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ARTICLE IN PRESS
Journal of Applied Research in Memory and Cognition xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Applied Research in Memory and Cognition

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

Spatial Category Bias in a Three-Dimensional Virtual Environment

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One bias in spatial memory is that individuals remember a target toward the centroid of its region, the *category bias* or *prototype effect*. The standard approach to investigate the bias follows the category adjustment (CA) model by Huttenlocher, Hedges, and Duncan (1991), with the use of a two-dimensional (2D) dot-in-circle task in which observers see a target in a blank circle and indicate its location after a brief interval. However, it is unclear whether the work has ecological validity. Investigations using real life spaces compromise control. The current paper investigated the effect in a 3D virtual environment, as it lends high levels of experimental control in a simulated naturalistic space. The pattern found with the 2D dot-in-circle task was replicated with its 3D virtual counterpart. We discuss how our method, in addition to increasing ecological validity under controlled conditions, eliminates concerns regarding studies that applied the CA model to more ecologically valid environments.

General Audience Summary

People misplace the position of an object based on its region, a bias called the *prototype effect*. The standard paradigm to investigate the bias has employed a 2D dot-in-circle task that does not seem equivalent to the spaces that we experience in everyday life. Investigations using real life spaces compromise experimental control. Virtual environment (VE) systems offer new prospects for spatial memory research, as it lends high levels of experimental control in simulated naturalistic 3D spaces. Thus, we used a 3D virtual simulation of the dot-in-circle task to increase ecological validity whilst maintaining high experimental control. We note that the rising presence of virtual systems in various domains gives cause for scientific inquiries of human spatial memory and cognition. In fact, understanding how humans make positional judgments in virtual environments is critical in cases such as medical, military, and aeronautical training because an individual's physical safety may depend on accurate spatial judgments that may be learned and practiced in VEs. Thus, it is important to examine different aspects of spatial cognition in VEs to assess whether they carry over to the physical world.

Keywords: Spatial memory, Category-adjustment model, Category bias, Spatial memory bias, Spatial cognition, Virtual environment

The ability to remember where objects are is essential to our functioning in everyday life, yet systematic distortions are notorious in spatial memory. One common bias seems to stem from the use of prototypes to estimate locations from memory, as formalized in the classic category adjustment model by Huttenlocher, Hedges, and Duncan (1991). The standard approach to investigate the effect of prototypes is to use a two-dimensional dot localization task: on each trial, observers see a single target in an otherwise blank circle; the target disappears, and individuals indicate its location after a brief interval. Responses in this task are predictably biased toward the centroid of the quadrant in which the target appears, suggesting that

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We thank Brian Roberts for his assistance in developing the virtual environment. Partial data reported here were presented at 24th Meeting of the Object Perception, Attention, and Memory, Boston, MA, United States.

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Please cite this article in press as: Sampaio, C., et al. Spatial Category Bias in a Three-Dimensional Virtual Environment. *Journal of Applied Research in Memory and Cognition* (2017), http://dx.doi.org/10.1016/j.jarmac.2017.08.001

observers impose mental regions demarcated by Cartesian axes onto the space and combine the target's metric position with its surrounding region.

Data generated from the dot-in-circle task have been largely employed to understand the effect of prototypes and to make inferences about the structure of human spatial memory. However, it is unclear whether the paradigm truly apprehends human spatial memory as it occurs in everyday life. That is, a criticism of this line of research is that the method may lack ecological validity (Liben, 2003): a uniform space on a flat surface hardly resembles 3-dimensional (3D) environments that people experience in quotidian life. Investigations of the prototype effect using real life spaces, however, tend to compromise experimental control (e.g., Sampaio & Cardwell, 2012). Virtual environment (VE) systems offer new prospects for spatial memory research, as it lends high levels of experimental control in simulated naturalistic 3D spaces.[1]

Our aim in the current work is to test the prototype effect in a 3D virtual environment using Huttenlocher et al.'s (1991) category adjustment approach. The specific question we address is whether spatial memories learned from a 3D virtual version of the classic dot-in-circle task leads to the same prototype bias found with the 2D flat displays. To replicate the dot-in-circle task in a 3D virtual space, we created a square room with a round table at its center. The targets were 3D geometric shapes voided of any meaningful associations with everyday objects.

In extending Huttenlocher et al.'s (1991) category adjustment approach to locating 3D targets in a VE, our work not only approximates the real world under rigidly controlled conditions, but also eliminates critical concerns regarding the few studies that attempted to generalize the prototype effect to more ecologically valid spaces. First, the research that has tested Huttenlocher et al.'s (1991) approach in more ecologically valid environments still used either dots as targets or static 2D images of real environments. Holden, Curby, Newcombe, and Shipley (2010), for example, tested memory for points on photographs of natural scenes. They found evidence for estimates of locations being adjusted by unevenly shaped spatial categories, supporting the conclusions from the extensive dot-in-circle data (though the prototypes were not the same as those in the dot-in-circle tasks). While these spaces were visually richer than the typical circular shapes, they were nonetheless 2D images of physical environments and the targets were still small specks. Little work to date has aimed at exploring the bias in real-life navigable spaces, arguably because it is truly a challenge to achieve full experimental control in these environments.

In an effort to expand the empirical work on Huttenlocher's prototype effect to long-term memories in the real world, Sampaio and Cardwell (2012) examined people's memory for sizable 3D structures within a university campus (e.g., a fountain within a square and a set of stairs within a grassy area). However, they tested memory for the locations learned through navigation on 2D projected images of the campus from an aerial view. Likewise, Uttal, Friedman, Hand, and Warren (2010) studied how people learn locations of buildings and landmarks in a real-world university campus using a map of the space. Specifically, they tested memory by placing an X representing each location on a computer screen. A potential problem with both of these studies is that the space in which a memory is tested along with its categories exert greater influence on estimates of location than originally encoded categories (Sampaio & Wang, 2012). Hence, the bias obtained in these studies could have been (at least in part) due to the structure of the figural spaces used to test the memories instead of that of the real life environments in which individuals encoded the locations. Furthermore, the subjects in these studies had to transfer their knowledge acquired in navigating a 3D space to a 2D representation of the space at retrieval (cf. Holden, Newcombe, & Shipley, 2013). Holden et al. (2013) were the pioneers in examining location memory in a 3D environment without crossing of space levels between encoding and retrieval. However, the targets they used were nevertheless dots created by a laser pointer. In studying the bias in a VE, we therefore eliminate these reservations regarding the few studies that attempted to expand the prototype effect outside the dot-in-circle task to increase ecological validity.

Method

Participants

The participants were 35 undergraduate students from Western Washington University, who participated to partially fulfill a course requirement. Participants were required to have had previous experience with an Xbox controller and at least four years of video game experience.

Materials

Hardware. The virtual environment was created using the Unity game engine version 5.3.1f1. The environment ran on a desktop computer supported by an Intel Xeon E5-1607 3.1 GHz processor, 16 GB of memory, and a NVIDIA GeForce GTX 970 4 GB GPU. Visuals were displayed on a 53 cm × 30 cm monitor. Participants viewed the monitor from distance of approximately 50 cm and used an Xbox One controller to move and interact with the virtual environment.

Xbox One controller. Participants used an Xbox One controller to move and interact with the virtual environment. To move through the environment, participants used the left joystick on the controller: up, down, right, and left movements on the joystick maneuvered participants forward, backward, right, and left, respectively. To look around the environment, participants used the right joystick on the controller: up, down, right, and left movements on the joystick allowed participants to look up, down, right, and left, respectively. The "A" button, located on the top right of the controller, was used to select, pick up, and drop objects, and the right and left bumpers were used to move a selected object closer (left) or further (right) away from the participant.

Tutorial. A virtual room was created to deliver the instructions to participants; the room was small and had no windows,

[1] We acknowledge that VE may present potential challenges where it may differ from the physical world.