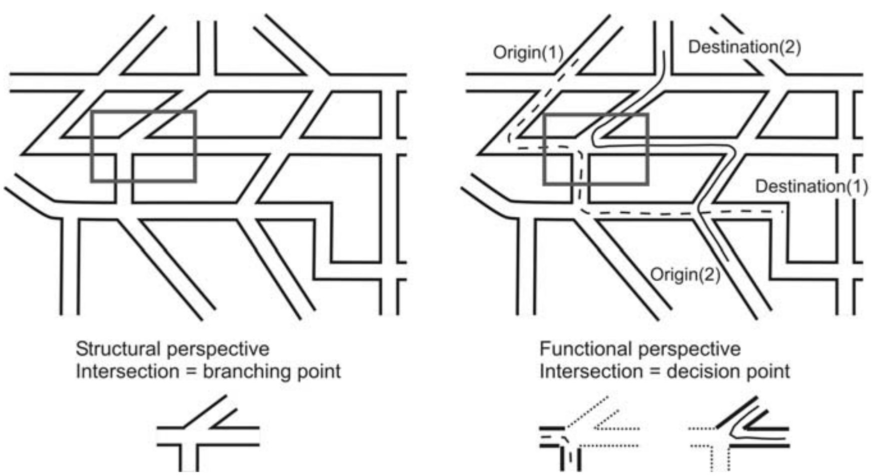

Figure 2. Distinguishing structural and functional aspects of route information

An important goal of the wayfinding choreme theory is the combination of prototypical functional and veridical information. Prototypical graphical instantiations communicate the action required at a decision point. This prototypical action representation is then embedded in a veridical spatial situation (see Herskovits' definition of schematization, Section 2).

Fig. 3 shows the results for prototypical turning directions at decision points explicated in Klippel (2003b). Participants adhere to the prototypicality of the turning actions, i.e. the functional aspects of decision points. It is important to note that they do not adhere to the prototypicality of the structure of the intersections. The experiments confirmed a seven direction model for turning actions which is taken as a basis for the graphical representation of turning actions at decision points. The seven resulting wayfinding choremes are employed to schematically depict route information.

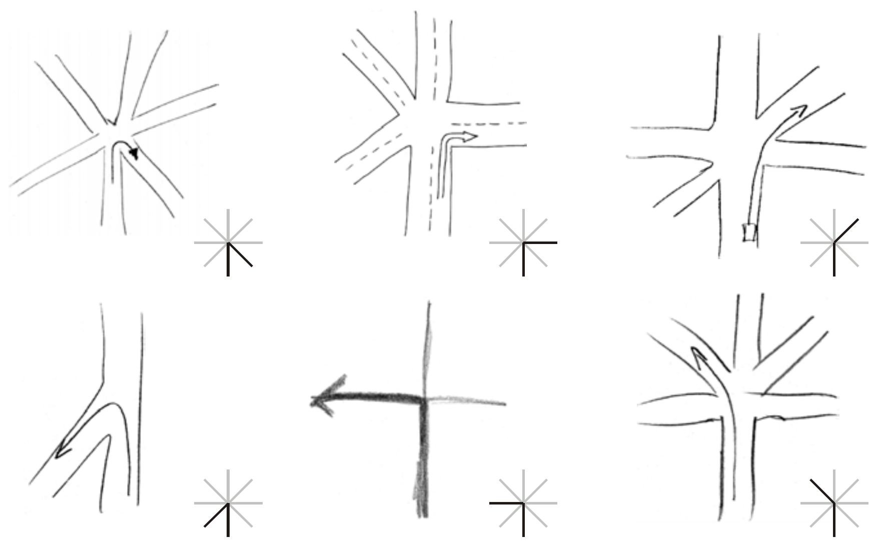

Figure 3. The behavioural basis of wayfinding choremes (Klippel, 2003b)

4.2 Focus maps

Zipf and Richter (2002) present the approach of focus maps. These maps are designed such that a user's attention is drawn towards the map part of interest. Clearly, this map part, the region of interest, depends on the task at hand. In the case of wayfinding, it is the area along the route to be taken. By focusing on this region, the user's mental processing of the map information is guided to the area of relevant information. The map shows the remaining parts of the depicted environment, as well, but they are recognizable as less relevant. This way, they can still be used, for example, to orient oneself with respect to an area well known but not in focus. Hence, with focus maps, a user's interpretation process is inadvertently focused on the region of interest. This eases the map reading process as the amount of information to be processed is reduced.

Zipf and Richter (2002) achieve the focusing effect by employing two techniques: a generalization to different degrees and fading colours. In the region of interest, map features are displayed veridically; generalization of these features is kept to a minimum. With increasing distance to this region, map features' degree of generalization increases, i.e. map features that are far off from the region of interest are simplified to a high degree. This is the first step in order to create a funnel towards the region of interest. The second step lies in the use of colours. Since in map making colour is often used to denote a feature's class membership, it is not feasible to use completely different colours inside and outside the region of interest. However, it is possible to use different shades of the same colour category; bright and shiny colours for features inside the region of interest, dimmed and greyish ones for features outside. As with generalization, colours fade out with increasing distance. The combination of increasing degree of generalization and fading out of colours results in a kind of funnel that focuses the user's attention on the region of interest.

4.3 Chorematic focus maps

In Klippel and Richter (2004) wayfinding choremes and focus maps are combined, resulting in *chorematic focus maps*. From a representation-theoretic point of view, these maps should be well suited for wayfinding assistance. Their design process comprises four steps: first, calculating the route, i.e. connecting origin and destination; the route determines the area on the map to be depicted. Second, relevant aspects for the given task are selected. In the third step, these aspects are used to construct a focus map. In the last step, functionally relevant parts of the selected route, i.e. the branches of a decision point that will be used by a wayfinder, are replaced by the corresponding graphical wayfinding choreme (see Fig. 3).

Wayfinding choremes and focus maps complement each other ideally. Both approaches draw their motivation from cognitive principles of information processing. One approach, wayfinding choremes, is cognitive-conceptual and highlights the relevant information by employing conceptual prototypes. The other, focus maps, is data driven and keeps the relevant information veridical but deemphasizes other information. Their combination eases information processing significantly. With focus maps a user's attention is drawn towards the map's region of interest. This focuses the mental process, map reading, on the location of the relevant information, its *where part* so to speak. Graphical wayfinding choremes emphasize the functionally relevant parts of decision points. Additionally, further information remains veridical. By this procedure, the route and the corresponding actions to take stick out in the map and are easy to process. Wayfinding choremes emphasize, so to speak, the *what part* of the information. In combination, the resulting map allows a user to concentrate *on* the relevant information *in* the relevant part of the map; thus, the cognitive effort to process the information is drastically reduced, and map reading should become easier.

4.4 Multimodality

Paper maps and their digital counterparts are monomodally focused on the visual sense (disregarding, e.g., tactile maps). Yet, they can mimic various modalities. This is possible through the representation-theoretic characteristics of signs and symbols (e.g., Palmer, 1978). Following the idea to reflect cognitive principles of knowledge representation in maps (see Section 2), we generally can distinguish between abstract mental conceptualization on the one hand and various output modalities by which these abstract mental concepts can be externalized on the other hand. In the case of wayfinding choremes (Klippel, 2003a), this fact is terminologically reflected by adopting a Chomskian (1986) distinction. Chomsky differentiates between I-language and E-language. 'I' stands for internal and denotes an abstract part that underlies the observable behavioural aspects of language. 'E' stands for external and means these observable behaviours. Correspondingly, the wayfinding choreme theory refers to mental conceptual primitives, i.e. abstract mental concepts of basic route direction elements, as I-wayfinding choremes. In contrast, the (graphic) externalizations of I-wayfinding choremes are termed E-wayfinding choremes:

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

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

Whereas the wayfinding choreme theory primarily deals with graphical and verbal externalization, other forms are possible for maps. One prominent example is the use of symbols for gestures that Hirtle (2000) terms *map gestures.* Map gestures can be compared to gestures used together with (verbal) route directions, for example, 'the hotel is over there' plus gesture. The gesture can subsume a variety of necessary actions without specifying them in detail (see also Tufte, 1997).

The wayfinding choreme theory discusses the possibility of chunking primitive route direction elements into secondary or higher order elements, termed HORDE (cf. Klippel, Tappe, and Habel, 2003). Whereas the current theoretical state of HORDE allows for identifying the route direction primitives involved, this is not necessarily the case for map gestures. Fig. 4 depicts an example. The map is used as part of a route direction. The map gesture subsumes all actions necessary to get from the S-Bahn station 'Landungsbrücken' to the nearby docks. Like most interurban train stations, the station 'Landungsbrücken' has more than one exit. Moreover, from each of these exits various options exist to reach the docks. On the one hand, this makes the situation complicated as different sequences of route directions elements have to be arranged. On the other hand, the situation is comparatively easy. Even though there are several possibilities, the destination is rather obvious—a classical you-can't-miss-it situation. The environment constrains the movement in the most important direction by the river, which conceptually functions as a giant T-intersection; in the terminology of Lynch (1960), an 'edge', terminating the general possibility of moving in one direction.

Figure 4. A map gesture (cf. Hirtle, 2000) describing a generic route from the train station to the dock. It subsumes all possible routes to reach dock '4' from station 'Landungsbrücken'

In this sense, the wayfinding choreme theory combined with map gestures reflects a fundamental aspect of knowledge representation: granularity. Or, to quote Hobbs (1985): "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" (p. 435).

5 Applications

The ideas and approaches detailed so far are important elements in several applications. The schematization algorithm explained in Section 3, for example, is used in a system that computes the placement of You-Are-Here maps for a given environment (Richter & Klippel, 2002). The system's underlying model is based on spatial cognition research; its basic representation is a graph that consists of routes calculated in advance. Locations along these routes that are relevant for the placement of You-Are-Here maps are determined locally before being reduced to those actually needed in a global judgment of all locations. We employ the schematization algorithm to simplify the graph; this reduces computational complexity. The algorithm ensures that the structure of the simplified graph stays similar to the environment's system of paths, which is a prerequisite for the system's success.

Another application area is the field of robotics. We use schematic maps as means of communicating with mobile robots (Freksa, Barkowsky, and Moratz, 2000). The approach is based on the presumption outlined earlier in this chapter that meaningful interaction requires an appropriate level of abstraction for intelligently solving tasks in a given domain. In the domain of wayfinding in a structured environment, a representation of space on the abstraction and granularity levels of decision-relevant entities is considered appropriate. The approach especially makes use of qualitative ordering information of environments' features for localization and navigation of the robot and for communication with a human user. The robot employs qualitative spatial reasoning on the information provided by the schematic maps and its sensor readings both for planning and for plan execution. This way, it tries to match the given information, i.e. the map, with the perceived information, i.e. the real world.

6 Conclusions

In this contribution, we set out to give an overview of several approaches that evolved within cognitive science and that aim at making graphic representations cognitively adequate. A central concept for cognitively adequate representations of environmental knowledge is that of a schematic map. Even though all maps are schematic for reasons of graphic constraints, our intention was to show that schematization may be usefully applied as a cognitively relevant concept that has a special significance beyond graphic and spatial requirements and should not be applied to every map. Thus, although from a cartographer's perspective every map is schematic, not every map is a *schematic map*. It is important to note that we refer to cognitive adequacy here in both meanings of Strube (1992): the external representation resembles a mental internal representation; additionally it supports cognitive processes. The latter statement is supported by the assumption that correspondence between an internal and an external representation facilitates map reading.

Within this general framework, the project *Spatial Structures in Aspect Maps* has approached several facets of representing spatial knowledge in a cognitively adequate way and has explored major fields of research in cognitive science drawing on results from artificial intelligence, cognitive psychology, and linguistics. Formal methods relying on different kinds of spatial knowledge (e.g. topological or ordering information) and qualitative calculi have been specified for schematizing information, providing a different perspective for cartographic research on this topic. Psychological results on prototypical representations and the focus of attention have been extended by behavioural experiments providing the necessary results for map design. Linguistic and psychological approaches on conceptualization and the importance of an action-oriented characterization of spatial information have been employed to shape a theory of cognitive-conceptual map design and to specify a grammatical approach to (graphic) route directions on a conceptual level. Action-oriented approaches have gained high visibility under various hotly discussed topics in cognitive science; amongst others, the embodiment of cognition, situatedness, and the central role of events in current research efforts (e.g., Worboys & Hornsby, 2004). Work in the aspect map project has been extended to incorporate findings of research on multimodality to the design of maps and map symbols. Finally, these finding have been shown to be applicable not only in map design but also in fields such as the interaction with robots by schematic maps.

Finally, to sum up, we discussed the following types of maps in this chapter: Schematic maps: intentionally simplified representations aiming at cognitive adequacy; aspect maps: a class of maps that adopts a hierarchy of aspects to decide whether or not certain aspects have to be depicted in a map; wayfinding choreme maps: map design based on identifying conceptual primitives, for example, prototypes for turning actions at intersections; and focus maps: application of various graphic means to centre the attention of a map user on spots of highest interest.

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