Cognition 129 (2013) 447–456

Contents lists available at ScienceDirect

Cognition

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

Intrinsic frames of reference in haptic spatial learning

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ARTICLE INFO

Article history:
Received 2 August 2011
Revised 4 June 2013
Accepted 8 August 2013
Available online 14 September 2013

Keywords:
Haptics
Reference frame
Functional equivalence
Geometry
Modality
Spatial memory

ABSTRACT

It has been proposed that spatial reference frames with which object locations are specified in memory are intrinsic to a to-be-remembered spatial layout (intrinsic reference theory). Although this theory has been supported by accumulating evidence, it has only been collected from paradigms in which the entire spatial layout was simultaneously visible to observers. The present study was designed to examine the generality of the theory by investigating whether the geometric structure of a spatial layout (bilateral symmetry) influences selection of spatial reference frames when object locations are sequentially learned through haptic exploration. In two experiments, participants learned the spatial layout solely by touch and performed judgments of relative direction among objects using their spatial memories. Results indicated that the geometric structure can provide a spatial cue for establishing reference frames as long as it is accentuated by explicit instructions (Experiment 1) or alignment with an egocentric orientation (Experiment 2). These results are entirely consistent with those from previous studies in which spatial information was encoded through simultaneous viewing of all object locations, suggesting that the intrinsic reference theory is not specific to a type of spatial memory acquired by the particular learning method but instead generalizes to spatial memories learned through a variety of encoding conditions. In particular, the present findings suggest that spatial memories that follow the intrinsic reference theory function equivalently regardless of the modality in which spatial information is encoded.

1. Introduction

Numerous activities in everyday life require remembering locations of objects in an environment. Because locations can only be defined relative to something else (e.g., Stilwell Hall is east of Chester Building), forming a mental representation of the environment entails establishing coherent frames of spatial reference in memory. Hence, extensive research has been carried out to investigate what types of reference frames are used in spatial memory (e.g., Easton & Sholl, 1995; Greenauer & Waller, 2008; Hintzman, O'Dell, & Arndt, 1981; Kelly, Avraamides, & Loomis, 2007; Marchette & Shelton, 2010; Montello, 1991; Mou & McNamara, 2002; Presson & Hazelrigg, 1984; Rieser, 1989; Sadalla, Burroughs, & Staplin, 1980; Shelton & McNamara, 1997, 2001; Werner & Schmidt, 1999; Yamamoto & Shelton, 2005, 2009a). Traditionally, this research has made a distinction between egocentric reference frames and allocentric reference frames (Klatzky, 1998). Egocentric reference frames specify locations with respect to observers themselves (e.g., a door is 10-ft away to my left). Allocentric reference frames determine locations in reference to environmental features that are external to the observers (e.g., a window is in the middle of the south wall). This dichotomy has been shown to be useful for understanding organization of human spatial memory (for review, see Shelton & Yamamoto, 2009).

The past decade, however, has seen a new development in the classification of spatial reference frames. On the

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http://dx.doi.org/10.1016/j.cognition.2013.08.011

basis of the discovery that spatial structures in the configuration of objects (e.g., bilateral symmetry) can be used to specify object locations in memory independently of observers' position and orientation (Mou & McNamara, 2002), McNamara, Mou, and colleagues formulated a theory that spatial reference frames are intrinsic to the object layout that is to be remembered (Mou & McNamara, 2002; Shelton & McNamara, 2001; for review, see McNamara, 2003). According to this theory (referred to as *intrinsic reference theory* hereafter), observers first establish a conceptual "north" of the layout, much like determining the "top" of a figure in form perception (Rock, 1973). This process gives rise to an intrinsic reference frame that consists of a primary north–south axis and secondary east–west axis, with which object locations are defined. A number of spatial cues can influence selection of the conceptual north, including egocentric orientations of observers in an environment (Shelton & McNamara, 1997, 2001), allocentric features of the surroundings (such as a floor mat and room walls; McNamara, Rump, & Werner, 2003; Shelton & McNamara, 2001), geometric structures of the spatial layout (Mou & McNamara, 2002), and the interaction among them (Kelly & McNamara, 2008; Mou, Zhao, & McNamara, 2007; Shelton & McNamara, 2001). For example, in the absence of any salient cues, the first egocentric orientation experienced by observes defines the primary reference axis. On the other hand, if the observers subsequently learn the same environment from another orientation that is reinforced by notable allocentric features (e.g., the new orientation is aligned with room walls), the primary reference axis is re-established based on this new orientation. In this manner, the intrinsic reference theory has proposed a novel framework within which reference frames are characterized as properties of the spatial layout, not of observers or the surroundings. Egocentric and allocentric spatial information provide cues that give life to certain reference frames, all of which are viewed as intrinsic to the spatial layout.

Following the seminal work by Mou and McNamara (2002), a number of studies were conducted to further demonstrate that geometric structures of a spatial layout constitute salient cues for selection of spatial reference frames (e.g., Kelly & McNamara, 2008; Mou, Fan, McNamara, & Owen, 2008; Mou, Liu, & McNamara, 2009; Mou, McNamara, Valiquette, & Rump, 2004; Mou et al., 2007). These studies provided crucial evidence for the intrinsic reference theory by verifying that reference frames can be inherent in the spatial layout itself. Nevertheless, many questions still remain regarding how intrinsic reference frames are used to organize spatial memory. An outstanding issue is that it is yet unclear how universal the role of layout geometry is in establishing reference frames. In the previous studies, an array of objects that had a single axis of bilateral symmetry (such as the one in Fig. 1) was typically utilized to help observers memorize object locations by using the symmetry axis (and the axis perpendicular to it as a secondary reference axis). Since this layout was always viewed in its entirety in the previous experiments, the symmetry of the layout would have been apparent to observers, especially when the symmetry axis was aligned with their egocentric view or allocentric features such as room walls (Kelly & McNamara, 2008; Mou et al., 2007). However, in everyday environments, it is quite common that only a fragment of the layout is visible at any given time (e.g., due to blockage of full view by obstacles) and objects must be seen sequentially (Yamamoto & Shelton, 2009b). Thus, compared to the situations examined in the previous studies, under natural conditions it may be more difficult for observers to notice the overall structure of the layout, and consequently, they are more likely to employ reference frames that are based on other cues than the geometry of the layout. In other words, it is possible that the effect of layout geometry may be restricted to (relatively rare) circumstances in which all objects in the layout can be perceived simultaneously. If this were the case, then it would dispute the importance of layout geometry in setting up spatial reference frames, and in turn, the generality of the intrinsic reference theory.

In relation to the issue discussed above, it is worth noting that vision can allow observers to perceive an entire spatial layout at once thanks to its large field of view. It should be pointed out that having a wide field of "view" (or, more generally, spatial bandwidth; Loomis & Lederman, 1986, chap. 31) that can cover the entire spatial layout is not a condition applicable to all modalities. In haptic and proprioceptive spatial learning (i.e., when a spatial layout is learned through touch or blind-walking), object locations must be experienced one by one (or a few at a time when they are close together) due to restrictions inherent to each modality. Therefore, it is also possible that layout geometry plays a role in establishing reference frames only in modalities that have wide-enough spatial bandwidth (i.e., vision and presumably audition). If this were the case, it would limit the scope of the intrinsic reference theory. On the other hand, if layout geometry provided reliable spatial cues for selecting reference frames in other modalities, such a finding would have an important theoretical implication not only because it shows that the intrinsic reference theory is extended to modalities with narrow spatial bandwidth, but also because it suggests that underlying spatial representations function equivalently regardless of the modality in which spatial information is encoded (Loomis & Klatzky, 2008).

Thus, the present study was conducted to examine the generality of the intrinsic reference theory by investigating whether the geometry of a spatial layout influences selection of reference frames when the entire layout cannot be perceived simultaneously through vision. In two experiments, in a manner similar to previous studies (Kelly & McNamara, 2008; Mou & McNamara, 2002; Mou et al., 2007, 2009), participants learned a spatial layout that had a single axis of bilateral symmetry. A critical difference from the previous studies was that participants in the present study were blindfolded throughout the experiments and experienced object locations solely through touch. This prevented them from perceiving all object locations at the same time, making the symmetry axis harder to detect. If the intrinsic reference theory is applicable to conditions in which (visual) perception of the entire layout is precluded, participants' memories for the spatial layout should be organized by the symmetry axis and the axis perpendicular to it. Such a finding would demonstrate