Spatial Thinking with Geographic Maps:

An Empirical Study*

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Abstract

Geographic maps are a well–established way of representing domain–specific knowledge in a way which integrates symbolic and pictorial representation. This paper proposes an interdisciplinary approach to the understanding of how maps represent and organise knowledge, combining artificial intelligence knowledge representation theory with empirical findings and methods from cognitive psychology.

Schematic maps represent knowledge in a different way than topographic or city maps; in particular, distances and directions cannot be evaluated in the same way as in topographic or city maps. However, information from different types of maps must often be combined to answer everyday questions. An inference task involving such a combination, in order to locate a train station shown in a schematic map with respect to a part of a city map, was analysed theoretically with respect to how location judgments change with assumptions about what spatial information is contained in the schematic map. The same task was investigated empirically in a study in which subjects were asked to locate a train station and to describe their thinking in a subsequent verbal report. Results indicate that subjects' judgments and verbal reports can be grouped according to the theoretical analysis.

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1. *Geographic maps as knowledge representations*

Maps are a well–established way of representing geographic knowledge which has proved useful over centuries. They are particularly interesting with respect to how they represent or organise the knowledge they contain because they combine pictorial representation with symbolic representation. Representation is pictorial in that maps are images in the sense that many spatial relations in them represent spatial relations in the world. Representation is symbolic in that maps contain annotations in the form of natural language expressions or text elements: names or descriptions of places; and in that maps contain pictorial elements which can only be understood symbolically, e.g. colour codes for road types.

This makes maps interesting for (knowledge) representation theory: How is geographic knowledge represented in maps, and how can it be extracted? Maps are also interesting for cognitive psychology: Maps can provide access to the way humans perceive, represent, and interact with their spatial environment. The existent standards of mapping techniques have evolved over a long time; thus, the way people construct and use geographic maps provides valuable clues to the underlying mental structures and processes for spatial knowledge.

Some types of geograpic maps are particularly interesting in the investigation of these questions: topographic maps (showing the characteristics of the earth's surface in a particular region), city maps (showing the street layout and other characteristic features of a city), and schematic maps (e.g. public transport network maps).

Like any representation, a map only represents certain aspects of the geographic world. This is particularly obvious in schematic maps, which highlight certain aspects of the represented geographic world and abstract from others. But what aspects are represented? Despite the seeming simplicity of schematic maps, it is often difficult to 'read' them correctly: valid interpretations are often neglected, or worse, schematic maps are overinterpreted (e.g., Monmonier, 1996). To distinguish correct interpretations and overinterpretations, one needs to investigate both the represented geographic world and the representing cartographic elements.

In the following, we shall mainly be concerned with spatial aspects: spatial relations between places in the represented geographic world, and spatial relations between cartographic elements. This makes the problem of overinterpretation particularly clear: In so far as maps are pictures, each cartographic element has a concrete position in the reference frame of the map, geometric relations like directions and distances between these elements are all fixed and unique. Therefore, it may seem straightforward in many contexts to assume that directions and distances correspond to directions and distances between the represented geographic locations. However, the representation relation is often more complicated. For example, the relative lengths of train connections in a map may not correspond to the relative lengths of these train connections in reality: They may be the result of graphical considerations. Studying the correspondences between represented and representing aspects–the way they are intended by the cartographer, and the way they are read by the map user–helps to elucidate how maps represent knowledge, as well as how people understand maps.

These considerations have been the basis for the development of the aspect map approach (e.g. Barkowsky et al., 1997; Berendt et al., in press) taking into account empirical results and theoretical ideas from cognitive psychology. The current paper reports work done in that framework. The main aim is to develop a computational architecture for processing geographic maps, which reflects the way this is done by people. A central modelling idea is to distinguish between the information obtained from the picture and the map's legitimate information content.

Since maps are not only abstracted representations of the world, but are intended to be used by humans, many psychological questions arise: How are maps interpreted? Which information is read off maps? How is the information given in maps represented mentally, and which processes work on these representations? How are aspects from different maps combined mentally, and how are they supplemented by additional cognitive processes in order to come to good spatial estimations? Are there ways to facilitate map comprehension? Are there principles that can guide good map production?

Humans are able to extract topological relations between objects when given graphical configurations (Knauff, Rauh & Renz, 1997). They are also able to represent and reason with qualitative relations specifying orientational information (Rauh, Schlieder & Knauff, 1997), and they are able to take into account metrical information (at least to some extent). But, the central question is how these different types of information are extracted and on what level of granularity, and how these different types of information can be combined. Do people make distinctions between possible and necessary relationships, and are they able to extrapolate given information in an intelligent way in order to come to good guesses or estimations?

Whereas many of these questions are more concerned basically with the psychology of spatial thinking, some also address important issues from a cognitive ergonomics point of view.

2. The problem: determining the information content of a schematic map

Whenever a map is read, the information obtained from the picture must be evaluated to obtain the map's legitimate information content. In some cases, this is unproblematic, because the aspect of interest is known to be represented in the map. For example, one may consult a public transport network map to find out the name of the next station on a given line: It is clear that the aspect "being a neighbouring station on a city train line" is represented by, e.g., the next dot on the line of the respective colour.

Sometimes, however, evaluation is not as straightforward as this. There are cases in which it may not be clear whether the aspect(s) of interest is/are represented in the aspect map. In particular, are or in what sense are direction and distance represented in the schematic map? Also, often the visualization that has been used to create this map is an abstraction, i.e. it cannot be inverted (at least not in a strict mathematical sense). For most of the visualization's output values, one can only specify a *range* of input values.

In principle, the same questions have to be asked about other types of maps. However, we assume here that the distortions caused by projection and other cartographic processes in, e.g., a city map are minor compared to those in a schematic map.

The question of which aspects are represented and which ones are evaluated becomes particularly interesting when different maps have to be combined. As an example, consider the situation that from a transport network map, one wants to find out something about the location of a station in the city. This may happen if we only have a partial map of the city which does not show the station we want to walk to. The city map does show directions and distances along with street names, all of which we can use to orient ourselves. Inferring direction and distance to our goal station, if this is possible, allows us to restrict the possible locations of that station with respect to the city map, so we can plan a walking route in the right direction (and maybe decide whether walking is worth the effort depending on the distance). But are or in what sense are direction and distance represented in the schematic map?

2.1 An example: locating a city train station

This will be demonstrated using an example which involves two real maps. The first is a city map which shows the Hamburg university campus and some adjoining streets, as well as one city train station (*Hallerstraße*), another city train station (*Dammtor*), and the city train line going through the latter (see Figure 1 (a)).[1] In the following, this map will be called "campus map". An important city train station within the Hamburg public transport network, *Schlump*, is close to the depicted area, but outside it. The second map is a part of the Hamburg public transport network map, which shows all three stations (*Hallerstraße*, *Dammtor*, and *Schlump*), the city train line going through *Dammtor*, as well as all other city train lines and stations in that region (Figure 1 (b)). The task is to locate *Schlump* with respect to the campus map.

1 Only this city train line in this area is shown on the campus map. This is because it is overground, while the other lines are underground.

3. A formal approach

To answer the questions posed in the preceding section, we have to describe the representing cartographic elements and relations between them as well as the information content, i.e. the represented geographic elements and relations between them. In the carto–semiotic literature, various formalisations of maps have been proposed (e.g. Bertin, 1981; for an overview, see Head, 1991). However, these do not address explicitly the question of spatial information content that is relevant to us, and they do not examine *different* possibilities of what a map could represent / how a map might be interpreted, and therefore also do not examine the structural relations between different possibilities. A general classification of spatial knowledge which is increasingly used in artificial intelligence and cognitive science is based on mathematical concepts of space and distinguishes between *topological*, *orientational*, and *metrical* knowledge (e.g., Schlieder, 1996). This will be the basis for the classification of evaluation possibilities used here.

With respect to our question, *topological* knowledge refers to relations of *connectedness* between spatial objects in a map. *Orientation* knowledge refers to relations that locate points with respect to directed lines (axes): *left of*, *on*, or *right of* a line. *Metrical* knowledge refers to *distance* and *direction*.

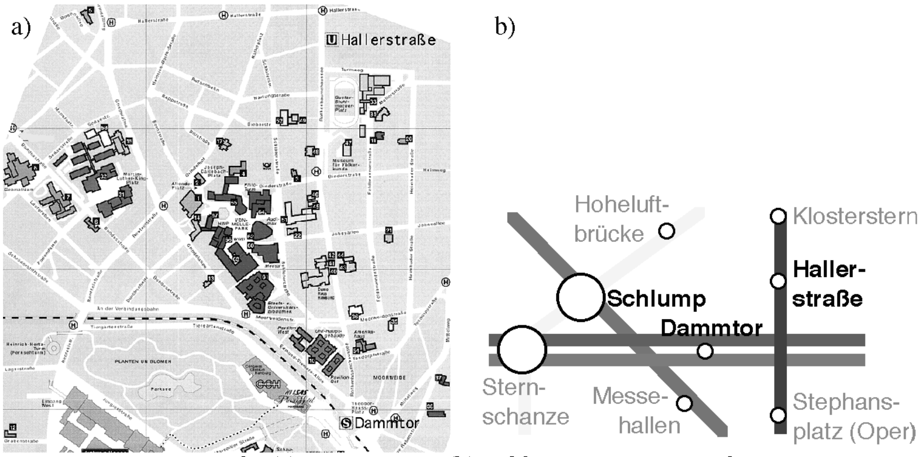

Figure 1: Example: (a) campus map, (b) public transport network map

3.1 Cartographic elements and cartographic relations

We concentrate on *station and train line symbols* as cartographic elements. In Figure 1(b), these are white dots with a black circle around them. In Figure 1(a), station symbols are quadratic boxes containing a "U" or circles containing an "S". In both maps, station symbols are identified by text labels next to them. *Line symbols* are the thick lines in Figure 1(b) and the checkered line in Figure 1(a).

The campus map is only analysed with respect to metrical knowledge as determined by the positions of the station symbols.

To determine topological relations in the schematic map, line segments between station symbols are considered, and relations like *is the next station on line x* or *are connected via line x* can be determined from the maps in a straightforward way.

Orientation relations in the schematic map are defined for station symbols relative to reference axes, which can be train line symbols other than the line the station is on, or the axes of externally imposed reference systems, for example reference systems based on cardinal directions. If a station symbol is completely contained in one of the halfspaces induced by a reference axis, it is considered to be located *on the* respective (*left* or *right*) *side of* that axis. If a station symbol is intersected by a reference axis, i.e. if the symbol contains points in both halfspaces induced by that axis and points on the axis, it is considered to stand in the relation "*left of* or *on* or *right of* the axis", i.e. there is no unique orientation relation of this station symbol with respect to this reference axis.

To determine metrical relations, the centre points of station symbols are connected by straight lines. The length of this line is the *distance* between the two station symbols, and its angle with respect to a fixed reference direction (e.g. the horizontal from left to right) is the *direction* between the station symbols.

3.2 Evaluation possibilities

Using these cartographic elements and relations, we can describe how the information from the two maps may be combined. Figure 2 shows the campus map and the regions where *Schlump* may be located, depending on how the schematic map is evaluated. We distinguish the following five possibilities of evaluation:[2]

1) *topological*: The transport network map only contains information about the connections between stations. *Schlump* could be anywhere with respect to the campus map (hatched region in Figure 2 (a)).
2) *orientation with respect to axes specified within the map:* The transport network map only contains orientation information which locates points (stations) with respect to axes contained in the transport network map (lines). Therefore, all that can be inferred from it is that *Schlump* lies *on the same side of* the city train line as *Hallerstraße*. Assuming a straight continuation of the city train line outside of the campus map, *Schlump* could be anywhere in the hatched region of Figure 2 (b).
3) *orientation with respect to axes specified outside the map*: This assumes that the transport network map gives approximate information about cardinal directions. For example, what is *left of* and *above* a reference object in the transport network map is *northwest* of it on the campus map. Using a sector model for cardinal directions like that proposed by Frank (1992), we see the following: With respect to *Dammtor*,

2 From a formal point of view, this list is not exhaustive, but it describes a plausible selection of possibilities based on everyday notions of what a simple schematic map could inform us about: connection, rough cardinal direction, or distances and directions.

4) *Schlump* is in the *northwest* or *west* sector (Figure 2 (c)). This means that *Schlump* could be anywhere in the hatched region of Figure 2 (d).
5) *orientation with respect to axes specfied within and outside the map:* This is a combination of (2) and (3) and yields the hatched region in Figure 2 (e).
6) *metrical*: This assumes that the transport network map gives exact information about directions and distances. Therefore, the triangle formed by *Hallerstraße*, *Dammtor*, and *Schlump* on the transport network map can be scaled and superimposed on the campus map.
   This means that *Schlump* must be at the hatched location in Figure 2 (f).

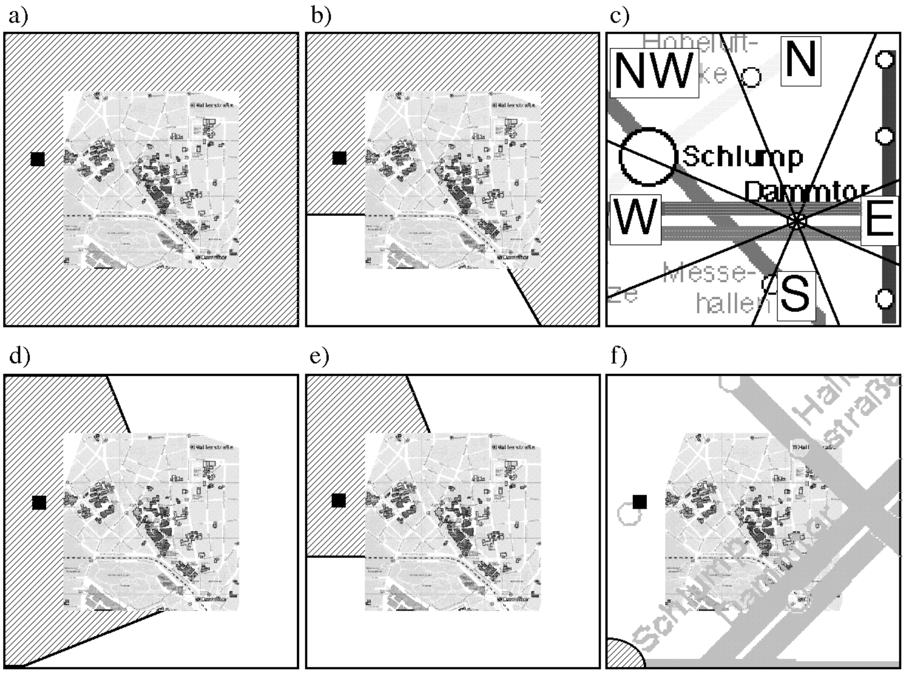

Figure 2: Positions of *Schlump* for different evaluation possibilities:
(a) topological, (b) orientation I, (c) 8–sector interpretation of the transport network map, (d) orientation II, (e) orientation I+II, (f) angles + distances (transport network map superimposed on campus map).

All maps contain a square at the correct position of *Schlump*.

The preceding paragraphs have outlined the logically possible ways of specifying a location for *Schlump*. But how do people tackle this question?

4. An empirical study

4.1 Subjects

Subjects were 26 (10 female, 16 male) University of Freiburg students between the ages of 20 and 33 years, drawn from a list of people interested in participating as subjects in empirical studies/psychological experiments, maintained by the Abteilung Kognitionswissenschaft of the Albert-Ludwigs-Universität Freiburg. They were paid for participation.

4.2 Materials

Subjects were given (i) the transport network map as shown in Figure 1(b) and (ii) a three–page booklet with the campus map as shown in Figure 1(a) on the front page. Page 2 of the booklet asked for a verbal report how the subject arrived at his/her judgment. On page 3 additional questions had to be answered about both types of maps: With respect to the transport network map, we asked whether (i) the directions and (ii) the distances on the transport network map correspond to the real directions or distances, respectively. Additionally, we asked whether (iii) north is on top of a transport network map. With respect to the campus map, there were the following questions, whether (i) subjects noticed the quadratic grid on the campus map, and (ii), if so, whether they thought that this quadratic grid corresponds to the points of the compass? The last two questions asked (i) whether the subject knows the shown city area, and (ii) whether the subject knows which city these maps were about.

4.3 Procedure

Subjects participated individually. First, the subject was asked to give an estimate of the location of the train station *Schlump* and to indicate this location on page 1 of the booklet. After that, subjects had to give a verbal report on page 2 how they arrived at their estimate. Then, subjects answered the questions on the last page of the booklet.

4.4 Results

Classification of subjects according to their verbal reports. Two independent raters classified the verbal reports into the theoretical categories given in the previous section according to the following criteria: If the city train line was explicitly mentioned as reference object, and the stations *Dammtor* and/or *Hallerstraße* were explicitly mentioned as reference object(s), and cardinal directions were explicitly mentioned as relations, the description was classified as evaluation possibility (4). If only the city train line was explicitly mentioned as reference object, the description was classified as evaluation possibility (2). If only the stations *Dammtor* and/or *Hallerstraße* were explicitly mentioned as reference object(s), and cardinal directions were explicitly mentioned as relations, the description was classified as evaluation possibility (3).[3] If angles and/or distances or the process "projection" were mentioned, the description was classified as evaluation possibility (5).

The concordance of the two raters was about 92.3%, i.e. 24 of 26 verbal reports were classified independently in the same way. After a joint discussion, the ambiguous two verbal reports were assigned to their final categories. 3 subjects had to be excluded because they knew Hamburg or because they judged themselves as unable to read maps and said they had guessed the position (and did not give a verbal report of how they had arrived at their estimate). So, 23 subjects were included in the subsequent statistical analyses.

According to the analysis in section 3, evaluation possibility (2), (3), and (4) are correct, with (4) specifying the smallest region. Evaluation possibility (5) is not correct; it is an 'overinterpretation' of the transport network map.

Results were as follows:4 subjects (17.4%) described evaluation possibility (3) and located *Schlump* in the corresponding region. 8 subjects (34.8%) described evaluation possibility (4) and located *Schlump* in the corresponding region.
9 subjects (39.1%) described evaluation possibility (5) and located *Schlump* in the corresponding region.
2 subjects (8.7%) mistakenly thought *Schlump* lies on the city train line shown on the campus map, and located it there.

So most subjects read transport network map as containing some rough information about cardinal directions, which is in line with the results presented in the theoretical analysis above and also with the correct evaluation of the current transport network map, as the correct position of *Schlump* shows. Interestingly, no subject described evaluation possibility (2). In other words, if the transport network map was taken to contain

3 One subject classified as (3) and one classified as (4) mentioned the station *Messehallen* as reference object. *Messehallen* can–with some cunning–be located on the campus map, and in terms of information content used, the description is equivalent to one using *Dammtor* or *Hallerstraße*. Therefore, this deviation was not used to form a different category of evaluation possibilities.

the aspect 'orientation', this was taken to be 'orientation with respect to axes within *and* outside the map'.

Judgments of locations for sub–groups. After categorising subjects according to their verbal reports, we analysed their location judgments of the train station *Schlump*. Using the method described in Batschelet (1981), we computed 95% confidence ellipses for sub–group 4 and sub–group 5 that are shown in Figure 3.[4] Since these confidence ellipses do not overlap, one can reject the hypothesis that the means of location estimations are the same for both sub–groups. This indicates that their judgments were systematically different, and this difference can be easily explained by the different criteria which they stated as the basis of their estimates in their verbal reports.

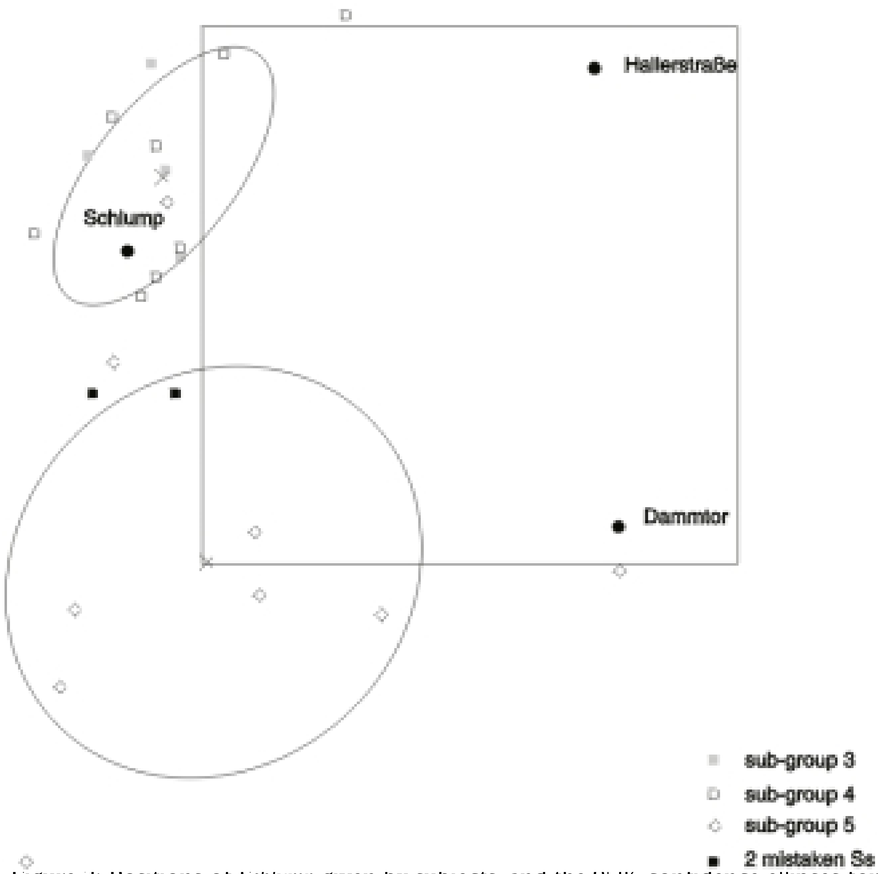

Figure 3: Positions of *Schlump* given by subjects, and the 95% confidence ellipses for subgroups 4 and 5.

4 Sub–group 3 and the remaining 2 subjects could not be analysed because of the low number of observations.

4.5 *Discussion*

The results of the empirical study showed that people use different aspects of maps, and that they were able to verbalize which aspects they extracted from maps. The results also showed that a considerable number of people extract information that lead to overinterpretations of maps and thus to sytematic errors (biases) in location judgments (see sub–group 5).

Another point we would like to stress is that our task seems to involve processes of reasoning on the one hand and processes of judgment and decision making on the other (at least for about half of the subjects). Sub–group 4 in particular seems to take into account orientation within and outside the map, determine corresponding regions and reason from the relation between them. After that, they seem to judge the location within the resulting region, based on criteria that have still to be discovered.

Therefore, our task of combining maps is related to the two subfields of the psychology of thinking, namely the psychology of reasoning and the psychology of judgment and decision making, and can be regarded as a good instance of bringing together methods, results, and theories developed in these two subfields.

Further investigations are planned for determining relevant processes of extraction of regions, of reasoning from the relation between them, and of estimation of points within selected regions that necessarily entails the point that is asked for.

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