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Introduction to the Special Section on Spatial Reference Frames: Examining What and How Information Is Encoded Through the Integration of Cognitive, Behavioral, and Neuroscience Approaches

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A spatial reference frame is a system of axes that assigns coordinate values to objects and regions in a given space and can serve as a means for specifying spatial information such as orientation and position. A longstanding literature has focused on the encoding of spatial position, examining what and how that information is encoded. The set of articles selected for this special section present current research on these two themes and are distinguished by their integration of cognitive, behavioral, and neuroscience approaches.

Keywords: spatial reference frames, egocentric, allocentric, spatial representation, integration of approaches

Our interactions with the world critically depend upon spatial information. For example, we are able to return to our car upon leaving the grocery store because we remember where the car was parked. When we encounter a detour, we can (usually) construct an alternative route to work by making a series of spatial inferences based on our representation of the space between our home and workplace. We can tell someone who is lost how to go from Place A to Place B on the basis of our ability to map our internal representation of the space connecting these places onto language. We can assess whether our luggage might fit in the trunk of the car by imagining it in different orientations and different arrangements. And we can successfully pick up a coffee mug on the desk because we can encode its location and form an appropriate motor plan. Such spatial interactions cut across a diversity of cognitive domains, including spatial memory, spatial inferences, spatial language, and action in space, and a common component across these domains is the need to specify spatial position.

There is a long-standing and diverse literature in the cognitive sciences investigating the way in which such spatial information is encoded that dates back to Tolman's (1948) cognitive maps. One critical issue that has been addressed corresponds to *what* information is encoded in the internal representation of space. For example, Cheng and Newcombe (2005) reviewed a large body of research across species that examines whether the spatial location of an object is encoded relative to geometric information regarding the configuration of the space or relative to featural information present in the space. For example, in a rectangular room, one can encode the location of an object relative to the corners formed by the short and long walls (geometric) or relative to a single wall with a distinctive color (feature). A second critical issue corresponds to *how* the spatial information is encoded. Across domains, it is commonly assumed that a spatial reference frame is used to specify location (Levinson, 1996). A spatial reference frame can be thought of as a system of axes that assigns coordinate values to objects and regions in a given space. Specifying a coordinate frame involves selecting an origin and orientation for the primary axes, and a critical issue is specifying how these selections are made. Information could be represented *egocentrically*, based on an origin centered on the observer, or it could be represented *allocentrically*, based on the encoding of interobject relations and metric distances and angles within the scene itself. Evidence for both types of representations has been obtained, associated with distinct neural regions (e.g., Colby & Goldberg, 1999; Gallistel, 1990; O'Keefe & Nadel, 1978; for a recent review, see Burgess, 2008).

These two key questions about what information is encoded in the spatial representation and how this information is encoded in terms of different types of reference frames serve as themes for this special section on spatial reference frames. These themes, coupled with a robust and interdisciplinary history that cuts across cognitive domains, make spatial reference frames an ideal arena for showcasing the advances that arise from a tight integration of cognitive, behavioral, and neuroscience approaches. The seven articles selected for this special section all rely on an integration of these diverse approaches to address one or both of these two fundamental questions, with some authors using existing neural models to motivate theoretical distinctions and others using patient data to test specific theoretically derived predictions. This pointed focus on these two questions is complemented by our selection of articles across a variety of cognitive domains including spatial

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memory, navigation, spatial language, and action, enabling an assessment of whether there are domain-general principles governing what and how spatial information is encoded. The focus is further complemented by our selection of articles across scales of stimuli and environments, ranging from tabletop displays to navigable environments and including novel, well-learned, immediate, and remote environments.

The first theme of *what* is encoded is addressed across the articles in terms of the nature of the information that is encoded and how it is structured. Sargent, Dopkins, Philbeck, and Chichka (2010) examine how egocentric and allocentric information is used during spatial updating, focusing on the structure that is used to encode spatial information within a hierarchical representation (McNamara, 1986; Stevens & Coupe, 1978) that encodes collections of objects as units, with higher order relations specifying the spatial relations among these units. This concept of a hierarchical structure also occurs in Holden, Curby, Newcombe, and Shipley (2010), who suggest that both perceptual and conceptual information is used to segment complex natural scenes into constituent parts that are spatially related. Within this work, there is a strong influence of task expectation on the way in which this spatial information is organized. Similarly, for Smith, Hood, and Gilchrist (2010), expectations in the form of probabilities of an object being in a given location are critical determinants of search behavior for hidden targets. For Avraamides and Kelly (2010), the important point is that the representation that is constructed on the basis of linguistic descriptions of the environment is functionally equivalent to the representation that is constructed from visually presented scenes. This question of equivalence is also addressed by Bek, Blades, Siegal, and Varley (2010), who tested patients with severe agrammatic or global aphasia and demonstrated that these patients are able to successfully integrate geometric and feature cues, even when performing a concurrent dual task to eliminate any residual ability to code this information linguistically. Bek et al. argue on the basis of their findings that these spatial representations are independent of linguistic representations.

The second theme cutting across these articles regarding *how* information is encoded examines the role of egocentric and allocentric reference frames. Sargent et al. (2010) argue for an interactive system that coordinates the use of both egocentric and allocentric codes to encode information, and they describe an existing neural systems model and discuss how it could be extended to account for their evidence. Similarly, Avraamides and Kelly (2010) argue for a multiple systems view for spatial memory, drawing on the literature from the neurosciences to suggest a difference in durability of the two types of information. In their view, egocentric information is largely transient and plays a leading role in the encoding of immediate environments, whereas allocentric information is more enduring and bears on representations of both immediate and remote environments. In contrast, as suggested by the data of Ciaramelli, Rosenbaum, Solcz, Levine, and Moscovitch (2010), the transient and enduring distinction may not map cleanly onto egocentric and allocentric representations, and the relative reliance may be more dependent upon task. Ciaramelli et al. examined patients with brain damage to the posterior parietal cortex and showed that this area seems to play a critical role in accessing remote egocentric representations that subserve navigation and reexperiencing, as well as accessing allocentric representations under high demands and spontaneous retrieval. Finally, Humphreys, Wulff, Yoon, and Riddoch (2010) examined patients with visual extinction to assess how egocentric and allocentric frames mediate the allocation of attention across objects for action, revealing differential reliance on a self (ego) reference frame.

It is important to note that these two themes regarding what information is represented and how it is represented are not strictly independent. For example, Sargent et al. (2010) argue that the interrelations among the objects within a unit are encoded allocentrically but that the relations across units are encoded egocentrically. Similarly, Smith et al. (2010) argue that the learning of probabilities of likely target locations depends critically on the combination of room-based and body-based spatial cues. Humphreys et al. (2010) argue that the depiction of information in images in either a first person (egocentric) or third person (allocentric) perspective influences the type of information that is attended.

The articles in this special section offer a snapshot of a set of current and sometimes conflicting views on what spatial information is encoded and how it is represented within different types of reference frames across cognitive domains. The integration of the cognitive and behavioral work with neuroscience models and patient data illustrates a rigorous methodological approach to these questions and should lead the way to a clarification of these issues in future work. We encourage researchers on these issues to follow the course set by the articles in this special section by employing such an integrative perspective, thereby bringing the long history of neuroscience and animal work on spatial representation into tighter contact with the more traditional human cognitive paradigms.

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