Spatial Cognition: The Role of Landmark, Route, and Survey Knowledge in Human and Robot Navigation[1]

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Abstract. The paper gives a brief overview of the interdisciplinary DFG priority program on spatial cognition and presents one specific theme which was the topic of a recent workshop in Göttingen in some more detail. A taxonomy of landmark, route, and survey knowledge for navigation tasks proposed at the workshop is presented. Different ways of acquiring route knowledge are discussed. The importance of employing different spatial reference systems for carrying out navigation tasks is emphasized. Basic mechanisms of spatial memory in human and animal navigation are presented. After outlining the fundamental representational issues, methodological issues in robot and human navigation are discussed. Three applications of spatial cognition research in navigation tasks are given to exemplify both technological relevance and human impact of basic research in cognition.

The German Priority Program on Spatial Cognition

Spatial cognition includes acquisition, organization, use, and revision of knowledge about spatial environments. The priority program on spatial cognition focuses on investigating and modeling natural cognitive systems engaged in representing and processing spatial knowledge and on theoretical issues involved. The research projects within the program engage in (1) empirical investigations on human spatial abilities; (2) theoretical investigations on the potential and limits of various approaches to representing and processing spatial knowledge; (3) modeling and implementing different representation and processing schemes and evaluating them with respect to their biological plausibility; and (4) investigating possibilities of applying spatial formalisms in the framework of computer-based systems (e.g. human-computer interfaces). The different approaches investigated are to be related to one another.

The work program of the initiative includes the following four areas of research:

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1 The priority program on spatial cognition by the Deutsche Forschungsgemeinschaft currently supports 15 interdisciplinary research projects at 13 research institutions (http://www.informatik.uni-hamburg.de/Raum).

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1. Basic concepts and basic processes. Topics to be investigated are spatial representations and their properties, especially questions like: What makes a representation a *spatial* representation? Which aspects of spatiality are needed for which types of tasks? What are the formal / mathematical properties of different spatial representations and which concepts of topology and geometry can be assumed for cognitive space?

2. Spatial representation and higher cognitive processes. This area of research is concerned with the relations between basic concepts and their use. It addresses questions like: How is spatial knowledge acquired, e.g. how is landmark knowledge transformed into route knowledge and into survey knowledge? What is the learnability of different representational formats?

3. Spatial representation and action. This area of research focuses on problems or tasks in which cognitive systems interact with their environment, i.e. they move in the environment or they influence the environment. Which types of spatial representation are suitable for navigation? Which types of inference processes are required for spatial orientation and which are required for planning action sequences?

4. Spatial representation and language. Natural language descriptions of spatial situations can be viewed as the linguistic image of mental / internal representations of these situations. In particular, this concerns the partial correspondence between the spatial inventory of natural language and the 'cognitive ontology' of space. In this framework, the following problem areas require attention (among others): Which cognitive entities can we assume to exist in the system of natural language (dimensionality, shape, orientation, …)?

The spatial cognition priority program is particularly oriented towards cognitively oriented subareas of computer science / artificial intelligence, psychology, linguistics, anthropology, and philosophy which are concerned with complex behavior in dealing with physical space. Due to the nature of the research tasks, project cooperations and interdisciplinary projects appear particularly promising (cf. Freksa & Habel 1990). In the following sections we present a specific example of interdisciplinary research which was the topic of a recent workshop held at the University of Göttingen[7].

Landmark, Route, and Survey Knowledge

Different forms and representations of spatial information can be identified in systems navigating in complex surroundings. One of the most common distinctions in spatial navigation research concerns the difference between landmark, route, and survey knowledge of an environment. Landmarks are unique objects at fixed locations, routes correspond to fixed sequences of locations as experienced in traversing a route; survey knowledge abstracts from specific sequences and integrates knowledge from different experiences into a single model. The main focus of the 1997 Göttingen workshop on landmark, route, and survey knowledge was to bring together the concepts used in robot navigation and psychological theories on human navigation and to discuss the differences between these forms of spatial knowledge. In addition, a common terminology was sought to ease communication in the interdisciplinary cooperation.

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A Taxonomy of Spatial Knowledge in Navigation Tasks

We present a hierarchical taxonomy of spatial knowledge based on navigational behaviors on which higher-level concepts are built. The model is intended as a framework for empirical investigations and results, for example about navigation performance and conjectured mental representations.

At the stage of basic behaviors and elementary navigation tactics two settings need to be distinguished: space, either open or enclosed, and networks of passages. Basic behaviors in a passage (e.g. a tunnel, a corridor, a trail) may be wall following, passage following (centered between walls, avoiding obstacles), turning into a designated passage at a junction, etc. Elementary navigation tactics can take advantage of the limited choice alternatives within a passage, e.g. n-way branching. A junction constitutes a decision point. Characteristic views, which depend on the direction at which the junction was approached, may be associated with the decision of selecting a particular passage. These views are characterized by local landmarks like prominent visual objects, odors, sounds, or tactile percepts if they are stable, fixed and persistent.

Elementary navigation tactics in space, on the other hand, include directional navigation (e.g. guided by a compass), dead reckoning (using a homing-vector accumulated from self movement), and celestial or landmark navigation. In landmark navigation, several landmarks are used to determine a relative target position by triangulation; thus, a view from a particular location corresponds to a specific configuration of landmarks. It is interesting to note that navigation tactics in space seem to be equally applicable to open or enclosed space (e.g. an ocean, a town square, a room). As in the other cases, animals are likely to use combined tactics to increase robustness.

Elementary navigation steps are highly task-dependent. This can be formalized by a pair (tactic, target designator), where the target designator captures the spatial knowledge needed to instantiate the general tactic and determines a tactical decision. The actual representation of a target designator and its reference system depends on the particular tactic. For example, for navigation in space a vector to the target relative to the present position and orientation could be used; for branching a particular view and branch designator would suffice.

In this view of tactical navigation, a route consists of a sequence of such navigation steps: $<$ (tactic, location designator) $>$ in the general case, and $<$ location designator $>$ in the specialized case of homogeneous application of the same tactic. In the general case, different tactics may be concatenated, e.g. homing towards the bee hive, followed by searching for the entry when in the vicinity of the target; or following a route through a city using different transportation media. Similarly, navigation in a network of roads may be combined with landmark navigation across an enclosed space such as a large crowded city square. Moreover, different navigation tactics may be combined to achieve a tactical goal, e.g. vector navigation and explorative navigation such as path finding in a maze of passages.

Strategic navigation includes planning. The point of reference, in this case, changes to that of an observer with survey knowledge. The most basic form seems to be a combination of routes (in particular for navigation in passages) into a net or directed graph. There are two ways in which routes might be combined. Either two target-location designators emanate from the same source-location but denote different targets or two (target) location designators lead to the same target-location but potentially emanate from different sources. Thus aliasing leads to a notion of location as a node in a route graph in which the edges are labeled with navigation tactics.

A route graph can thus be generalized to yield a map as a set of location abstractions as nodes and a set of tactic abstractions as edges. Different tactical aspects of navigation may lead to different maps with different kinds of abstractions for the spatial knowledge contained in locations by introducing topological or Cartesian relations. This abstract information contained in a map (or an overlay of several maps) will then have to be sufficient for re-constructing routes.

Acquisition of Route Knowledge

A psychological perspective further qualifies this taxonomy. We can distinguish different ways of acquiring route knowledge. Exposure to a route without additional information on the context or surroundings merely leads to a series of connections between a configuration of points. In this simple form of a route the surroundings are irrelevant. A more elaborate form of route knowledge might result by resorting to schemata. For example, one might know that a specific area consists mainly of single-street villages. Familiarity with any village of this kind includes knowledge that there usually is a main street from which roads lead off to the sides. This scheme or prototype can be enriched by specific features, like particularly noticeable thatched buildings or other salient features.

Route knowledge also is gained if one becomes familiar with the context of the surroundings. When following a familiar path one can look right and left and notice that there is a small park at the corner, or that a road runs parallel to the path followed. Having followed a route may also entail having stood at a junction, making a decision to go either right or left or straight ahead. Then the junction becomes a decision point. Another way to acquire route knowledge consists of combining parts of two or more known routes into a new route. Finally, route knowledge can be acquired by use of a street map.

On a more formal note, we can distinguish between the level of mental representations, the stimulus presentations that lead to those representations and the tasks or operations that can be performed due to the existence of mental representations. The relationship between the kind of stimuli and their mental representation needs to be examined through the use of these stimuli in navigation tasks (see Herrmann, 1993).

Our surroundings can be described as a multitude of pairs of places and objects. In respect to spatial knowledge these stimuli will be referred to as landmarks. Landmarks which are on or near a route will be labeled route marks in contrast to distant landmarks. To know which of these are mentally represented, the tasks that people perform regarding these entities have to be evaluated. For route marks we can further differentiate their function – whether they are decision relevant or irrelevant.

A route can be viewed as a sequence of objects or events. Sequences can either be continuous or discrete, and they can result from different sensory channels, i.e. they can be equivalent to a cognitive linearization. Picture sequences, decision sequences, glance sequences and movement sequences can be distinguished. Following a way can be seen as a movement sequence, examining the context at certain locations as a picture sequence. A decision sequence might consist of a sequence of right and left turns. An example of a glance sequence would be the continuing flow of images while walking through a town (see also Schweizer, 1997).

Mental maps, a term which will be used as generic term for various kinds of survey and map knowledge, can either be in "field perspective" or "observer perspective" (drawing on Nigro and Neisser's (1983) distinction between "field" and "observer memory"). Both kinds of mental representations may refer to the same configuration in the environment. The field perspective of this configuration is closely linked to perceptual experience. It occurs under the "egocentric perspective" in a retinomorphous reference system, that is, one perceives oneself in the environment (see also Herrmann, 1996). There is an "in front", a "behind", a "right" and a "left". The same scene can also be represented in observer perspective. The constellation is then represented from a point-of-view above it – from a bird's eye view (see also Cohen, 1989). In front and behind become above and below (Franklin, Tversky and Coon, 1992). With the terminology now introduced we can describe the transition from route to survey knowledge.

Landmarks are a necessary condition for the formation of decision sequences and picture sequences. These are discrete sequences, which will not yet be considered as routes. Route knowledge begins in field perspective. It requires that one can find the way from an arbitrary point on a route to another point further away on the route. This operation can only be performed unidirectionally. Route knowledge, however, can be elaborated by using operations of inversion or by recoding of field perspective to observer perspective (FO-recoding). In each case the result is a new route. Route knowledge after inversion is still in field perspective while it becomes observer perspective after FO-recoding. Therefore, three different kinds of routes in route knowledge can be distinguished: (a) the original route which was not elaborated and is in field perspective, (b) a route which was inverted and is also in field perspective, and (c) a route which was recoded and is now in observer perspective. Different kinds of survey knowledge result from the elaboration of the routes available in field or observer perspective.

The different forms of spatial knowledge introduced so far are closely linked to the tasks that they enable a person to perform. As mentioned earlier, only through these different behaviors can characteristics of mental representations be inferred. Knowledge about route marks should result in the reproduction of those route marks in memory tests. When asked to name single objects, this is often done in the order of acquisition (see also Herrmann et al., 1995). It may even be possible to estimate route distances from the number of route marks mentioned. Given route knowledge, it should be possible to find the way to a destination, and, after elaboration, to find the way back. It should also be possible to give judgments of directions on the route and estimates of distance. Survey knowledge should enable a person to find new ways. Euclidean distances and judgments of directions independent of the route taken should be possible once FO-recoding has taken place. These empirical predictions can be used to test what kind of mental representation a person has constructed while studying a route.

Spatial Reference Systems

Intuitively, route knowledge differs from survey knowledge in three main respects: (a) information is accessed sequentially as an ordered list of different locations, (b) the number of paths emanating from each location is small, and (c) an egocentric reference system is used to decide where to go from a given location (similar to the field perspective mentioned above). Survey knowledge, on the other hand, usually is regarded as an integrated form of representation with fast and route-independent access to individual locations. It enables the inference of spatial relationships between arbitrary pairs of locations and it is organized in a global, often allocentric coordinate system. In this dichotomy, a network of interconnected routes would not automatically be considered survey knowledge since the spatial relationship between arbitrary points might not be readily accessible. Conceivably, the shortest path between two points might consist of a large number of intermediate points.

The dichotomy of route and survey knowledge has received a great deal of attention in spatial cognition research. There are, however, problems associated with this classification. On one hand, spatial knowledge can be acquired sequentially within a global frame of reference. This is the case, for example, when an observer samples the contents of a map by fixating attention at different locations. It seems obvious that in this case survey knowledge is formed and the borders of the map are used as a two-dimensional reference system. On the other hand, an observer can easily acquire a form of survey knowledge of objects that surround him or her. In this case the representation formed is retrieved egocentrically, with the front-back axis more easily accessible than the left-right axis (e.g., Franklin, Tversky and Coon, 1992).

To complicate things even more, survey knowledge acquired through maps can be accessed faster and is less error prone when the observer is oriented in a particular way (orientation-dependent behavior), while in other cases, such as the representation of buildings on a college campus, orientation-independent access has been demonstrated (Sholl, 1987). It becomes apparent from this brief and incomplete list of problems, that the mere distinction between route and survey knowledge is insufficient to describe or explain the demonstrated performance in spatial cognition. An alternative would be the classification of spatial representations along different categories or dimensions, some of which have already been listed above: sequential vs. random access to spatial information, egocentric vs. allocentric reference systems, a single global vs. multiple local reference systems, and the orientation dependence of spatial representations. Other categories or dimensions might be added to this list.

A simple example might illustrate this. In his model of biological spatial navigation, Poucet (1993) introduces a hierarchy of three different stages in building a survey representation of the environment. At a first stage, different place representations are formed. Each has a different reference frame associated with it. At a second stage, the different place representations are linked to each other but retain their different reference frames (local chart). Only at a later stage the reference frames for the different place representations are changed to a common reference system. As should become clear, the different stages imply different behaviors (or tactics) that can be used to empirically test the characteristics of each proposed spatial representation. Spatial relations between random locations, for example, should be more easily accessible within a common reference frame than with multiple reference frames, while a global reference frame should be optimal.

Visual Navigation and Spatial Memory

In animal navigation research three basic mechanisms of spatial memory are usually distinguished: (1) *Path integration* or *dead reckoning* is the continuous update of the egocentric coordinates of the starting position based on instantaneous displacement and rotation data (see Maurer and Séguinot, 1995, for review). Odometry data are often taken from optic flow but other modalities such as proprioception (e.g., counting steps) may be involved as well. Since error accumulation is a problem, the use of global orientation information ("compasses", e.g., distant landmarks or the polarization pattern of the skylight) is advantageous. Path integration involves some kind of working memory in which only the current "home-vector" (coordinates of starting point) is represented, not the entire path. (2) *Piloting* occurs when approaching a place whose local position information matches a stored "snapshot". This mechanism requires long-term storage of the local position information, such as a view or snapshot visible at that point. From a comparison of the stored view with the current view, an approach direction can be derived. Moving in this direction will lead to a closer match between the two views (Cartwright & Collett 1982, Franz et al. 1997). (3) in *guidance* the recognized views (local position information) are associated to movements. Here, long-term memory of the local position information (view) is required as well. When recognized, it triggers an action, i.e. a movement or a behavioral routine. The existence of such associations has been shown in bees (Collett & Baron 1995) and humans (Gillner & Mallot 1997).

Using these basic mechanisms, different levels of complexity of spatial knowledge and behavior can be formulated. Concatenating individual steps of either piloting or guidance results in routes. These routes will be stereotyped and could be learnt in a reinforcement scheme. More biologically plausible, however, is instrumental learning, i.e., the learning of associations of actions with their expected results. This can be done step-by-step without pursuing a particular goal (latent learning). Instrumental learning entails an important extension of the two view-based mechanisms in that the respective consequences of each of a number of possible choices (either movements or snapshots to home to) are learnt. This offers the possibility of dealing with bifurcations and choosing among alternative actions. Thus, the routes or chains of steps can be extended to actual graphs which are a more complete representation of space, or cognitive map (Schölkopf & Mallot 1995, Franz et al. 1997). The overall behavior is no longer stereotyped but can be planned and adapted to different goals.

In recent psychophysical work, Gillner and Mallot (1997) have investigated the role of guidances, i.e., associations of views to movements, in human spatial memory. Subjects explored a virtual town with a hexagonal street raster ("Hexatown") simulated on a computer screen. Movements were ballistic turns (60 degrees left or right) or translations down a street leading to the next junction point; they were selected by hitting the left, right, or go button of a computer mouse. At each node of the raster, a unique object was simulated that could be used as position information. (i) In a route finding task, subjects were asked to find the shortest route to a given goal in Hexatown. About 30% of the subjects showed a distinct tendency to simply repeat their previous motion decision when returning to a view for the next time. By evaluating only the wrong decisions, it was assured that this persistence tendency was independent of the current goal. The persistence rate could be as high as 60% of all erroneous decisions. (ii) In a transposition experiment, subjects learned a (bi-directional) route to a goal and back. After learning, single buildings along the route were exchanged. Exchanges were either performed within places (i.e. among the three objects standing in the three angles of each junction) or across places. The movement decision at the replaced building was recorded and the trial was stopped to prevent relearning. 40 out of 43 subjects did not notice the replacements. Average movement decisions were weighted sums of the movements associated to the same objects during the training phase. In conclusion, subjects seem to store simple associations of views to movements, rather than more elaborate maps, at least for the initial stages of map learning. This finding is well in line with the view-graph approach to spatial memory.

Methodological Issues in Robot Navigation and Human Navigation Research

Although human and robot navigation differ substantially in many respects (sensory systems, available behaviors, long term memory and experience, etc.) the basic navigational issues are the same. This was amply demonstrated in the preceding sections. Thus, general theoretical and analytical approaches dealing with navigation in either context can easily be integrated. Differences exist primarily in two areas. While psychologists and biologists are concerned with understanding the mechanisms that enable humans and other organisms to navigate, the goals in robotics research are to provide robust and efficient means to achieve navigational skills in technical applications. Whether or not these are biologically plausible is not the main issue. On the other hand, robotics research usually has control over the amount of spatial information represented and the form of representation used. Empirical evaluation of the system therefore focuses on questions of efficiency and robustness of the proposed or *implemented* mechanisms whereas in psychological research empirical data is used to *infer* the underlying processes. Robotics, in this respect, is using a synthetic approach which is not available to psychology.

The two approaches complement one another in important ways: biological systems proof the existence of effective and efficient methods of orientation and navigation that can be used as helpful starting points in the construction of artificial systems for similar tasks. In synthetic approaches, on the other hand, we can isolate specific aspects and test hypotheses generated in empirical biological and psychological research. In addition, robotics research poses questions to be empirically investigated in the complex environments of biological systems. It also makes explicit the algorithms and representations as well as the technical problems associated with certain navigational strategies which can be used to restrict psychological theorizing to computationally and biologically plausible models. Thus, by approaching the open questions of spatial representations from both sides in a coordinated manner, we hope to identify the relevant issues more directly and find the missing pieces of the puzzle more quickly.

Applications

In this concluding section we are going to present three applied research projects that were discussed at the Göttingen workshop. Two projects on robot navigation and a third project on the external representation of spatial information for the blind will be briefly outlined.

The Navigating Wheelchair

An electric wheelchair that is equipped with a computer and several sensors is employed as a robotics platform. It is the objective of the Bremen group to determine the 3D-structure of the environment from images collected by a camera that is fitted to a pan-tilt-head with “structure from motion” image processing methods. The 3D-information can be used to extract certain features, e.g. corners or edges. Combinations of such features should be used as landmarks and route marks respectively. At present, only artificial 2D-marks are employed that are identified by an image processing algorithm.

An architecture with multiple layers has been chosen for the control system of the wheelchair. The architecture is strongly influenced by psychological models through interdisciplinary discussions within the DFG priority program. It consists of three levels: “basic behaviors”, “route knowledge” and “survey knowledge”. Several basic behaviors, e.g. wall-following and turn-into-door, form the basis of the navigation method. They enable the wheelchair to move in corridors and to enter and exit rooms. These basic behaviors are fairly robust against changes in the environment.

At the second level of the hierarchy, the environment is represented as a set of routes. A route is a static way from a starting position to a target place. The wheelchair can drive along such a route by a concatenation of different basic behaviors. Route marks are used to trigger the starting and changing of basic behaviors. Therefore, a route is represented as a sequence of basic behaviors and the route marks that trigger these behaviors.

As soon as the recognition of route marks is not only seen as a binary decision but as a process with a particular uncertainty, the representation of knowledge becomes more complex. To develop a solution for this problem, several psychological findings can be employed: for example, expected route marks can be detected with a higher probability than unexpected ones (directional effect). In that way, marks that have been recorded in sequence can support each other in the recognition process.

The autonomous generation of survey knowledge constitutes the third layer of the architecture. At this stage, knowledge about the spatial relationships between the routes is represented. On the basis of survey knowledge, new routes can be generated from multiple learned ones and shortcuts can be detected. The wheelchair can recognize that a particular segment of one route is also part of another route if the same sequence of route marks exists in both of them. Thus, routes can be combined into a graph that can be used to plan shortcuts as well as bypasses around obstacles. If no route knowledge is available dead reckoning must also be integrated into the navigation strategy to find shortcuts or bypasses by exploration.

Finding Short-Cuts in an Office Environment

Gutmann and Nebel deal with the acquisition of survey knowledge of an office floor plan by a Pioneer 1 mobile robot equipped with a SICK laser range finder. In their approach the robot stores range scans taken by the SICK range finder from different positions along a route through the office space together with its internal position information based on dead-reckoning. Through matching stored scans the positional information can be greatly enhanced. To allow the robot to find short-cuts and novel routes, the scans from each position are used to create a graph where the vertices are the scans with their corresponding scan positions. Between each pair of scans a weighted edge represents the number of common points between the two scans (termed visibility). For navigation the robot can then use the graph to search for a new path. A new path is determined by choosing edges with high visibility and thus a high probability of unobstructed movement. An optimal path is found by maximizing the product over all probabilities along the path.

Tactile Maps for Blind People

The specific difficulties for spatial navigation in the blind were discussed by Harder. While sighted people almost exclusively use vision for mobility tasks, such as navigation, the blind have to make use of different perceptual modalities. The serial component in their multimodal spatial information input is very important. Blind people rely on different strategies in navigation than the sighted, using more route marks than sighted and memorizing the shorter parts in between (Harder, 1993). A problem occurs when a blind person has to navigate in an unfamiliar environment since tactile maps are rare. One way to remedy this problem is pursued at the University of Magdeburg by developing technologies to produce task adopted tactile route maps from widely available geographical databases.

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