



## Review

# Computational cognitive models of spatial memory in navigation space: A review



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## ABSTRACT

Spatial memory refers to the part of the memory system that encodes, stores, recognizes and recalls spatial information about the environment and the agent's orientation within it. Such information is required to be able to navigate to goal locations, and is vitally important for any embodied agent, or model thereof, for reaching goals in a spatially extended environment.

In this paper, a number of computationally implemented cognitive models of spatial memory are reviewed and compared. Three categories of models are considered: symbolic models, neural network models, and models that are part of a systems-level cognitive architecture. Representative models from each category are described and compared in a number of dimensions along which simulation models can differ (level of modeling, types of representation, structural accuracy, generality and abstraction, environment complexity), including their possible mapping to the underlying neural substrate.

Neural mappings are rarely explicated in the context of behaviorally validated models, but they could be useful to cognitive modeling research by providing a new approach for investigating a model's plausibility. Finally, suggested experimental neuroscience methods are described for verifying the biological plausibility of computational cognitive models of spatial memory, and open questions for the field of spatial memory modeling are outlined.

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## 1. Introduction

A wealth of neurophysiological results from human and animal experiments have, in recent years, helped shed light on the mechanisms and brain structures underlying spatial memory. Although it is possible to investigate spatial cognition purely from the point of view of one of the cognitive sciences, interdisciplinary analyses at the level of behavior as well as underlying neural mechanisms provide a more solid foundation and more evidence. Within the broader scope of cognitive sciences involved in investigating memory systems, such as psychology and neuroscience, computational models play a unique and important role in helping to integrate findings from different disciplines, as well as generating, defining, formalizing, and testing, and generating hypotheses, and thus helping to guide research in cognitive science.

There are multiple relevant reviews concerning the psychology of spatial cognition (Allen, 2003; Tommasi & Laeng, 2012) as well as its underlying neuroscience (Avraamides & Kelly, 2008; Burgess, 2008; Moser, Kropff, & Moser, 2008; Tommasi, Chiandetti, Pecchia, Sovrano, & Vallortigara, 2012). Although some of these reviews also mention the occasional computational model, no systematic review of computational models of spatial memory has been published in the last decade (note that Trullier, Wiener, Berthoz, & Meyer, 1997 have reviewed biologically based artificial navigation systems, and Mark, Freksa, Hirtle, Lloyd, & Tversky, 1999 published a review of models of geographical space). The main contributions of the current paper lie in providing a review of computational cognitive models of spatial memory (taking into account implemented models of cognition across disciplines, including psychology, neuroscience, and AI); providing a comparison of these models; reporting possible underlying neural correlates corresponding to parts of these models to aid comparison and verification; and finally outlining open questions relevant to this field which have not been fully addressed yet.

### 1.1. Spatial memory and representations

Biological agents such as mammals, as well as embodied autonomous agents, exist within spatially extended environments. Given that these environments contain objects relevant to the agent's survival, such as nutrients or other agents, they need to take the positions of these objects into account. The purpose of spatial memory is to encode, store, recognize and recall spatial information about the environment, and the objects and agents within it.

Spatial representations can be categorized based on the reference frame used. Egocentric representations represent spatial information relative to the agent's body or body parts. In contrast, allocentric representations represent spatial information relative to environmental landmarks or boundaries, independent of their relation to the agent. We will return to these types of representations, and the way they are encoded in mammalian brains, in Section 2.

In addition to navigation space – the space of potential travel – other forms of spatial representation have also been considered in

the literature (e.g. representations of the positions of body parts or external representations such as maps or diagrams—Tversky, 2005).

In this review, we will focus on representations of navigation space and the space around the body, because the largest number of computational cognitive models account for them, and also because they are the most ubiquitous and generalizable representations. Whereas information concerning the space of the body strongly depends on the specific form of embodiment (such as body size and shape), and the use of external spatial representations is exclusive to humans, the types of representations and strategies required for navigation space are similar for different kinds of bodies and agents.

### 1.2. Relevance of computational cognitive models to spatial memory research

Computational models attempt to formally describe a part (or parts) of cognition in a simplified fashion, allowing their simulation on computers (McClelland, 2009; Sun, 2008b), and providing more detail, precision, and possibly more clarity than qualitative descriptions. In addition, computational models might facilitate the understanding and clarification of the implications of a theory or idea, in ways that would be difficult for humans without simulation on computers (McClelland, 2009). Since spatial memory is an interdisciplinary research area (drawing on at least psychology, neuroscience, and artificial intelligence), involving multiple representations and processes, it is especially important to formulate theories precisely, using a common language. Computational models can provide such a common ground.

The development of computational cognitive models also requires making a large number of design decisions, possibly leading to novel hypotheses, which can then be evaluated. This process usually constitutes an ongoing cycle of development, testing, and revision. Critically, most of this is performed on a computer and thus can be quick and efficient.

This efficiency is especially important for modeling mechanisms with representations that are not easily explicated or measured directly, such as in the case of spatial cognition. Humans cannot easily report the structure of their spatial representations and the mechanisms operating on them. There are a large number of structures and mechanisms that could partially account for spatial skills (e.g. navigation), and a time-efficient way of defining them, and investigating their implications in an automated fashion is important to facilitate the evaluation of their plausibility.

Once a theory or hypothesis has been encoded computationally, generating predictions from it is a straightforward matter of providing model parameters and input data, and running the model on a computer. This is usually more efficient than obtaining experimentally verifiable predictions from a verbal/conceptual theory. The predictions can subsequently be tested or verified using data obtained from empirical experiments with humans or animals, and comparing this data with the model predictions

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