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Cognitive Space and Spatial Cognition

The SFB/TR 8 Spatial Cognition*

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Abstract Space and time are two of the most fundamental categories any human, animal, or other cognitive agent such as an autonomous robot has to deal with. They need to perceive their environments, make sense of their perceptions, and make interactions as embodied entities with other agents and their environment. The theoretical foundations and practical implications have been investigated from a cognitive perspective (i.e., from an information processing point of view) within the DFG-funded *Sonderforschungsbereich/Transregio SFB/TR 8 Spatial Cognition* over the past twelve years jointly by the Universities of Bremen and Freiburg. The research covered fundamental questions: what are the specific requirements of reasoning *about* space and time, for acting *in* space, and for any form of interaction including communication in spatio-temporal domains? It has been a success story in all research lines from foundational research to applications of spatial cognition in robotics, interaction and communication. The SFB/TR 8 actually shaped a new research field by extending a previous subfield of cognitive science with its own interdisciplinary techniques.

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1 Introduction

Whenever and *whereever* we are – we are always located in space and time. We do not need to be conscious, alert, or do any action: space and time are two of the most fundamental categories of our pure existence. This holds for any cognitive agent, be it artificial or natural.

Movement in space is one of the most fundamental actions any agent can perform. Further, we often do reason about space and time. Both reasoning and movement require to represent and process spatio-temporal information to find our way. Often learning of new spatial structures is involved, such as a landscape, streets of a city, a path in a large building or simply a layout or a map. A successful interaction with space requires to infer locations of objects, and agents need to be able to manipulate objects physically and mentally.

Biological agents like humans and animals have developed the abilities to reason about space and time, to navigate through known and unknown environments without getting lost, to self-localize, and to communicate spatio-temporal information. Technical systems, in contrast, are much worse at these task compared with biological systems. To enhance a technical system's spatial cognition, the task seems to be easy at a first look: Why not simply identify and transfer the spatial cognition of humans and to some extent of other animals to technical systems? This requires to understand – in an implementable way – how humans perceive and reason about space. However, this is besides all progress still a non-trivial research question.

To tackle this question requires neuroscientific, behavioral, and psychological experiments to uncover behavioral regularities of humans while dealing with spatio-temporal problems. In a next step we need to develop cognitive and computational models, systems that are able to explain and predict empirical findings and regularities. We need to understand the formal aspects and computational complexity of qualitative knowledge representations and reasoning, as well. Additionally, as we often encounter multi-agent scenarios we need to take the communication of spatial information into account. Known challenges about the self-localization problem (SLAM) as well as perception and the interpretation of perception are pertinent research questions. The major challenge of the SFB/TR 8 was how human cognitive abilities can be accomplished by technical systems, and especially how to interpret existing spatial structures in order to transform them computationally into new structures representing new knowledge and insights.

2 Spatial Cognition Research

The investigation of information processing aspects of space and time leads to the question in which ways and to what extent the pertinent structures of space support or impede cognitive processing and intelligent decision-making: on one hand, these structures are quite specific and may bias more general cognitive abilities such as abstract thinking; on the other hand, spatio-temporal information processing structures may be aligned with the spatial and temporal structures that cognitive agents are immersed in; thus spatial cognition may perfectly support cognitive agents in what they need to do. In the SFB/TR 8, spatial cognition has been studied in a variety of ways (cp. Fig. 1): empirical cognitive psychology and cognitive systems research investigate spatial abilities of humans and autonomous robots such as spatial orientation and wayfinding; this research explores what kind of cognitive resources (perception, memory, reasoning, communication, action) are employed to perform on spatial tasks. Spatial cognition also has been studied on the theoretical level of logics and mathematics: which kinds of information are required to solve certain spatial tasks and what is the computational complexity of solving spatial tasks in certain knowledge

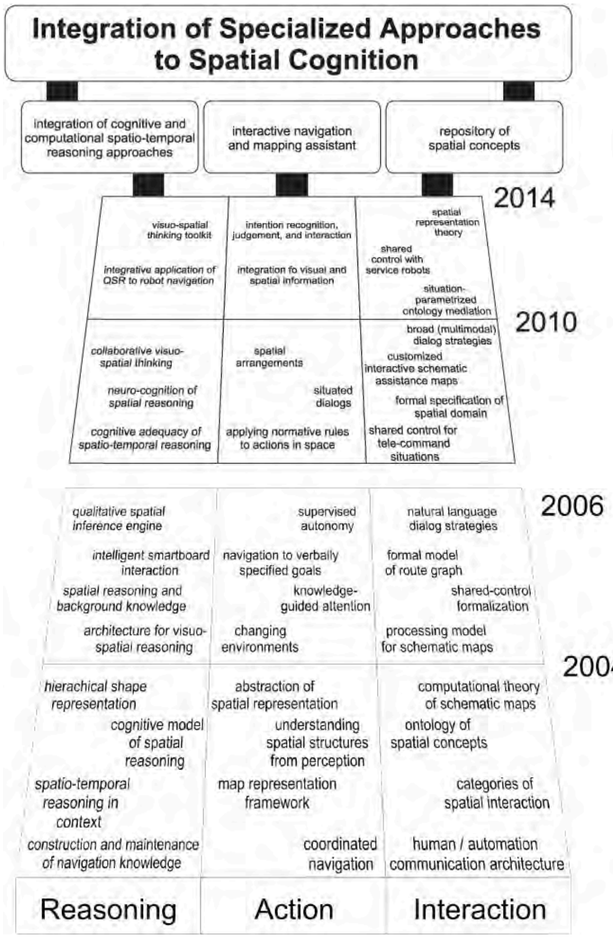

Fig. 1 The roadmap of the SFB/TR 8 over twelve years.

representation structures? Research in the SFB/TR 8 focused on high-level computational aspects of spatial cognition and was structured into three research areas (cp. Fig. 1):

- The *reasoning area* comprised projects concerned with mental and formal representations of space and with inference processes using these representations;
- The *action area* comprised projects that are concerned with the acquisition of information from spatial environments and with actions and behavior in these environments;
- The *interaction area* comprised projects that are concerned with communication about space by means of language and maps; it addresses presentation formats and interfaces for the exchange of spatial information between cognitive agents.

2.1 Which research questions have been approached by the SFB/TR 8?

Spatial cognition can be regarded as an *exemplary domain of cognition* in general, i.e., all relevant aspects and problems of cognition can – to some extent – be found in spatial cognition. Over the duration of the SFB/TR 8 the notion of spatial cognition has undergone a significant change. Having been a subdiscipline of (mainly psychologically dominated) cognitive science, spatial cognition has become an interdisciplinary field of research of its own. In this development, the SFB/TR 8 has played a key role and has gained recognition as an internationally renowned research institution. Supported by the interdisciplinary nature of the SFB/TR 8, the field of spatial cognition is now understood as a truly interdisciplinary research field with informatics, artificial intelligence, cognitive psychology, linguistics, and cognitive geography as the main contributing disciplines, besides others. Moreover, it is not just the established disciplines that now contribute to spatial cognition research but also numerous subfields that provide innovative research methodologies, among them formal methods, various types of robotics, semantics, innovative empirical techniques, and many more.

Through the research over the twelve-year duration of the SFB/TR 8, much has been learned about the use of space, spatial structures, and the various potential descriptions of these. The multi-methodological approach has led to many research results. These range from how humans internally represent spatial information [16,14] and process this information neurally [13], over formal representation for behavior of processes, e.g., vessel movements [19], to better navigation strategies for humans [10] and for robots [20]. Furthermore, spatial reasoning methods in different knowledge representation paradigms [7,18,15,5,12] over estimation of 3D-orientation from sensor data [8] and new frameworks (particle filter based approach, optimization based approach) for map building in robots [9,3] and humans [11] have been systematically analyzed. This also comprised frameworks for spatially situated dialogue interaction [1,17], integrating planning [4], and design questions [2] to name only a few.

Spatial cognition also has been studied on the level of technical construction in artificial intelligence: based on the theories of spatial cognition we can build artifacts that implement exactly those aspects of perception, memory, information processing, communication, and action that are hypothesized to be responsible for intelligent processing of spatial information.

A special feature of the synthetic constructive approach is that we can build virtual worlds that violate certain spatial structures of physical spatial worlds; this allows for testing theories about processing spatial information in ways in which they cannot be tested by conventional methods in physical space. Furthermore, we must critically scrutinize the objectives of spatial cognition: what is the set of tasks or other occupations that are pursued by a cognitive system? This kind of question has been investigated by looking at specific application domains like communication about space (cognitive linguistics), making maps that effectively and efficiently permit wayfinding (cognitive geography), or constructing physical spaces that serve specific functions (cognitive architecture). This allows us to measure cognitive performance with respect to well-defined goals.

2.2 Application scenarios and transfer projects

The SFB/TR 8 has not only concentrated on theoretical foundations and basic research, it has also considered various application scenarios. It has inspired projects on navigation assistance for elderly people and people with dementia, projects on design assistance, theoretical and practical implementations of tools for heterogeneous ontological engineering.

Over the duration of the SFB/TR 8, two transfer projects were initiated: The first project's objective was the design and development of a safe speech-controlled wheelchair with driving assistance. The project aimed at increasing mobility and autonomy of users who are presently unable to safely operate an electrical wheelchair. The driving assistance compensates manual impairment, for instance by avoiding obstacles and passing through doorways, or supports users who cannot continuously control the wheelchair but can give intermittent discrete commands [6]. To prove the effectiveness of the system, a clinical study in cooperation with Neurologisches Rehabilitationszentrum Friedehorst was conducted.

The second idea of a transfer project grew out of a cooperation with Fraport AG. The design division at Fraport was interested in optimizing the signage at Frankfurt airport and the SFB/TR 8 was able to provide methodology and expertise in terms of eye tracking and virtual reality techniques. First exploratory studies showed that this endeavor appeared to be interesting for both parties and has lead to a recent application.

3 Outlook: What will be future research activities in the field of Spatial Cognition?

3.1 New research questions

The work pursued over the duration of the SFB/TR 8 raised numerous new research questions. In autonomous robotics, for instance, a move from geometry-oriented to more semantics-driven reasoning has been pursued. Also, dealing with dynamics and changing spatial situations will be taken into focus of future robotics research. In humanoid robotics, the vision of developing fluently acting robots with a more natural real-time behavior will be an appealing field of research in the future.

In the research field of planning in computer science there is a strong need of bridging the gap between symbolic and continuous approaches to planning. Also, situation-dependent criteria to decide which method of planning is best employed in a given problem or task need to be devised. The application of spatial cognition results in navigation assistance systems for people with cognitive and motoric impairments has been identified as a fruitful domain for future product-oriented developments. From a more theoretical point of view, results obtained in spatial cognition research can be employed in the investigation and for the understanding of a wide variety of media and information artifacts like film, pieces of architecture, maps, diagrams, sketches, and even interactive situations like meetings or unstructured interaction patterns between people as well as people and machines. The field of design cognition offers a wide field of research questions and application perspectives for providing technical assistance to designers of spatial environments and architectural artifacts. Also, investigating and modeling the use of signs and signage will need more thorough attention in future research. And, last but not least, the field of spatial cognition provides exciting new opportunities for employing physical spatial substrates in interactive spatial scenarios and in the combination with abstract processes of spatial computation.

3.2 Cooperative Research

Jointly with the International Spatial Cognition Quality Network (IQN), the SFB/TR 8 gained considerable international visibility. This visibility was a factor in the establishment of the NSF Spatial Intelligence and Learning Center in 2006. With this center, the SFB/TR 8 engaged into a strategic partnership and shared / cosponsored the international Spatial Cognition conference series that had been established by the SFB/TR 8, as well as other scientific activities. Together with the UCSB Center of Spatial Studies, the SFB/TR 8 continued the highly visible International Spatial Cognition Summer Institute it had established in 2003. Numerous excellent researchers in the vicinity of spatial cognition at additional research centers worldwide are connected in the IQN whose hub was located in the SFB/TR 8.

Spatial cognition is a vibrant and exciting field and will continue despite the official ending of the SFB/TR 8. Its importance can be shown by the last years Nobel prize winners J. O'Keefe, M. Moser, and E. Moser for their discoveries of cells that constitute a positioning system in the brain or on new SFBs such as the SFB/TR 62[1]. Adopting Feynmans dictum: "What I cannot create I do not understand"[2] reveals that there is still a way to go until we will have obtained enough understanding to create artificial cognitive agents that have comparable spatial cognitive abilities, thus sharing our cognitive space as equals.

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References

1. Bateman, J.A., Hois, J., Ross, R., Tenbrink, T.: A linguistic ontology of space for natural language processing. Artificial Intelligence **174**(14), 1027–1071 (2010)
2. Bhatt, M., Schultz, C., Freksa, C.: The 'Space' in Spatial Assistance Systems: Conception, Formalisation, and Computation. Book: Representing Space in Cognition: Behaviour, Language, and Formal Models., pp. 171–214. Series: Explorations in Language and Space. Oxford University Press (2013)
3. Burgard, W., Moors, M., Stachniss, C., Schneider, F.E.: Coordinated multi-robot exploration. Robotics, IEEE Transactions on **21**(3), 376–386 (2005)

[1] `www.sfb-trr-62.de/`

[2] `http://archives.caltech.edu/pictures/1.10-29.jpg`

4. Dornhege, C., Gissler, M., Teschner, M., Nebel, B.: Integrating symbolic and geometric planning for mobile manipulation. In: Safety, Security & Rescue Robotics (SSRR), 2009 IEEE International Workshop on, pp. 1–6. IEEE (2009)
5. Dylla, F., Wallgrün, J.O.: Qualitative spatial reasoning with conceptual neighborhoods for agent control. Journal of Intelligent and Robotic Systems **48**(1), 55–78 (2007)
6. Fischer, C., Shi, H., Jian, C., Schafmeister, F., Menrad, N., von Steinbüchel, N., Schill, K., Krieg-Brückner, B.: Modelling user behaviour while driving an intelligent wheelchair. In: A.L.N. Fred, J. Filipe, H. Gamboa (eds.) HEALTHINF 2010 - Proceedings of the Third International Conference on Health Informatics, Valencia, Spain, January 20-23, 2010, pp. 330–336. INSTICC Press (2010)
7. Gantner, Z., Westphal, M., Wölfl, S.: GQR-A fast reasoner for binary qualitative constraint calculi. In: Proc. of AAAI, vol. 8 (2008)
8. Grisetti, G., Kummerle, R., Stachniss, C., Frese, U., Hertzberg, C.: Hierarchical optimization on manifolds for online 2d and 3d mapping. In: Robotics and Automation (ICRA), 2010 IEEE International Conference on, pp. 273–278. IEEE (2010)
9. Grisetti, G., Stachniss, C., Burgard, W.: Improved techniques for grid mapping with Rao-Blackwellized particle filters. IEEE Transactions on Robotics **23**(1), 34–46 (2007)
10. Hölscher, C., Tenbrink, T., Wiener, J.M.: Would you follow your own route description? cognitive strategies in urban route planning. Cognition **121**(2), 228–247 (2011)
11. Klippel, A., Richter, K.F., Barkowsky, T., Freksa, C.: The cognitive reality of schematic maps. In: Map-based mobile services: theories, methods and implementations, pp. 57–74. Springer Verlag (2005)
12. Mossakowski, T., Moratz, R.: Qualitative reasoning about relative direction of oriented points. Artificial Intelligence **180**, 34–45 (2012)
13. Ragni, M., Fangmeier, T., Brüssow, S.: Deductive spatial reasoning: From neurological evidence to a cognitive model. In: Proceedings of the 10th international conference on cognitive modeling, pp. 193–198 (2010)
14. Ragni, M., Knauff, M.: A theory and a computational model of spatial reasoning with preferred mental models. (2013)
15. Renz, J., Nebel, B.: Qualitative spatial reasoning using constraint calculi. In: Handbook of spatial logics, pp. 161–215. Springer (2007)
16. Schultheis, H., Barkowsky, T.: Casimir: An architecture for mental spatial knowledge processing. topiCS - Topics in Cognitive Science **3**, 778–795 (2011). Issue on Modeling Spatial Cognition
17. Tenbrink, T.: Space, Time, and the Use of Language: An Investigation of Relationships. Cognitive Linguistics Research [CLR]. De Gruyter (2007)
18. Wallgrün, J.O., Frommberger, L., Wolter, D., Dylla, F., Freksa, C.: Qualitative spatial representation and reasoning in the SparQ-toolbox. In: Spatial Cognition V Reasoning, Action, Interaction, pp. 39–58. Springer Berlin Heidelberg (2007)
19. Wolter, D., Dylla, F., Wölfl, S., Wallgrün, J.O., Frommberger, L., Nebel, B., Freksa, C.: Sailaway: Spatial cognition in sea navigation. KI **22**(1), 28–30 (2008). URL http://www.kuenstliche-intelligenz.de/fileadmin/template/main/archiv/pdf/ki2008-01_page28_web_teaser.pdf
20. Wurm, K., Dornhege, C., Eyerich, P., Stachniss, C., Nebel, B., Burgard, W.: Coordinated exploration with marsupial teams of robots using temporal symbolic planning. In: Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS). Taipei, Taiwan (2010). DOI 10.1109/IROS.2010.5649820. URL http://ais.informatik.uni-freiburg.de/publications/papers/wurm10iros.pdf

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