Spatial Cognition: From Rat-Research to Multifunctional Spatial Assistance Systems

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Spatial cognition research is making rapid progress in understanding the acquisition, organization, utilization, and revision of knowledge about spatial environments, be it real or abstract, human or machine. Much of the success would have been impossible without a combination of methods and approaches from AI and cognitive psychology. This article describes current interdisciplinary spatial cognition research in Germany. In addition it presents a prognosis: The understanding of the cognitive and computational correlates underlying spatial cognition will soon reach a level where the integration and development of efficient multifunctional spatial assistance systems will become feasible.

1 Introduction

In 1948, the psychologist Edward Tolman described experiments in which rats were trained to follow a path through a complex maze to reach a food box. After the rats performed perfectly (chose the shortest way to reach the goal), the trained path was blocked; the rats had to select another path from a variety of alternatives. Astonishingly, most of the rats found a path that was close to the most direct connection to the food box, whereas not a single rat erroneously tried to follow the original path on which they had been trained. On the basis of these findings, Tolman argued the rats had *"acquired not merely a strip-map … but, rather, a wider comprehensive map to the effect that the food was located in such and such a direction in the room"* (p. 204). Tolman's paper, entitled "*Cognitive maps in rats and men*," marked the starting point of psychological spatial cognition research. Today there is a great body of evidence on how humans (and animals) learn routes, find ways, navigate through familiar and unknown environments, and on the strategies they use when they get lost.

Contemporary research on robotics and AI is concerned with similar problems. For example, how must a mobile robot system be designed to improve its efficiency for tasks such as route choice and navigation? Certainly, the robot must acquire an internal representation of the environment – a cognitive map – and apply adequate procedures to plan movements. A related problem exists in the domain of geoinformatics. A geographic information system must be able to efficiently store, process, and retrieve geo-referenced data, i.e. data which is associated with locations defined in a geographic reference system. On the other hand, it should also interact with the user in a comprehensible way, that is, it should take the user's mental representations of spatial knowledge into account. Applications such as location-based services, geovisualization or semantic information retrieval lead to an especially close interaction between human and machine reasoning.

In the last years, a growing number of researchers from AI and robotics have addressed cognitive questions. Psychologists have become sensitive to the computational properties of robot navigation or issues of reasoning with diagrams and qualitative spatial representations. Research in this rapidly evolving interdisciplinary enterprise has a name: *Spatial Cognition Research*.

This article reports on some highlights of interdisciplinary spatial cognition research in Germany. It starts with a brief description of basic assumptions shared by the community thus providing the foundation of productive collaborations. Subsequently, some prototypical results of interdisciplinary spatial cognition research are reported, and a typical research cycle consisting of psychological and computational investigations is described. The article closes with the prognosis that the understanding of the specific cognitive and computational correlates underlying spatial cognition will soon reach a level where the integration and development of efficient multifunctional spatial assistance systems will become feasible.

2 Shared Assumptions

The common goal of spatial cognition research is to understand spatial representations and processes, be they real or abstract, human or machine. The primary issue is not the processing of sensory input from the visual modality, which is in the focus of image processing and of the psychology of perception. It is also not mainly concerned with the recognition and classification of objects based on features such as shape, size, texture, color, etc, although in this respect it partly overlaps with the subject of theories of object recognition. Rather, the subject matter of spatial cognition is how humans, animals, and machines represent spatial information from the environment, how they think about space, and how spatial representations can be used for reasoning. Thus, space is considered both as an *object* of cognition and a *means* of cognition.

Spatial cognition research is also committed to the hypothesis that spatial abilities rely on different types of representations. In this way, the orthodox view of AI that logic representations together with forms of logic inference be sufficient to exhibit intelligent behavior is complemented – and even pushed back – by representations in the form of diagrams, sketches, maps, or qualitative spatial representations. Accordingly, reasoning is described by means of procedures that inspect and manipulate such representations, and not by logic derivations. In this regard, spatial cognition research is influenced by the well-known "imagery debate" in the early 1980's of psychology (overview in: Tye, 1991), which led to the shared assumption in cognitive science that cognitive processes can rely on a

Auszug aus: Künstliche Intelligenz, Heft 4/02,
ISSN 0933-1875, arendtap Verlag, Bremen
www.kuenstliche-intelligenz.de
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number of different representational formats. Evidence from recent brain imaging studies supports this account. Such studies allow researchers to determine and to visualize problem-solving-related activity in the human brain by measuring differences in cortical blood flow.

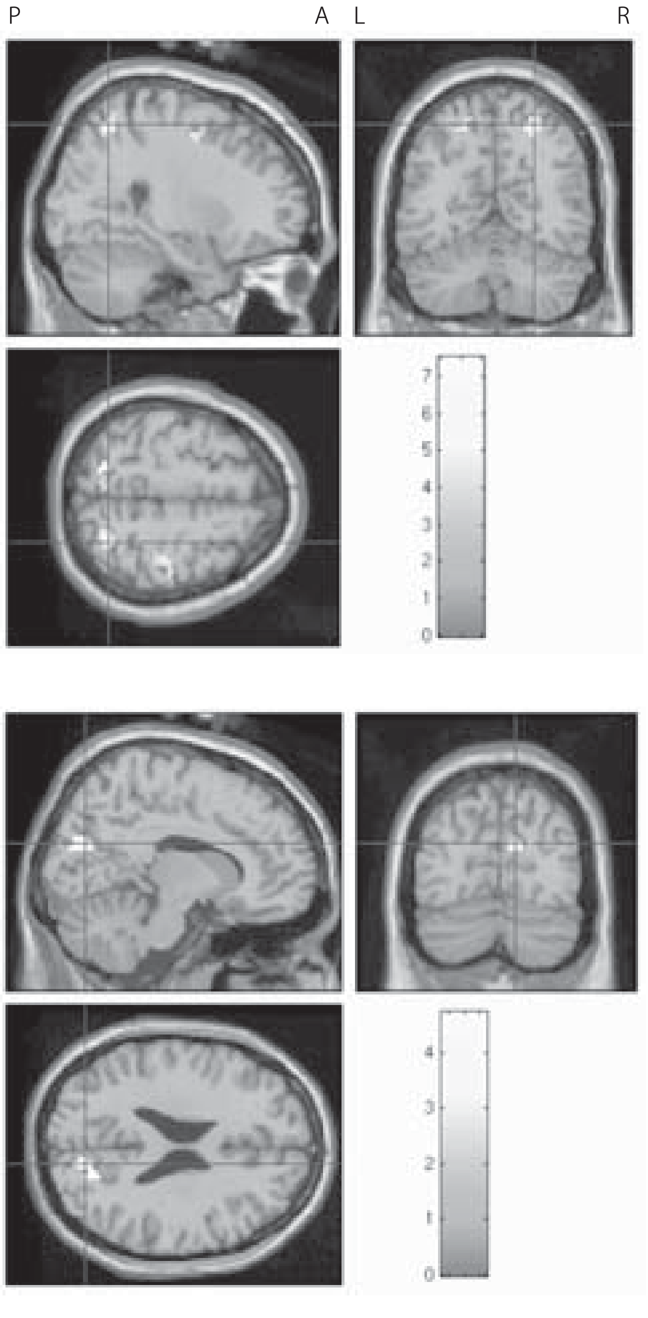

Figure 1. Images representing differentially activated brain areas during spatial reasoning. The brain is presented from three different perspectives: from the side (as if vertically cut through at about the position of the eyes), transverse (as if vertically cut through in parallel to the axis between the ears), and horizontal (as if horizontally cut through in parallel to the axis of the eyebrows). The upper three images show the typical foci of activation resulting from reasoning with spatial relations. The location of the highlighted areas indicates that the spatial information from reasoning problems is mapped to areas of the brain responsible for the multimodal integration of space from perception and working memory. The lower three images show the activity in the back of the brain suggesting that individuals naturally construct visual images, if the reasoning problem is easy to visualize (from Knauff, Fangmeier, Ruff, Johnson-Laird (in press); see text for details).

A typical finding is illustrated in Fig. 1. In this experiment, subjects solved spatial reasoning problems. The brighter a region in the image the more cortical activity was measured. The upper three images show that spatial reasoning activates cortical areas (in the top-back of the brain, usually referred to as posterior-parietal cortices) which are supposed to play a major role in the integration of sensory information into egocentric spatial representations. The lower three images show that reasoning with problems that are easy to visualize leads to additional activation in the back of the brain, an area that corresponds to the visual association cortex. These areas are typically involved in visual representations and mental imagery. In both sets of images, no language-related areas are highlighted as one would expect on the basis of pure logic representations and processes.

How can such visual and spatial representations be used in spatial cognition research? In the following section, we present a small collection of findings that have been primarily obtained within the "Spatial Cognition" priority program funded by the DFG. Further results from the program and more detailed pointers to the relevant literature can be found in the books edited by Freksa et al. (1998; 2000; in press).[1]

3 Joint Achievements

3.1 Route graphs as a common framework for human and robot navigation

For mobile robots, the task of *navigation* is essential. Robot navigation comprises self-localization, planning, and motion. Both self-localization and planning require an internal representation of the environment. But what does such a representation represent? When asking humans for directions to a destination, the usual route description consists of a number of intermediate points that break down the route into a number of shorter segments. Direction changes are typically related to the landmarks at the beginning and end of these segments. This indicates the important role of landmark and directional-change information for route navigation. Moreover, it was shown that information retrieval about objects along a route is easier in the direction of the route than in the opposite direction. These results indicate that navigation information is encoded in a direction-specific way, and that the relation between two objects or locations A and B is not necessarily the same as the relation between B and A (Werner et al., 2000).

Based on these findings, a group of robotics researchers and psychologists from the Universities of Bremen, Göttingen, and Mannheim introduced the concept of the *route graph* as a common framework to represent navigational knowledge in humans and robots. The formalism relies on the distinction of places, route segments, paths, and directions, and it can serve as the basis for complex robot navigation. A detailed description of the account can be found in Werner et al. (2000). A route graph used by the "Bremen autonomous wheelchair" is depicted in Fig. 2.

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[1] Due to the restricted space for this article, we quote only a minimum of the relevant literature. However, for a longer version of this article including a detailed list of references the interested reader is referred to the webpage: www.spatial-cognition.de. Moreover, requests for further information can be directed to one of the authors.

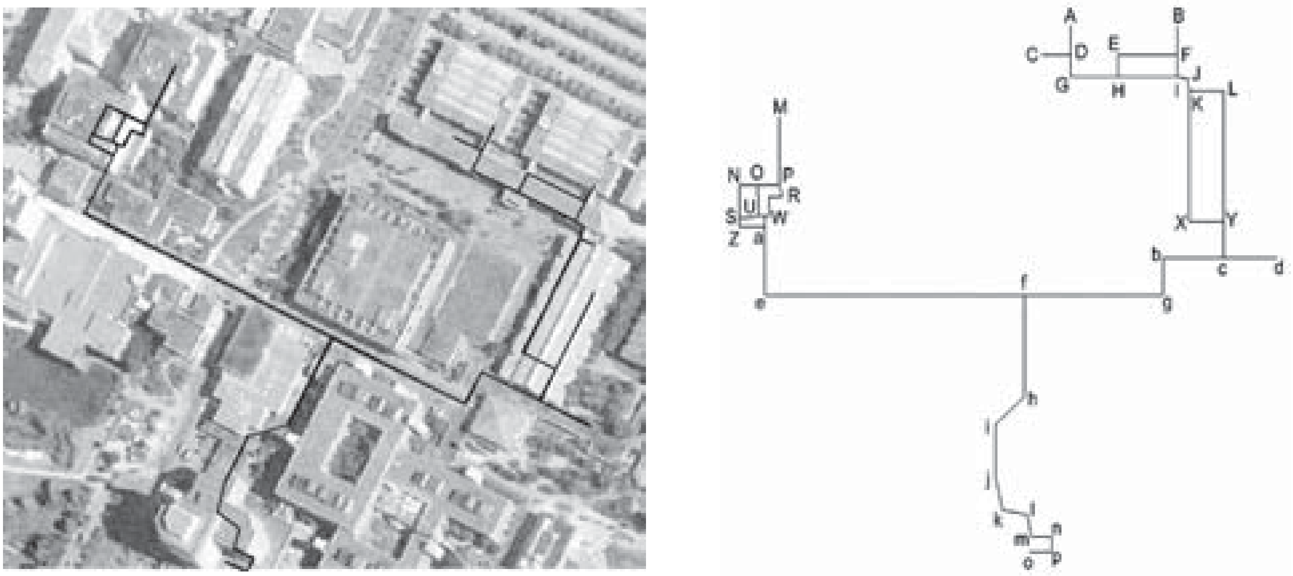

Figure 2. The aerial photograph on the left shows a part of the campus of the University of Bremen. The area shown covers about 380m x 322m. The solid lines mark the part of the environment that is represented as a route graph on the right. The depicted graph is a topological representation of the campus. It consists of 42 graph nodes and 130 junctions, i.e. transitions between directed graph edges. The represented corridors range in length from 4.3m to 179m (cf. Lankenau & Röfer, 2001).

3.2 Schematic maps as wayfinding aids

Finding a *specific location* in the environment is a special case of navigation and an essential ability of agents like humans, animals, and autonomous robots. A group of computer scientists and psychologists from the Universities of Hamburg and Freiburg addressed the issue of designing spatial environments and wayfinding maps in such a way that humans – and other cognitive agents – can easily find their way to a given destination. They identified a variety of dimensions related to the cognitive process of wayfinding, and they discussed how these dimensions can be considered in designing customized wayfinding tools. Important insights resulted from a psychological study where students from the University of Freiburg were given a tourist map and a city train map depicting parts of the city of Hamburg (Berendt, Rauh, & Barkowsky, 1998). The tourist map was rather accurate, but it did not contain the destination of the wayfinding task. The city train map contained the destination, but it did not reflect precise orientation information. After solving a positioning task for the target destination, the participants reported verbally how they arrived at their conclusion. Subjects were then classified according to their verbal report and the dimensions they used for inferring the target location. Figure 3 shows the tourist map around which the participants had to locate the inferred destination. The small circles indicate the results provided by the participants. The large hatched area indicates the region relating to the inference method A, whereas the hatched circle area shows the resulting location obtained using method B. Moreover, the 95% confidence ellipses for the two inference methods used by the participants are given in the figure. The small black square ("Schlump") indicates the proper position of the destination on the tourist map. As illustrated in the figure, the participants primarily used orientation information with respect to a city train line visible in the map together with rough cardinal directions taken from the city train map (method A), or they mentally superimposed the two maps using geometric operations of scaling and rotation (method B).

3.3 Preferred mental models as efficient spatial configuration heuristics

Another spatial cognition problem that arises in a variety of contexts such as regional planning architecture or document layout is to find appropriate *spatial configurations* of objects. Formally, such tasks consist in finding two- or three-dimensional arrangements of objects that satisfy a set of spatial constraints. Two characteristics make spatial configuration problems hard. First, they are mostly too complex to be exhaustively solved mentally. Second, the system is weakly constrained; this means that many (n > 100) solutions can exist. Therefore, a simultaneous visualization of all solutions is not feasible.

Researchers from the Universities of Bremen and Freiburg found a way to attack this problem. In a series of experiments, human participants had to solve spatial configuration problems. The results showed that if a spatial configuration problem has multiple solutions, reasoners prefer to generate only one of these solutions. All participants consistently preferred the same solution (Knauff, Rauh, & Schlieder, 1995). Moreover, if the participants had to decide whether a given configuration fulfills certain constraints, configurations that conformed to the preferred solution were verified faster and more often correctly than other possible configurations. In general, the results showed that individuals focus on a subset of possible configurations – and often just on a single solution. So why not using such preferences as heuristics in a computational configuration system? At present, the group develops a system that takes the psychological findings into account to devise heuristic strategies for the presentation sequence of solutions, and to design an assistance tool that incorporates these strategies (Schlieder & Hagen, 2000).

3.4 Cognitive and computational properties of spatial calculi

In the spatial reasoning community, several *formalisms* for the representation of topological, ordinal, and metric models have been developed. Especially topological knowledge is of

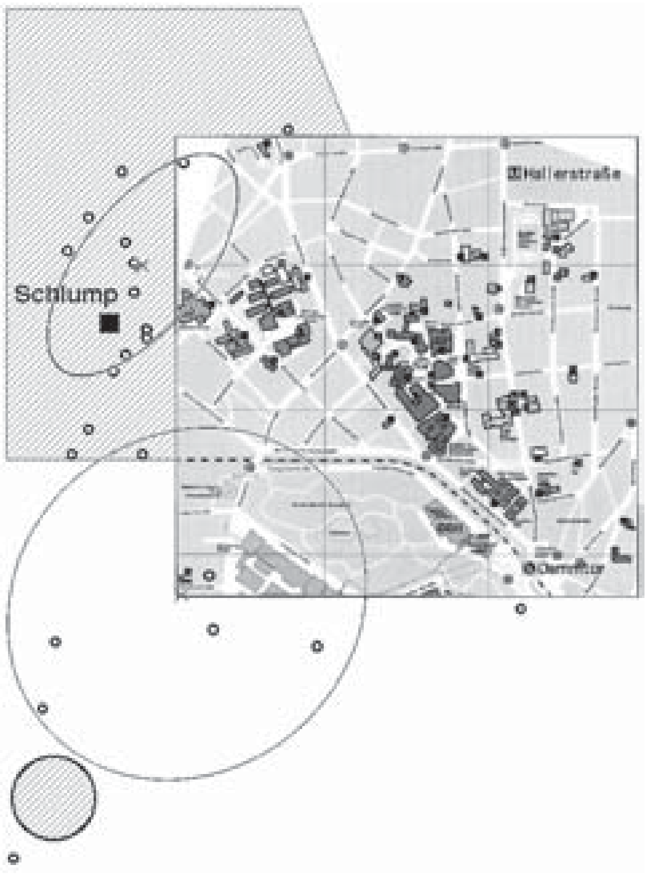

Figure 3. The destination positions estimated by the participants, the areas corresponding to inference methods A an B (see text), the 95% confidence ellipses for the respective guesses, and the true position of the destination on the tourist map (from Berendt, Rauh & Barkowsky, 1998

great interest to psychologists since it is easily accessible and remains invariant under different transformations such as change of perspective, translation, rotation, or scaling. Given this situation, a group of computer scientists and cognitive psychologists from Freiburg University started an intensive collaboration. They used their specific methods to investigate two of the most important topological calculi from AI, namely the RCC-theory of Randell et al. (e.g. Randell, Cui, & Cohn, 1992) and the work of Egenhofer and colleagues (e.g. Egenhofer, 1991). Formally, the two approaches result in two different sets of topological relations, making a total of four dissimilar relational systems. Which of these systems is computationally and cognitively least demanding? The collaboration led to a surprising result: On the one hand, the formal investigations identified one particular relational system as tractable and showed that certain algorithms can solve reasoning problems with these relations efficiently (Renz & Nebel, 1999). On the other hand, psychological experiments showed that the same system was cognitively less demanding and thus much more frequently used by humans than the other systems (Knauff, Rauh, & Renz, 1997).

4 Interdisciplinary Methods

There is a wide spectrum of possibilities to combine psychological and computational approaches in spatial cognition research. Sometimes computational systems are simply inspired by already existing psychological evidence. In other cases, the design of computational models is merely based on what the researcher believes to happen in his mind when solving spatial reasoning problems. However, the community is increasingly aware that such introspections can be fatally misguiding. Likewise, people typically do not distinguish between different types of introspections: representational states and cognitive operations. Thus, the main job of psychologists in spatial cognition research is to investigate what mental representations and operations are effective in human spatial cognition. To reach this goal, they usually conduct experiments under highly controlled conditions. Typically, one or more independent variables are varied systematically and the effects on human performance or brain activation are measured. For instance, we can investigate what makes a spatial inference problem easy to solve by varying the logical form or the way it is presented to the individuals (e.g. as a verbal description or as a diagram). If the problem gets easier, participants should make less errors and it should take less time to give corrects answers.

Computer scientists in spatial cognition research carry out theoretical studies, empirical investigations (for instance to determine computational properties of spatial calculi, or to examine where the theoretical analysis fails), and system implementations. These complementary approaches form the basis for the cooperation in spatial cognition research. A typical spatial cognition research cycle may look as follows:

- psychological evidence suggests the use of certain types of representations, reference systems, and cognitive operations;
- a computational model is designed to implement such features identified in human cognition research;
- a computational model is implemented to simulate and explore the model in specific situations;
- the computational model is empirically tested and the behavior is compared to human behavior;
- differences in behavior trigger new empirical human experiments that allow a refinement of the computational model;
- a refined computational model is implemented in a robot environment and is tested in the context of real-world perceptions and actions;
- the algorithmic approach is analyzed with respect to correctness, completeness, and computational complexity. These results are fed back to the psychological investigations, etc.

5 Perspective and Challenges

As a consequence of the intensive international research activities in several disciplines, cognitive models are now available that explain several specific human spatial abilities. Computational approaches are available by which many specific functions of spatial cognition can be technically realized. However, little is known about the *interrelationship* of specific processes and how they should be combined to solve complex spatial tasks. The *integration* of computational solutions for assisting different cognitive functions in the spatial domain has been identified as a central and difficult problem.

The integration problem appears in virtually all fields of spatial cognition research. Spatial navigation, for instance, calls for the integration of local and global knowledge such as partial views of the environment and surveys provided by maps. Qualitative spatial reasoning requires the integration of topological, ordinal, and metrical information in a unified relational reasoning formalism whose computational properties have been made explicit. Diagrammatic reasoning needs the integration of internal (mental) and external representations as well as the integration of propositional and pictorial representation formats. And communication about space is impossible without integration of spatial, conceptual, and linguistic representations.

In all these areas, integration cannot be achieved by simple composition. Applying multiple computational realizations of a cognitive function in parallel simply shifts the problem to the integration of the results. But once more the technical issues are closely related to the integration of spatial information in the human cognitive system. In the future, new experimental paradigms from cognitive psychology and brain imaging studies from cognitive neuroscience are expected to give rise to a deeper understanding of how the human mind/brain manages the interaction between different subsystems involved in spatial cognition. For instance, we know today, that there is a single biological architecture for spatial perception and for spatial imagination rather than two independent systems. Both cognitive functions are realized by a unified architecture that uses shared subsystems for storing and transforming visuo-spatial information (e.g. Kosslyn, 1994). This leads us to propose a comparable architecture for technical systems: assistance systems for complex spatial tasks cannot be built by simply composing existing computational approaches. Spatial cognition research in the future will increasingly focus on the integration of spatial representations to build multifunctional spatial assistance systems.

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