# Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition: Reasoning, Action, Interaction

## Sonderforschungsbereich/Transregio SFB/TR 8 Raumkognition: Schließen, Handeln, Interagieren

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Abstract englisch
The Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition was established by the German Science Foundation (DFG) at the universities of Bremen and Freiburg in January 2003. 13 Research projects pursue interdisciplinary research on intelligent spatial information processing. This article introduces the research field of spatial cognition and reports on aspects from cognitive psychology, cognitive robotics, linguistics, and artificial intelligence.

Abstract deutsch
Der Sonderforschungsbereich/ Transregio SFB/TR 8 Raumkognition wird seit Anfang 2003 von der Deutschen Forschungsgemeinschaft (DFG) an den Universitäten Bremen und Freiburg gefördert. 13 Projekte forschen interdisziplinär zu Fragen der intelligenten Verarbeitung räumlichen Wissens.

Dieser Artikel gibt einen Einblick in das Forschungsgebiet Raumkognition und berichtet über Arbeiten aus den Bereichen der kognitiven Psychologie, der kognitiven Robotik, der Linguistik sowie der Künstlichen Intelligenz.

Keywords/Schlagwörter
spatial cognition, mental reasoning, cognitive robotics, linguistic descriptions, knowledge integration, spatial assistance.
Raumkognition, räumliches Denken, kognitive Robotik, räumliche Sprachverarbeitung, Integration von Wissen, räumliche Assistenz.

# 1. Introduction

In January 2003, the German Science Foundation (DFG) established the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition at the Universities of Bremen and Freiburg. The center currently carries out 13 research projects in the research areas *Spatial Reasoning, Spatial Action,* and *Spatial Interaction.* Approximately 50 researchers are currently involved in the center.

The center is complemented by the International Quality Network on Spatial Cognition (IQN) that was established in 2002 by the German Academic Exchange Service (DAAD) with funds of the Future Investment Program (ZIP) of the German Federal Government. Approximately 30 universities worldwide engaged in spatial cognition research currently participate in this network.

The center and the network were established on the basis of the Spatial Cognition Priority Program funded by the DFG from 1996 to 2002, in which researchers from more than a dozen research institutions were involved across Germany. This program built up strong links to international projects and programs and participated in the joint organization of workshops, conferences, a book series [1], and a journal.

## 1.1 What is Spatial Cognition?

Many everyday situations are so easy for us to handle that we do not realize that they involve complex mental operations in our mind. However, when computer scientists working in the area of artificial intelligence attempt to replicate these abilities with computers and robots, we become aware of the types of functions that are required to achieve this performance.

Take for example spatial orientation. You leave work. On your way home you get the idea of stopping by a shop which has announced special offers on the radio. While you are still on your usual way home you think about how to deviate from your route to reach this shop. You only have partial information about your environment and about the position of the shop in your ‘mental data base’.

Nevertheless you are able – possibly with the help of other people – to develop a plan that enables you to find your destination.

What is going on here? You build up a mental map of your environment and you do this without visual access to the elements from which the map is constructed – sometimes even without ever having seen these elements! You do this while you move in your environment, that is, your own spatial relation to the environment changes and while it changes you follow up on your present location and your destination in the real environment.

On one hand, you ‘represent’ your spatial environment in your mental map; on the other hand, you employ your mental map to perform spatial inferences allowing you to carry out actions you have never performed before in this way. Finally, you are able to physically carry out these mentally conceived actions in the spatial environment, that is, you must establish a correspondence between your mental map and the physical environment and you must transpose your body movements to the position, orientation, and scale of this environment.

But this is not yet enough: you are also able to communicate with another person about your spatial environment (and sometimes you even may agree on it with her). To achieve this, not only mental maps need to be set into correspondence with real environments, but also the mental conceptions of different persons – or different ‘cognitive agents’, as cognitive scientists say to account for animals and robots as well – must be aligned.

## 1.2 Spatial Cognition: An Interdisciplinary Field of Research

Cognitive Science – to which Spatial Cognition belongs as a field of research – is not only concerned with human thinking and communication; rather, it is concerned with general principles and thought processes as they are used not only by humans and animals, but also by machines [2]. It is not our goal to abate human thinking and to replace it by intelligent machines – this would have fatal implications for the development of our brains. Rather, we want to augment human abilities and support humans in the exertion of their own capabilities through spatial assistance systems.

For this plan to succeed it is essential that human and machine – be it a computer or a robot – understand each other well. As we all know, we understand each other best, when we operate on the ‘same wavelength’. Translated to cognitive processes this means that the interaction partners require comparable and compatible concepts and structures of thought; it is not sufficient for them to use the same vocabulary. It has proven helpful to gear towards tried and tested structures and processes in nature rather than adapting human concepts to the needs of computers – although without any doubt the clear conceptions of informatics and computer science render most valuable assistance in inter-human communication about states of affairs.

Cognitive science in general and spatial cognition in particular are highly interdisciplinary research areas. All disciplines concerned with thinking or with spatial structures contribute. In the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition, the disciplines involved are artificial intelligence, theoretical informatics, robotics, cognitive psychology and neuropsychology, computational linguistics, biology, geography and cartography, architecture, and philosophy.

The different disciplines approach the object of research with a wide range of methodologies: within informatics, the range extends from the analysis of abstract information structures with respect to their computational properties to the implementation of spatial reasoning algorithms on computers and robots whose behavior can subsequently be analyzed empirically. Consequently, behavioral scientists can perform comparative studies between natural and artificial cognitive systems to identify characteristic differences.

In this way, certain properties of natural and artificial cognitive systems can be compared. The methods from the different disciplines complement one another in excellent ways: natural systems provide a proof of existence for certain cognitive capabilities – in the last decades, behavioral and neuroscientists have made much progress in understanding *how* these capabilities are achieved. Informatics, on the other hand, knows the architecture and the components from which computational structures are built precisely; to what extent the processes implemented by those structures correspond to natural cognitive processes is initially not so clear, however.

By comparing certain properties – for example the relative processing times for a variety of tasks in natural and artificial systems – interrelationships between the architectures of these systems and their processes can be explained effectively.

In the following, we report on psychological and neuropsychological issues, especially related to mental reasoning using diverse forms of representation and to brain imaging techniques. Then, we give a short overview on activities in cognitive robotics within the SFB/TR 8, followed by a section that discusses linguistic problems in spatial cognition research. Finally, we briefly sketch out the central overall goal of the SFB/TR 8 and the scenario used to integrate the diverse aspects of research pursued in the SFB/TR 8.

## 2. Psychological Issues

If researchers try to compare natural and artificial systems they are confronted with a serious challenge: the computer scientist has built the system and thus knows how it works. But how do we know how the human mind works? You might believe you can answer this question if you just reflect carefully enough on what happens in your head when you drive the way from your office to your home, if you study a map to find a new destination, or if you try to solve a complex spatial task, for instance, if you intend to purchase a new fitted kitchen and you have to find the optimal positions for the stove, the refrigerator, and the dishwasher.

In the best case, however, this reflection will tell you what you believe is happening in your head; but such introspection – the observation of one's own inner life – has almost nothing to do with your actual mental states. It also does not assist you if you try to understand the interrelationships between biological and technical implementations, how the processing of spatial information is effected by the natural or artificial architecture, or why biological systems perform so impressively well with spatial information.

The only way to gather such information – at least from the perspective of an experimental psychologist – is to conduct carefully designed experiments with human participants. Such experiments can use performance measures or neural activities as manifestation of the underlying mental representations and cognitive processes: How long does it take to solve the problem? How many errors are made? Which areas of the brain are activated? How often do human beings get lost on one route or the other?

This is only a small sample of what psychologists explore to get objective and quantitative indicators for human spatial cognition. From the many experimental discoveries of the last decades, one is of special importance for spatial cognition research: human spatial abilities do not rely on a single representation format. Humans – or better their cognitive systems – rely on different types of representations, and humans are very flexible in using one or the other type of representation depending on the requirements of the present problem.

In this respect, psychological results have had much influence on spatial cognition research, since psychologists questioned the orthodox view of artificial intelligence that representations built up from expressions of formal logics together with logical inference would be sufficient to exhibit intelligent behavior. Nowadays, spatial cognition systems rely on representations in the form of diagrams, sketches, maps, or images, and reasoning is described by means of procedures that construct, inspect, and manipulate such representations. From a psychological point of view such visuo-spatial representations and information from actual perception share (to a certain degree) common features. A special form of such representations is called "visual mental images". Based on numerous experimental findings, such representations are seen as structurally similar to real visual perceptions. They have a limited resolution, but individuals can scan and mentally manipulate them. And there is the impressive Perky effect, which is named after the German psychologist Cheves Perky. Perky in 1910 discovered for the first time that mental imagery supports visual perception and that people often merge images constructed in their heads with what is actually seen [3]. In other words, visual imagination can be so similar to real perceptions that they can be mistaken for the latter.

Evidence from recent brain imaging studies supports the role of visual and spatial representations in human spatial thinking. Brain imaging studies allow psychologists to determine and to visualize activity in the human brain that is related to problem solving by measuring differences in blood flow. A typical finding is illustrated in Fig. 1. In this experiment, human volunteers solved spatial reasoning problems while their brain activity was measured. The brighter a region in the image is depicted, the more cortical activity was measured during the experiment. 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 spatial representations. The lower three images show that reasoning with problems that are easy to visualize lead to additional activation in the back of the brain, an area that corresponds to the visual cortices. These areas are typically involved in visual representations in the form of mental images [4].

You now might argue that this experimental finding says exactly the same as your introspection does. If you ask people how they think about space, many of them indeed say that they rely on visual mental images. They often say that they form a mental picture and look at this picture through their ‘‘mind’s eyes’’ to find new information. However, there are at least three important aspects of such mental images that you will never consciously experience.

First, your “mental picture” is not a picture. The actual representation is much more abstract [5]. Imagine there would be something like a real picture in your head, then there most also be an “agent” who looks at this picture and tells you what it sees. But then you must imagine what you have heard and this must be inspected by another agent who tells you …, and so on. Obviously, there is no such “humunculus” in our brains.

The second lesson learned from psychological experiments is that prior knowledge can significantly influence which mental image is constructed and thus how efficiently a spatial reasoning problem is solved. Technically speaking, the abstract (logical) truth value of a spatial inference can be the same as the truth value of our prior knowledge – in this case the inference is supported. Or, the formal truth value conflicts with the truth value of the prior knowledge – then the inference is more difficult, which means it results in more errors or takes significantly longer. If an inference generated by a person is biased towards the truth value of the prior knowledge or even overwritten by it, this is called *belief bias* [6]. You will never experience this mental “bug”.

A third important discovery is that humans think in “preferences.” Many spatial problems of daily life have more than one solution. Often there are many ways to solve a problem, and from a logical point of view they are equally appropriate. Human beings, however, usually do not consider all possible solutions a problem might have.

Many studies have shown that whenever a spatial reasoning problem has multiple solutions, human beings focus on a subset of them (often just a single one), and this leads to erroneous conclusions and irrational decisions. Crucially, almost all individuals prefer and neglect the same solutions, and the preferred solutions are the ones that are easiest to visualize in the mental image [7]. Did you ever experience this mental “bottleneck”?

**Fig. 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), transversely (as if vertically cut through in parallel to the axis between the ears), and horizontally (as if 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 illustrating that individuals naturally construct visual images if the reasoning problem is easy to visualize (from [4]).

Cognitive psychologists use such findings in two ways: First, the findings provide guidelines for the design of technical systems. Why, for instance, should a spatial assistance system not also solve a problem by means of "preferred solutions" instead of searching the entire problems space? The second achievement of psychological studies is to define the "constraints" that a technical system must satisfy if is considered to work in a human-like fashion.

## 3. Robotics

Mobile robots are physical agents that need to reliably operate in their environment. Accordingly, the agents need the capability to navigate in the space, to reason about the state of their environment and to identify their own position in the environment. Furthermore, robots that are designed to fulfil service tasks for humans need the ability to communicate with their users. Finally, whenever a team of mobile robots is employed, the systems must be able to coordinate their navigation actions to prevent potential collisions and to most effectively carry out their tasks. Several projects within the SFB/TR 8 Spatial Cognition are concerned with mobile robots acting in space.

One question studied in the research center regards the acquisition of three-dimensional representations of the environment. In the past, the majority of research has focused on generating two-dimensional maps. Whereas three-dimensional models require a huge amount of memory, they have several advantages. The most important one is that they allow a mobile robot to reason about the three-dimensional structure of its environment when planning paths. Traditional techniques relying on two-dimensional maps only often yield sub-optimal paths or sometimes even fail to find a path although one exists. Furthermore, three-dimensional representations are necessary for planning manipulation actions.

One of the major challenges in the context of three-dimensional maps is the question of how to reduce their complexity. One particular problem studied within the SFB/TR 8 Spatial Cognition is the approximation of parts of three-dimensional range data by planar structures. We are especially interested in approaches that exploit background information. In typical buildings, for example, planar structures such as walls, floors, and ceilings are generally co-planar or perpendicular to each other. To utilize such constraints we have developed an algorithm that extracts planar structures from three-dimensional data and that simultaneously learns the typical directions of these planes [10]. When computing the parameters of the individual planes, our approach takes into account the information about the typical main directions. Experimental results suggest that the incorporation of these constraints produces more accurate models and at the same time supports the separation of objects from planar structures.

The task of extracting objects from the models is also an important research topic within this project. The knowledge about which objects are contained in a particular scene and where the individual objects are, is a major precondition for carrying out dialogs with users.

To acquire the three-dimensional data we have developed a mobile robot platform equipped with a manipulator. This manipulator carries a laser range scanner and a camera. This setup allows the robot to acquire highly detailed and colored three-dimensional maps (see Fig. 2). The advantage of this system over previously developed robots is the ability to flexibly move the scanner so that detailed and almost complete models can be acquired.

**Fig. 2.** A three-dimensional textured model of a corridor acquired by a robot.

A further research topic is the autonomous exploration of an environment using mobile robots. Here we study the question of how to control a potentially heterogeneous team of robots so that it effectively covers a previously unknown area. Strategies for efficient terrain coverage are important in various application domains including rescue, cleaning, mowing, and de-mining. In addition to the question of how to control the team of robots we also consider strategies for fusing the information obtained from the different robots. Additionally, we investigate techniques for gaze and attention control. So far, we have developed a decision-theoretic approach to control the actions of a mobile robot when learning a map of a so-far unknown environment [11]. Our approach simultaneously takes into account the uncertainty of the robot about its own position in the environment as well as its uncertainty about the state of the environment. Our algorithm especially considers so-called loop-closing actions that force the robot to re-visit previously known areas. These loop-closing actions help the mobile robot to re-localize itself in the map built up so far. In this way we avoid localization errors and obtain more accurate maps.

We have also developed a decision theoretic algorithm for controlling a team of mobile robots that explores an unknown environment [12]. This approach can deal with limited communication ranges and is able to handle situations in which the robots are temporally unable to communicate their maps and positions. An especially challenging problem in the context of multi-robot exploration is the situation in which the robots do not accurately know their relative positions, since this prevents them from building a joint and consistent map. To deal with this problem, we developed an algorithm that is able to reduce the relative pose uncertainties of the individual robots and in this way to avoid inconsistencies.

**Fig. 3.** Model of the robot to be developed within the SFB/TR 8 Spatial Cognition.

Cognitive function in humans is also a result of the extremely complex kinematic capabilities that we posses. Grasping for and manipulating objects, bending down and up, or sitting down on objects are examples of kinematic capabilities or motor skills. These motor skills play a fundamental role in representing the environment, in forming concepts about the environment, and in reasoning about constituting relations of objects, including ourselves, within the environment. Within the research center we are developing a multifunctional four legged/armed robot that is kinematically capable of walking and climbing either on four or on two legs/arms as well as being able to grasp and manipulate objects (see Fig. 3). The robot will be equipped with a camera system as well as with distance measurement sensors (such as ultrasound and infrared sensors) in its 2-degree of freedom head segment. Additionally, the system comprises tactile sensors integrated in the hands/feet. This robot will serve as a test bed for the implementation, test, and evaluation of a hybrid architecture for spatial learning, representation, and navigation control. We also want to investigate the role of manipulation acts in understanding spatial geometries as well as the interplay of complex motor acts (behaviors) and perceptual structures for robot exploration. The goal is to develop a hybrid architecture that allows the control of spatial learning and representation techniques and their integration with the ability to explore and navigate unknown space by a mobile robot.

## 4. Space and Language

Space and language are intimately connected. If we consider the problem of finding some particular room in a complicated, and perhaps changing, office complex, it is obvious that no simple set of three-dimensional coordinates from a GPS system would be effective. Similarly when we consider route planning and navigation aids, what is required is an effective route description that takes into account just what the user needs to know, when they need to know it.

But it is here that the real problems start. To focus on the office scenario, which is just one of the areas that we are examining in depth in the research center, we need to know that the 'best' route may depend on the time of day (for example, if there is a congress which might lead to certain routes being blocked), on the purpose of following the route (if it is an emergency then certain otherwise not available routes may become available), and on the possibilities for movement that the user has (for example, a user in a wheelchair may need to be guided along different routes to one who is not).

But even more than this, a good route description needs to be responsive to the state of knowledge of the user: it is worse than useless giving a route description that builds on information that the user does not have access to. It is also far from ideal to always assume that the user knows virtually nothing and so to give over-precise instructions. In contexts where one can assume a generic state of knowledge shared by the majority of users (for example, in car navigation systems), the problem is far simpler. When we move away from these rigid scenarios, the importance of being responsive to the particular needs, abilities and knowledge of the user comes dramatically to the fore.

Experiences in AI with expert systems have shown that users are very much more likely to accept recommendations made if the system can justify its statements. This means, not only to state that something is the case but to back it up with reasons and motivations. The appropriate reasons and motivations again depend entirely on particularities of the user. For example, the user may know that the quickest way to the meeting room on the fifth floor is through this particular corridor and with that particular elevator. But that user might not know that just this morning this particular elevator is undergoing maintenance. It is then essential for a route description to state this explicitly in its recommendations: that is, not to say "the best way is along this corridor and then right" but "the best way is along this corridor and then left because the elevator is being serviced". Without such motivations, the trust of the user in the system is automatically reduced because it appears, at first, to be giving less than accurate information.

Flexibility to this degree demands not only that a computational system be able to express in natural human language concepts involving space and routes, but also that it is able to engage in dialogue with its users. Since an appropriate response, such as a good route description, depends on the goals of the user, the system must be able to ask clarifying questions to users if their goals are not clear. The system must also be able to provide explanations for its recommendations and actions should the user not understand just why some particular course of action is being recommended or pursued.

This kind of functionality extends the possibilities for interaction between computational system and user significantly. For example, although finding one's way is often achieved with the support of maps and other visual aids, there are always situations where this is not possible. In emergency situations, such as during a fire where visibility is restricted by smoke, following a map would be difficult (and dangerous as the layout of the building changes). Also, in situations where the user is already dealing with considerable visual input, providing additional route description via maps can lead to dangerous information overload. And, of course, if the user does not have good eyesight, then a strictly visual navigational aid is of little help. In these and similar cases, dialogic communication between system and user can rely more effectively on spoken natural language.

But the move to dialogue brings its own challenges and problems. When we investigate how humans interact concerning space, since these are our best models of how this can be done most naturally and effectively, we see a degree of flexibility that is still well beyond the capabilities of artificial agents of any kind. Dialogue entails negotiation: negotiation of the aims of the dialogue, of the terms that are to be used, of how even space is to be conceptualized. Interlocutors in a speech situation do not suddenly change their perspectives so that, for example, 'right' (my right) suddenly becomes 'left' (your left), even though from the 'facts of the matter' both might be adequate descriptions. The very meaning of spatial terms as used in natural dialogues also appears to depend strongly on what the terms are being used for, what the goals of their users are, and what the terms are referring to.

Turning to interaction with artificial agents brings the sophistication of this kind of communication into sharp relief. Human interlocutors are generally able to work out well what is meant: robot interlocutors are left, on the other hand, with severe difficulties. A robot has to know that moving to a position 'in front of the TV' implies a very different notion of distance to that involved in moving 'in front of the football ground' in order to meet someone. This variability is inherent in the way linguistic descriptions work, and much fundamental work needs to be done in order to tease out just how this variability can be restricted and understood. Robotic agents also present challenges for dialogic interaction because of their very different perceptual capabilities. Whereas for a robot, establishing that a solid object is exactly 3.56 meters away is often straightforward, the corresponding linguistic description "the object 3.56 m ahead" is for most users less than helpful. Conversely, a natural description for a human user, such as "just in front of the door" requires a complex interpretation on the side of the robot: can it recognize 'doors'? What is 'in front of' in this context? How 'just' is 'just'? etc.

It is then essential for robotic agent and human user to be able to negotiate a 'common wavelength' if joint solutions for tasks are to be achieved effectively. With this in mind, we are currently investigating empirically within the SFB/TR 8 Spatial Cognition how particular spatial configurations are best communicated between robots and human users with different goals and perceptions, and how the particular preconceptions that users have concerning the abilities of the robots influence (sometimes quite negatively) their dialogic strategies. This research also aims at making the interaction run more smoothly by providing the robotic agents with the ability to give subtle clues concerning just what they can perceive and what not. These clues are then built into their linguistic utterances in very much the same way as we now know human interlocutors to do.

In order to meet these challenges, it is necessary to adopt an intensively interdisciplinary approach. Technical and formal specifications of computational systems must also be combined with traditionally non-technical approaches to language, particularly those concerned with dialogic interaction and strategies for successful and effective communication. We are also bringing to bear the rich tradition of work on how language constructs views of space, and how this is different and similar across different languages and cultures. This lets us address issues of the mental representation of space from a further, linguistically motivated perspective. The confluence of theories of very different origins, and their practical application within functioning computational systems, opens up many new opportunities and shows how more abstract information about how language functions is now having a direct bearing on very practical questions of computational implementation.

## 5. Goals and Perspectives

As a result of research activities both inside and outside the SFB/TR 8, numerous results related to partial problems of spatial cognition have already been obtained. However, the integration of the different spatial competences for solving complex real-world tasks has been recognized as a central and difficult research problem.

## 5.1 The Integration Problem

The difficulty of this *integration problem* is due to the fact that spatial tasks performed in the real world are not based on just a single activity, but rather a set of interrelated spatial tasks have to be coordinated, for example to perform route planning and navigation tasks.

This integration, however, cannot be achieved by simply composing the diverse partial solutions. Rather, the problem has to be addressed at the root. The technical issue of finding an integrated system design corresponds to a class of problems that has been identified in several areas of spatial cognition research: the *integration* and *specialization* of spatial representations and processing mechanisms [8, 9]. Both aspects of the problem are addressed in the SFB/TR 8 Spatial Cognition.

As a scenario for the integration of specialized results from spatial cognition research, the idea of providing spatial task assistance to agents interacting in complex, variable environments is used in the research center.

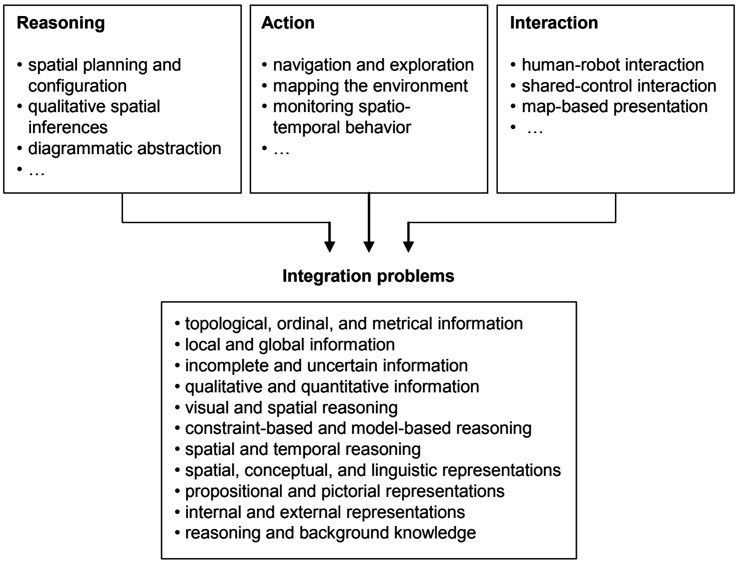

**Fig. 4.** Integration problems and their relation to spatial assistance tasks with respect to the three research areas *Reasoning*, *Action*, and *Interaction* in the SFB/TR 8.

## 5.2 Spatial Task Assistance for Variable Environments

Consider a large building complex, in which people, autonomous robots, or information facilities move around and/or interact with each other. Examples for such an environment may be conference buildings, exhibition grounds, or smart office buildings. Spatial task assistance in such an environment requires a thorough understanding of the interplay between natural and artificial cognitive systems, between internal and external representations, between visuo-spatial information and information from other perceptual modalities, between spatial inference and background knowledge, and so on. This framework is illustrated in Fig. 4. The figure indicates that the design of any system that performs complex spatial assistance tasks requires that several, if not all, of the core integration problems are solved.

The spatial task assistance paradigm provides a rich framework for the study of integration and specialization requirements. The overall goal of the SFB/TR 8 is the integration of scientific competence for reasoning about space, for acting in space intelligently, and for interacting in spatial environments.

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