Cognition 126 (2013) 459–474

Contents lists available at SciVerse ScienceDirect

Cognition

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

Geometric cues, reference frames, and the equivalence of experienced-aligned and novel-aligned views in human spatial memory

Jonathan W. Kelly [a,*], Lori A. Sjolund [a], Bradley R. Sturz [b,*]

[a] Department of Psychology, Iowa State University, W112 Lagomarcino Hall, Ames, IA 50011-3180, USA
[b] Department of Psychology, Georgia Southern University, P.O. Box 8041, Statesboro, GA 30460, USA

ARTICLE INFO

Article history:
Received 11 June 2012
Revised 19 September 2012
Accepted 11 November 2012
Available online 8 January 2013

Keywords:
Spatial memory
Reference frames
Geometric cues

ABSTRACT

Spatial memories are often organized around reference frames, and environmental shape provides a salient cue to reference frame selection. To date, however, the environmental cues responsible for influencing reference frame selection remain relatively unknown. To connect research on reference frame selection with that on orientation via environmental shape, we explored the extent to which geometric cues were incidentally encoded and represented in memory by evaluating their influence on reference frame selection. Using a virtual environment equipped with a head-mounted-display, we presented participants with to-be-remembered object arrays. We manipulated whether the experienced viewpoint was aligned or misaligned with global (i.e., the principal axis of space) or local (i.e., wall orientations) geometric cues. During subsequent judgments of relative direction (i.e., participants imagined standing at one object, facing a second object, and pointed toward a third object), we show that performance was best when imagining perspectives aligned with these geometric cues; moreover, global geometric cues were sufficient for reference frame selection, global and local geometric cues were capable of exerting differential influence on reference frame selection, and performance from experienced-imagined perspectives was equivalent to novel-imagined perspectives aligned with geometric cues. These results explicitly connect theory regarding spatial reference frame selection and spatial orientation via environmental shape and indicate that spatial memories are organized around fundamental geometric properties of space.

1. Introduction

Spatial memories are critical to everyday navigation. For example, finding a detour to avoid campus construction requires a navigator to retrieve a memory of the surrounding space, determine his or her current location within that remembered space, and then plan an appropriate alternative route based on the retrieved memory. Imagining different perspectives within the remembered environment, as one might do when comparing potential routes, typically reveals preferred access to a small number of specific perspectives (Greenauer & Waller, 2008, 2010; Hintzman, O'Dell, & Arndt, 1981; Kelly, Avraamides, & Loomis, 2007; Kelly & McNamara, 2008, 2010; Marchette, Yerramsetti, Burns, & Shelton, 2011; Mou & McNamara, 2002; Shelton & McNamara, 1997, 2001; Werner & Schmidt, 1999; Yamamoto & Shelton, 2005), and such orientation-dependence is thought to reflect the reference frame structure of spatial memories (Klatzky, 1998; Shelton & McNamara, 2001). Perspectives aligned with a reference frame are directly represented in memory, and are therefore relatively easy to retrieve, whereas misaligned

* Corresponding authors. Tel.: +1 515 294 2322 (Jonathan W. Kelly), +1 912 478 8539 (Bradley R. Sturz).

E-mail addresses: jonkelly@iastate.edu (J.W. Kelly), bradleysturz@georgiasouthern.edu (B.R. Sturz).

0010-0277/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cognition.2012.11.007

perspectives must be inferred, and this inference process results in longer latencies and larger errors (see Shelton & McNamara, 2001).

Reference frame selection has been found to depend on a combination of experienced views and environmental structure. Shelton and McNamara (2001, Exp. 1) conducted a paradigmatic study in which participants studied a layout of seven objects placed on the floor of a rectangular room. Participants experienced the layout from multiple views, two of which were aligned and one misaligned with the wall surfaces of the surrounding room. After learning, participants performed judgments of relative direction (JRD) in which they imagined standing at the location of one object, facing a second object, and pointed toward a third object from the imagined perspective. Pointing performance was best when imagining experienced perspectives aligned with the room walls. Performance when imagining the misaligned-experienced perspective was no better than imagining non-experienced perspectives. The authors interpreted these findings as evidence that participants remembered the object locations using a reference frame, and that reference frame selection was determined by a combination of experienced views and environmental structure.

The salience of environmental structure in reference frame selection has been repeatedly demonstrated in studies investigating spatial memory organization (Hintzman, O'Dell, & Arndt, 1981; Marchette et al., 2011; Yamamoto & Shelton, 2005; McNamara, Rump, & Werner, 2003; Montello, 1991), and room shape has been shown to be a particularly powerful environmental cue to reference frame selection such that performance is best when imagining experienced perspectives aligned with the room walls (Kelly & McNamara, 2008; Shelton & McNamara, 2001; Valiquette & McNamara, 2007; Valiquette, McNamara, & Labrecque, 2007). To date, however, the specific environmental cues represented in memory that influence reference frame selection remain relatively unknown.

In contrast, research in the area of spatial orientation has long been interested in the environmental cues responsible for the determination of heading (Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1994). Extant literature suggests that fundamental geometric properties of space are responsible for successful orientation with respect to the environment (Cheng, 2005; Lee, Sovrano, & Spelke, 2012; for a review, see Cheng & Newcombe, 2005). For example, orientation may be accomplished by global geometric cues, such as the principal axis of a space,[1] and/or local geometric cues, such as the length and orientation of a single wall surface or the angle formed by the intersection of two wall surfaces (Bodily, Eastman, & Sturz, 2011; Cheng & Gallistel, 2005; Lubyk, Dupuis, Gutiérrez, & Spetch, 2012; McGregor, Jones, Good, & Pearce, 2006; Pearce, Good, Jones, & McGregor, 2004; Sturz et al., 2011). For clarification, the principal axis of space is a summary parameter of the entire shape that passes through the centroid and approximate length of the entire space (for a detailed mathematical and mechanical definition, see Cheng, 2005; Cheng & Gallistel, 2005).

In orientation tasks, after learning to locate a goal situated in one corner of an otherwise featureless rectangular room, a disoriented navigator appears to attempt to return to the goal by relying on its location relative to geometric cues (e.g., the trained egocentric side of the principal axis of space) or by relying on its location relative to features that define the corner (e.g., the 90° corner formed by a short wall on the left and a long wall on the right). Using these global and local geometric cues leads to equivalent (above chance) performance in these orientation tasks conducted in rectangular environments (for a review, see Cheng & Newcombe, 2005). Transformations (i.e., manipulations) of environmental shape have allowed researchers to delineate the relative contributions of global and local geometric cues and indicate that incidental encoding of environmental geometry is a fundamental and ubiquitous component of orientation (Bodily et al., 2011; Cheng, 1986; Gallistel, 1990; for a review, see Cheng & Newcombe, 2005; Sturz et al., 2011).

Despite recent advances in identifying the contributions of global and local geometric cues to reorientation, less is known about the relative influences of these geometric cues on reference frame selection and, ultimately, the organization of spatial memories. One intriguing possibility is that the geometric cues responsible for successful orientation are also the geometric properties of room shape that are directly represented in memory. As a result, these are the environmental cues that influence reference frame selection. A few recent studies provide promise for such a possibility – for example, spatial memory research showing the influence of layout axes on reference frame selection. After learning a layout of objects with a bilateral symmetry axis, the selected reference frame often corresponds to the symmetry axis of the layout (Kelly & McNamara, 2010; Mou, Liu, & McNamara, 2009; Mou & McNamara, 2002; Mou, Zhao, & McNamara, 2007). The influence of object layout axes suggests that global geometric cues, such as the principal axis, might be primarily represented in memory and, therefore, responsible for reference frame selection. However, commonly used experimental environments investigating reference frame selection often contain redundant global and local geometric cues. For example, past research on the role of room shape in reference frame selection has shown that spatial memories acquired within a rectangular room are organized around a reference frame selected from experienced views parallel to room axes and wall surfaces (Hintzman et al., 1981; Kelly & McNamara, 2008; Shelton & McNamara, 2001; Valiquette & McNamara, 2007; Valiquette, McNamara, & Smith, 2003; Valiquette et al., 2007). However, the global cue defined by the principal room axis and the local cue defined by the wall surface orientations are redundant (i.e., confounded) in a rectangular room.

[1] Research on reference frame selection has often described the environmental axis of symmetry as the relevant cue (Mou & McNamara, 2002; Kelly, McNamara, Bodenheimer, Carr, & Rieser, 2008), whereas research on orientation has often described the principal axis as the relevant cue (Cheng, 2005; Cheng & Gallistel, 2005; Sturz & Bodily, 2011; Sturz & Bodily, 2012; Sturz, Forloines, & Bodily, 2012; Sturz, Gurley, & Bodily, 2011). The axis of symmetry and the principal axis are often identical in built environments. Herein we refer exclusively to the principal axis, which was identical to at least one symmetry axis in the environments used in the current studies.