Biologically Inspired Cognitive Architectures (2013) **3**, 1–5

Available at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/bica

LETTER

Understanding human high-level spatial memory: An ACT-R model to integrate multi-level spatial cues and strategies

Changkun Zhao *, Jonathan H. Morgan, Frank E. Ritter

College of Information Sciences and Technology, The Pennsylvania State University, University Park, PA 16802, United States

Received 3 July 2012; received in revised form 8 July 2012; accepted 8 July 2012

KEYWORDS
Navigation strategy;
Spatial memory;
ACT-R;
Cognitive load

Abstract

The ability to process and use spatial knowledge is a basic cognitive ability. Two human navigation strategy types (map-based and route-based) relying on two different knowledge representations have been frequently observed. These studies suggest that the first strategy uses a sequential representation and the second uses a hierarchical cluster-based representation. These studies also suggest that humans also routinely use hybrid strategies, and that the ratio between cognitive load and relative utility mediated by situational factors influences, and when modeled, could successfully predict strategy choice. We created an ACT-R model to test these hypotheses by simulating navigation strategies, strategy choices, and strategy switches. This model deepens the empirical findings by defining more clearly the memory mechanisms involved in generating the basic representation types, and by positing a theory of interaction between these types based on ACT-R's associative declarative memory. We believe that such a work provides a concrete example on principles of these biological theories can be implemented and used in cognitive architectures.
Published by Elsevier B.V.

Introduction

How do spatial navigation and cognitive load interact? We start to explore this topic with a model. Researchers studying navigation behaviors have been particularly interested in two related aspects of spatial cognition: spatial knowledge, and navigation strategies that use these representations. Spatial knowledge refers to a basic understanding of spatial geometry, relations between objects, spatial cues, and event sequences relating to the passage through space. Whereas, spatial navigation strategies refer to the decision patterns based on evolving representations of this knowledge (Foo, Warren, & Tarr, 2005). It is widely accepted that spatial knowledge plays a key role in human navigation, and

Corresponding author. Address: 319 IST Building, Penn State, University Park, PA 16802, United States. Tel.: +1 (814) 321 4896.
E-mail address: cuz111@psu.edu (C. Zhao).

2212-683X/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.bica.2012.07.010

the representations of this knowledge can influence strategy choices and strategy switching.

Historically, Tolman (1948) conducted one of the first studies on this topic and he coined the term ''cognitive maps'' and was among the first to study how humans and animals organize spatial knowledge. Tolman studied the navigation behaviors of rats; he argued that cognitive maps correspond to sets of associations in the long-term memory of both humans and other mammals. Tolman also illustrated that these associations exist in long-term memory for both humans and rats because both species are capable of exhibiting novel shortcutting behavior. O'Keefe and Nadel (1978) grounded Tolman's cognitive maps in a functional analysis of the brain, arguing that cognitive maps are in essence sets of position vectors stored in the hippocampus. Further, they elaborated on the notion of cognitive maps by linking the formation of spatial representations to situational factors, arguing that cognitive maps most likely arise during ''unrewarded situations''. Recent neuroscience studies (Hafting, Fyhn, Molden, Moser, & Mose, 2005) have found that the entorhinal cortex contains a neuron map of the environment, which provides further support for the theory of cognitive maps.

In contrast to Tolman's cognitive map consisting of a single representation type, Montello (2001) and Siegel and White (1975) suggest a layered representation consisting of three levels and associated landmarks. The ordered trees algorithm was developed to represent regularities of verbal organizations. Hirtle and Jonides (1985) then applied this algorithm to the study of cognitive maps. Using 32 landmarks in a sample space, their subjects' responses indicated a hierarchical structure anchored by landmark clusters. These results also suggested that humans might ascribe shorter distances to within-cluster landmark pairs than across-cluster pairs, even when this is not necessarily true.

In contrast to topological or map-based representations, researchers have also observed route-based representations. These representation types rely on sequential memory and consist of landmarks, egocentric orientations, distances, and locations. Bennet (1996) and O'Keefe and Nadel (1978) argue that route-based representations are a weaker form of spatial memory, chiefly because these strategies rely on order and are vulnerable to shifts in the environment (e.g., the loss of an important landmark like a house, sign, or tree). Foo et al. (2005), however, dispute this claim, observing that humans primarily use route-based navigation along established paths. They argue that this indicates that route-based representations are not a secondary form, but rather a strong and sufficient representation. Further, Hart and Moore (1973) observed that route-based learning often takes place first upon encountering an unfamiliar place. As humans consolidate route-based representations, they argue that they also gradually begin constructing map-based representations of the environment by recognizing landmarks, connecting positions, and changing egocentric coordinates.

Both representation types are abstractions that rely on visual cues to create, but are in themselves to at least some extent tied to declarative memory. We can infer this from both O'Keefe and Nadel (1978) and Hirtle and Jonides (1985) work—the ability to verbalize spatial relationships indicates declarative memory retrievals. Consequently, it is widely accepted that these two types of high-level spatial representations, in contrast to visual cues, are an aspect of long-term memory that we can represent using declarative memory elements.

In this work, we propose a model that uses ACT-R's declarative memory to represent two types of spatial knowledge. We also begin to model how strategy selection depends on the spatial memory retention and cognitive load of the decision-maker.

Model implementation in ACT-R

Our model is different from previous navigation models (Gunzelmann & Anderson, 2004; Lathrop, 2008; Reitter & Lebiere, 2010; Zhao, Hiam, Morgan, & Ritter, 2011). It implements spatial knowledge with multi-level structures and proposes three navigation strategies with different cognitive costs that are dynamically selected.

Implementing spatial knowledge

To implement spatial knowledge in declarative memory, we first define the basic *location* chunk that represents an individual waypoint in the environment with identification information such as objects, landmarks, and topological connections. Out model uses this chunk to construct both route knowledge and map knowledge.

Sequential knowledge

We use *route* chunks to represent sequential transitions between the start location and the end location. Different from the conventional route, the *route* chunk of this model only consists of 4 *locations*, and we implement a longer path as a linked list of several *route* chunks. This approach is developed to match the limitations of human attention. When navigating along a long path, humans can only focus on a subset of the route because of the limitations of their working memory. According to Luck and Vogel's study (1997), the average number of visual items that a human can hold in visual short-term memory ranges from 3 to 5. Consequently, we take the mid-number 4 as the size of a *route* chunk. We expect we will examine and adjust this number in the future. Finally, implementing a route with a list of subset route chunks enables the model to integrate two long routes and also to discover shortcuts in the routes.

Fig. 1 explains how to implement a long route with the route chunks. In this figure, we use 3 route chunks to implement a route consisting of 10-locations. The first route

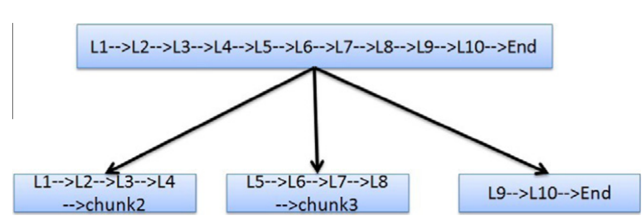

Fig. 1 An example of route chunk.