Cognition 116 (2010) 409–420

Contents lists available at ScienceDirect

Cognition

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

Reference frames during the acquisition and development of spatial memories

Jonathan W. Kelly [a,*], Timothy P. McNamara [b]

[a] Department of Psychology, Iowa State University, W112 Lagomarcino Hall, Ames, IA 50011-3180, United States
[b] Department of Psychology, Vanderbilt University, PMB 407817, 2301 Vanderbilt Place, Nashville, TN 37240-7817, United States

ARTICLE INFO

Article history:
Received 28 September 2009
Revised 4 March 2010
Accepted 1 June 2010

Keywords:
Spatial cognition
Spatial memory
Reference frames

ABSTRACT

Four experiments investigated the role of reference frames during the acquisition and development of spatial knowledge, when learning occurs incrementally across views. In two experiments, participants learned overlapping spatial layouts. Layout 1 was first studied in isolation, and Layout 2 was later studied in the presence of Layout 1. The Layout 1 learning view was manipulated, whereas the Layout 2 view was held constant. Manipulation of the Layout 1 view influenced the reference frame used to organize Layout 2, indicating that reference frames established during early environmental exposure provided a framework for organizing locations learned later. Further experiments demonstrated that reference frames established after learning served to reorganize an existing spatial memory. These results indicate that existing reference frames can structure the acquisition of new spatial memories and that new reference frames can reorganize existing spatial memories.

1. Introduction

Spatial memory plays a crucial role in everyday navigation and wayfinding. Finding one's way to a campus library without using a navigational aid depends critically on knowing the location of the library within the context of the campus environment. Recent spatial memory research has focused heavily on understanding the organization of this type of long-term spatial memory. One commonly replicated finding in this area is that spatial memories are orientation-dependent, whereby spatial memories are most easily retrieved (e.g., scene recognition judgments and inter-object pointing judgments are faster and more accurate) from one or two specific orientations (for reviews, see Avraamides & Kelly, 2008; McNamara, 2003). This has led researchers to argue that spatial memories are organized around reference frames centered on the environment, and that those reference frames influence the manner in which spatial memories are accessed. The current study examines the role of reference frames during the acquisition and development of spatial knowledge when learning occurs incrementally, as it often does in naturalistic settings.

The preponderance of evidence from spatial memory research indicates that reference frames are selected on the basis of cues available in the learning environment. Environmental cues such as room walls (Kelly & McNamara, 2008b; Kelly, McNamara, Bodenheimer, Carr, & Rieser, 2008; Shelton & McNamara, 2001), city streets (Montello, 1991; Werner & Schmidt, 1999), buildings, and lakes (McNamara, Rump, & Werner, 2003) can result in spatial memories organized around reference directions parallel to those environmental structures (and sometimes a second set of reference directions orthogonal to the first). Furthermore, learning from a view that is aligned with one or more environmental structures can serve to highlight and bolster the influence of those cues.

* Corresponding author. Address: Department of Psychology, W112 Lagomarcino Hall, Iowa State University, Ames, IA 50011-3180, United States. Tel.: +1 515 294 2322; fax: +1 515 294 6424.
E-mail address: jonkelly@iastate.edu (J.W. Kelly).

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doi:10.1016/j.cognition.2010.06.002

In a prototypical study by Shelton and McNamara (2001), participants learned the locations of seven objects placed on a square mat, which lay on the floor of a rectangular room. The edges of the square mat were aligned with the rectangular walls of the room. All participants studied the object layout from two perspectives, one aligned and one misaligned with the axes defined by the environment (i.e., the mat and the walls), and the learning order was manipulated. After learning, participants performed an imagined perspective-taking task, in which they imagined standing at the location of one object, facing a second object, and pointed to a third object from that imagined perspective. Regardless of the order in which participants experienced the misaligned and aligned study views, perspective-taking performance was best when imagining the aligned perspective, indicating that participants organized their memories around a reference frame consistent with the environmental axes defined by the walls and the mat.

Based on their findings and other related work, Shelton and McNamara (2001) proposed that reference frames are allocentric – fixed relative to the environment – and that egocentric and environmental cues combine to influence selection of allocentric reference frames. The allocentric nature of the reference frame is indicated by the finding that participants who first studied from the view aligned with the room axes selected a reference frame parallel to that aligned view, and subsequent studying from a misaligned view did not change the selected reference frame, indicating that the reference frame was fixed with respect to the environment.

Mou, McNamara, Valiquette, and Rump (2004) have outlined a model of spatial memory that accounts for orientation dependency in imagined perspective-taking tasks. According to this model, the bearings, or directions, between objects are represented in terms of reference directions in the spatial reference frame. People can retrieve the represented bearing when the imagined perspective is the same as the spatial reference direction but need to infer the bearing in terms of the imagined perspective when it is different from the spatial reference direction. Inference requires additional cognitive processing, which introduces error and increased latency to performance (e.g., Klatzky, 1998). It follows that performance should be worse on imagined perspectives misaligned with the spatial reference direction than on headings aligned with the spatial reference direction.

Much is now known about how reference frames are established during initial learning, and the relative roles of various cues when selecting those reference frames. In contrast, considerably less is known about the role of reference frames during subsequent development of spatial knowledge, despite the fact that memories for most real-world environments develop incrementally over repeated explorations. For example, a visitor learning a new campus might walk along multiple intersecting paths while traveling different routes to relevant buildings. Learning the campus layout during these explorations occurs gradually. In some cases, the visitor will encounter the same building or landmark from multiple directions, but he or she will rarely see the entire campus simultaneously. Within this naturalistic learning context, spatial memories acquired at different times and from different views might become integrated within a unitary reference frame, or they might be stored separately, each within a unique frame of reference. This is in contrast to most laboratory work on reference frames, in which participants typically study spatial layouts that are visible in their entirety from all studied perspectives (e.g., Shelton & McNamara, 2001). The current experiments explore the role of reference frames during the acquisition and development of spatial knowledge, when learning occurs incrementally.

Previous work on the integration of multiple remembered spaces has produced mixed results as to whether or not separately learned spaces are integrated within a single reference frame. In a frequently used paradigm, participants first learn two separate spatial layouts or routes, and they later learn the relationship between those two spaces. Those experiments commonly compare accuracy of distance and direction judgments for pairs of within- and between-layout locations in order to assess whether the two layouts were organized into a single reference frame or two separate reference frames. Some studies report larger errors for between- versus within-layout pairs, indicating a failure to fully integrate the two spaces (Golledge, Ruggles, Pellegrino, & Gale, 1993; Hanley & Levine, 1983; Ishikawa & Montello, 2006; Montello & Pick, 1993). Between-layout judgments are thought to take longer due to the additional cognitive effort required when reconciling the different reference frames, perhaps similar to the costs incurred during mental rotation of small-scale objects (Shepard & Metzler, 1971). However, other studies have found comparable performance for within- and between-layout pairs, indicating that participants successfully integrated the two separately learned spaces within a single reference frame during learning (Holding & Holding, 1988; Maguire, Burke, Phillips, & Staunton, 1996; Moar & Carlton, 1982). These equivocal findings could be due to methodological differences across studies, including differences in environmental scale and differences in the spatial relationships between the two environments and between the pairs of test objects. For example, judgments of within-layout object relationships are known to depend greatly on whether those objects are aligned or misaligned with environmental axes (e.g., Werner & Schmidt, 1999), and so within- and between-layout pairs need to be carefully selected with this variable in mind. Furthermore, comparison of within- and between-layout pairs may not be the most appropriate method for understanding the role of reference frames during spatial learning. For example, both spatial and temporal separation during learning are known to influence judgments of inter-object distances (McNamara, Halpin, & Hardy, 1992). Therefore, studies reporting larger errors for between- than within-layout pairs might have been influenced by similar temporal distance effects, and the results may have had little to do with differences in spatial reference frames.

In light of the challenges in interpreting existing work, the experiments presented here take a unique approach to understanding whether multiple layouts, learned incrementally, are integrated within a single reference frame, and how that integration occurs. Rather than focusing on