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Introduction to the Topic on Modeling Spatial Cognition

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Abstract

Our ability to process spatial information is fundamental for understanding and interacting with the environment, and it pervades other components of cognitive functioning from language to mathematics. Moreover, technological advances have produced new capabilities that have created research opportunities and astonishing applications. In this Topic on Modeling Spatial Cognition, research crossing a variety of disciplines and methodologies is described, all focused on developing models to represent the capacities and limitations of human spatial cognition.

Keywords: Spatial cognition; Cognitive model

Tolman (1948) is often credited as the origin of modern psychological research on spatial cognition. In the more than six decades of empirical, neurophysiological, and computational investigation since then, tremendous progress has been made in understanding the capabilities and limitations of human spatial information processing. A combination of technological advancement and important practical problems has given rise to an increased focus on understanding human spatial processing in the last 15 years. For instance, astonishing new applications, like Google Earth® and in-car navigation devices, offer unprecedented access to geographical data, while creating significant demand for research to generate ideas about human spatial cognition to drive development and design.

Technology has also led to rapid advancements in virtual environments, which can provide an alternative to maps or real navigation for acquiring information about a space (e.g., Richardson, Montello, & Hegarty, 1999), and have been used extensively to investigate various spatial phenomena (e.g., Hartley, Trinkler, & Burgess, 2004; Jacobs, Thomas, Laurance, & Nadel, 1998; Kelly & Bischof, 2008; Kelly, McNamara, Bodenheimer, Carr, & Reiser, 2009). More generally, immersive experience and teleoperation have important

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implications in areas as diverse as laparoscopic surgery (e.g., Keehner, Lippa, Montello, Tendick, & Hegarty, 2006) and piloting unmanned aerial vehicles (UAVs; e.g., Gluck et al., 2005).

Technological innovation is also apparent in robotics, where sophisticated artificial systems that can navigate through the environment create a need for efficient and effective mechanisms for representing and processing spatial information. To be useful, robots must be able to move through the environment without running into things (collision avoidance), and they must also be able to develop enduring representations of the layout of environment to enable robust navigation. Some approaches to addressing this challenge are both inspired by, and potentially contribute to, our understanding of human representation and processing of spatial information (e.g., Kuipers, 2008;Yeap & Jefferies, 2000).

Finally, the rise of brain imaging techniques for monitoring and localizing ongoing cognitive processing has offered a window into the neural pathways and mechanisms that are critical in human spatial information processing (e.g., Burgess, Maguire, & O'Keefe, 2002; Ekstrom et al., 2003; Haxby et al., 1991; Kosslyn, 1994). This has led to important insights regarding human spatial processing, and it has enabled critical comparisons to neural findings from research on other animals (e.g., Burgess, Jeffery, & O'Keefe, 1999; O'Keefe & Nadel, 1978; Tolman, 1948; Ungerleider & Mishkin, 1982).

Modeling spatial cognition

The impact of technology merely accentuates the critical role of spatial information processing in human cognition. It is clear that spatial information processing is brought to bear across a diverse range of human activities. From seemingly trivial acts like reaching for and grasping a mug (e.g., Mulliken, Musallam, & Andersen, 2008; Zipser & Andersen, 1988), to the challenge of maintaining a sense of orientation in a zero-G environment like that faced by astronauts on the International Space Station (Oman et al., 2000), representing and processing spatial information is critical to success. This is reflected in the diversity of approaches that have been adopted for investigating these processes. Tasks ranging from classic paradigms like mental rotation (e.g., Cooper & Shepard, 1975; Shepard & Metzler, 1971) and perspective-taking paradigms (e.g., Gunzelmann, 2008; Piaget & Inhelder, 1956; Sholl & Nolin, 1997; Wraga, Creem, & Proffitt, 2000), to naturalistic navigation (e.g., Dogu & Erkip, 2000; Malinowski & Gillespie, 2001) and spatial tasks in virtual environments (e.g., Aginsky, Harris, Rensink, & Beusmans, 1997; Dimperio, Gunzelmann, & Harris, 2008; Kelly & McNamara, 2008; Richardson et al., 1999) have been investigated to inform our understanding of the capacities and limitations of human spatial information processing. In addition, substantial research has focused on spatial processing of non-human animals, from monkeys (e.g., Cramer & Gallistel, 1997) and rats (e.g., O'Keefe & Nadel, 1978; Tolman, 1948), to pigeons (e.g., Keeton, 1969) and bees (e.g., von Frisch, 1967).

The diversity and breadth of spatial cognition research are also reflected in the variety of methodologies utilized to explore the topic. Single-cell recording, neuroimaging, behavioral experiments, and simulations have all been used in the context of spatial information processing to advance our understanding of the mechanisms of spatial competence. The achievements have been substantial. An impressive literature has been compiled, including a variety of theories in different contexts regarding spatial representations and processing.

Despite these research accomplishments, there remain substantial challenges in coming to a complete understanding of spatial cognition. Two related limitations in current theories are (a) limited integration across diverse research domains and methodologies, and (b) few quantitative, computational accounts of how spatial information processing is integrated with other cognitive abilities in performing complex, naturalistic tasks.

In 2009, the Air Force Office of Scientific Research sponsored the Modeling Spatial Cognition Workshop, bringing together representatives from diverse perspectives to describe recent advances in understanding spatial cognition and to discuss opportunities for future research. Attendees at the workshop included representatives from neuroscience, robotics, cognitive psychology, geographic information systems, and artificial intelligence. The papers published in this topic are contributed from a subset of those attendees, discussing the challenges, advances, and future directions for Modeling Spatial Cognition. They provide a cross-section of focus and methodology, illustrating the diversity of research underway and, in some cases, providing a vision for how these approaches may be brought together to provide a more comprehensive understanding of human spatial competence.

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