Cognition 129 (2013) 180–193

Contents lists available at SciVerse ScienceDirect

Cognition

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

Global frames of reference organize configural knowledge of paths

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ARTICLE INFO

Article history:
Received 24 September 2012
Revised 30 April 2013
Accepted 29 June 2013
Available online 25 July 2013

Keywords:
Spatial memory
Reference system
Route knowledge
Survey knowledge

ABSTRACT

Five experiments examined the organization of spatial memory of an irregular path learned by walking with vision. Two hypotheses were tested: (a) that participants would establish a single global frame of reference to organize the spatial memory of the path; or alternatively (b) that participants would establish path-aligned reference directions at each path leg but not establish a global frame of reference. Participants donned a head-mounted display and were asked to navigate through a virtual six-segment path with each turning point indicated by a virtual object. The six legs consisted of two groups of three legs. The legs within groups were aligned (parallel or orthogonal) with each other and between groups were misaligned (45° tilted) with each other. At each leg, participants only perceived the object at the end of this leg. After participants walked the legs 10 times they conducted judgments of relative directions (JRD, e.g. "imagine you are standing at X, facing Y, please point to Z"). The imagined headings in JRD were parallel to the experienced path legs. The paths varied in terms of the salience of the longest leg. Appearance of a room was also manipulated to highlight one group of the legs. The results showed that participants demonstrated significantly lower pointing error for (a) the longest leg when there was no room or (b) the first walking leg when there was no obvious longest leg or the longest leg was misaligned with the room. Pointing error was equivalent for the longest leg and the first walking leg when the longest leg was salient and misaligned with the first walking leg. These results suggested that participants established a single global frame of reference when there was a single salient context cue. However, two oblique reference frames can be established when there are two inconsistent contextual cues.

1. Introduction

In everyday life, people need to walk a variety of paths with multiple segments. For example, over the course of a day, a college student might walk an irregular path from one building to another, returning to the dormitory at the end of the day. A path (e.g., dormitory – building A – building B –...– dormitory) can be defined as a sequence of the landmarks (e.g., buildings) and the traversed legs between any two adjacent landmarks. Landmarks are usually learned by visual perceiving the location and the identity whereas the legs (e.g., distance, turning angle) are primarily learned by path integration (Siegel & White, 1975). A great deal of research has been conducted on the nature of spatial memory learned by walking (or navigation) and how people establish a reference system to organize spatial memory of object arrays. However, what is missing in the literature is a good understanding of how people establish spatial reference frames to organize spatial memory of a path by walking it with vision. This project was conducted to address this issue.

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http://dx.doi.org/10.1016/j.cognition.2013.06.015

Spatial knowledge acquired by path integration (or navigation) can be contrasted with spatial knowledge learned by map reading (e.g. Richardson, Montello, & Hegarty, 1999; Shelton & McNamara, 2004; Taylor, Naylor, & Chechile, 1999; Thorndyke & Hayes-Roth, 1982). Spatial knowledge acquired by walking (or navigation) consists primarily (at least initially) of route knowledge whereas spatial knowledge acquired by map reading consists primarily of survey knowledge. Route knowledge has a ground level perspective and is specific to the sequences of segments of the route traveled. Route knowledge supports estimation of the route distance, judgments of the order of the segments, and description the visual appearance of the route. Survey knowledge has a top-down perspective and embodies the information of direction and straight line distance between two places or landmarks. Survey knowledge supports estimation of straight-line distance, and judgments of directions (e.g. McNamara, in press for a review).

Survey knowledge can also be developed by walking (or navigation). Thorndyke and Hayes-Roth (1982) reported that participants who had extensive navigation experience in one specific building developed survey knowledge of the environment that was as good as the survey knowledge acquired by participants who learned the environment by map reading. Taylor et al. (1999) reported that participants who only learned one environment by navigation could develop better survey knowledge if they were explicitly asked to pay attention to the layout of the environment. Ishikawa and Montello (2006) reported that participants developed survey knowledge and route knowledge simultaneously even when participants learned a route by navigation for the first time. Participants could estimate the directions of the places on the route at above chance level after they were passively transported by automobile on this route only once.

The spatial memory literature indicates that spatial memory of objects' locations is organized in terms of a reference frame (e.g., Greenauer & Waller, 2010; Kelly & McNamara, 2010; Mou & McNamara, 2002; Shelton & McNamara, 2001; see McNamara, Sluzenski, & Rump, 2008 for a review). In a typical experiment, participants learned an array of objects in a room from a small number of viewpoints. At each viewpoint participants could see all objects. After learning the array, participants made judgments of relative direction (JRD) using their memories (e.g., "Imagine you are standing at mug, facing phone, please point to ball"). The imagined heading, which was defined by the direction between the first two objects (e.g., from mug to phone), included the headings parallel to the learning viewpoints and several novel headings. A common finding in such experiments is that JRD performance is better for certain key imagined headings than for others; for example, JRD performance is often better for imagined headings parallel to a learning viewpoint than for imagined headings parallel to novel viewpoints (see discussion below for important exceptions to this pattern).

Findings of this kind have been explained in a theoretical framework in which the bearings between objects (e.g., from mug to ball) are represented with respect to a reference direction (Mou, McNamara, Valiquette, & Rump, 2004; Rump & McNamara, 2013). When the imagined heading is aligned with the reference direction, the tested bearing between the first object and the third object (e.g., from mug to ball) in the JRD trial can be directly retrieved from memory, whereas when the imagined heading is misaligned with the reference direction, the tested bearing between the first object and the third object in the JRD trial must be inferred (e.g., Klatzky, 1998). These inferential processes produce costs in error and latency for JRD trials in which the imagined heading is misaligned with a reference direction relative to those trials in which the imagined heading is aligned with a reference direction.

One of the important findings in the studies of spatial memory of an object array is that not all viewing directions determine a reference frame. For example, Shelton and McNamara (2001, see also Kelly & McNamara, 2010) had participants learn an array of objects from two oblique viewpoints (0° and 135°), one of which was aligned with walls of the experiment room. The superior effect of the learning viewpoint was only observed at the learning viewpoint that was aligned with the external reference frames (e.g., the walls of the room). There was no evidence that the learning viewpoint that was misaligned with the external frames was superior to the novel viewpoints. However, the superior effect of the learning viewpoint misaligned with the external frames was observed if it was the only learning viewpoint. These results indicated that when participants experienced multiple oblique viewpoints, they established reference directions that were aligned with both the learning viewpoints and the external frames. Mou, Zhao, and McNamara (2007) also showed that when participants experienced multiple oblique viewpoints without any salient external frame in a circular room, they established reference directions that were aligned with both the learning viewpoints and the intrinsic feature of the array (e.g., axis of bilateral symmetry). These results indicated that participants had difficulty in establishing two oblique reference directions.

In some special circumstances, participants seem to be able to establish two oblique reference directions. For example, Shelton and McNamara (2001) showed that participants might represent two oblique viewpoints when one of them was aligned with the global external frame (i.e., the walls of the room) and one of them was aligned with the local external frame (i.e., the edges of a mat). Yamamoto and Shelton (2005) also showed that participants established two oblique reference directions. Participants learned an array of objects from two oblique orientations. Participants viewed the locations of the objects at one of learning orientation and walked without vision to the locations of the objects at the other learning orientation. The results showed equivalent performance at both experienced headings. These findings indicated that participants were able to establish two oblique reference directions when each of them was supported by a salient context. It is possible that under such circumstances participants treat the same array as two different arrays from two different viewpoints. Greenauer and Waller (2010) reported that participants established two oblique reference directions when they segmented objects into two different arrays even from a single viewpoint.