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Detecting the perception of illusory spatial boundaries: Evidence from distance judgments

Bradley R. Sturz *, Kent D. Bodily

Georgia Southern University, USA

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ABSTRACT

Spatial boundaries demarcate everything from the lanes in our roadways to the borders between our countries. They are fundamental to object perception, spatial navigation, spatial memory, spatial judgments, and the coordination of our actions. Although explicit spatial boundaries formed by physical structures comprise many of the actual boundaries we encounter, implicit and permeable spatial boundaries are pervasive. The prevailing paradigm for detecting implicit spatial boundaries relies on memory-based distance and location judgments. One possibility is that these biases in spatial memory may be attributable to initial biases in spatial perception, but the extent to which implicit spatial boundaries bias spatial perception remains unknown. An approach for detecting the perception of implicit spatial boundaries would be to infer it through known systematic biases in memory-based distance judgments. We harnessed known biases in memory-based distance judgments to infer perception of spatial boundaries by probing the extent to which distances were overestimated across potential spatial boundaries. Results suggest that participants perceived potential spatial boundaries as illusory spatial boundaries leading to biased judgments of distance. A control group eliminated simple two-dimensional distance cues as responsible for this bias. This bias provides a novel method to detect the perception of illusory spatial boundaries.

1. Introduction

Spatial boundaries are omnipresent. They demarcate everything from the lanes in our roadways to the borders between our countries. In addition to occupying specialized neural pathways in our brains dedicated to their detection and representation (Doeller & Burgess, 2008; Krupic, Bauza, Burton, Barry, & O'Keefe, 2015; Solstad, Boccara, Kropff, Moser, & Moser, 2008; Sutton, Twyman, Joanisse, & Newcombe, 2012) and their significant roles in fundamental processes such as object perception, spatial navigation, spatial memory, and the coordination of our actions, spatial boundaries also impact our judgments (Hartley, Trinkler, & Burgess, 2004; Kelly, Sjolund, & Sturz, 2013; Mou & Wang, 2015; Spelke, von Hofsten, & Kenstenbaum, 1989; Sturz, Gurley, & Bodily, 2011; Tversky, 1981). For example, a resident of the United States might erroneously judge Toronto, Ontario (Canada) as farther north than Seattle, Washington (United States) because a spatial boundary separates Canada (north of United States) from the United States (south of Canada) (Stevens & Coupe, 1978; Tversky, 1981).

Although explicit spatial boundaries characterized by continuous physical structures form many of the actual boundaries we encounter in our world, our lives are also filled with numerous implicit and permeable spatial boundaries. The prevailing paradigm for detecting these implicit spatial boundaries often relies on memory-based distance and location judgments. Specifically, detecting the presence of these implicit spatial boundaries has been inferred through biases in memory-based distance and location judgments (Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Hedges, & Vevea, 2000; McNamara, 1986). For example, the remembered location of dots in a circle appears to be biased by implicit quadrant boundaries (Huttenlocher et al., 1991), and the remembered distances of common objects from each other appear to be biased by transparent spatial boundaries (McNamara, 1986). Although such memory-based biases also appear to occur under more ecologically relevant conditions (e.g., Holden, Curby, Newcombe, & Shipley, 2010; Hutcheson & Wedell, 2012; Mou & Wang, 2015; Mou & Zhou, 2013), the detection of implicit spatial boundaries continues to rely on memory-based tasks.

* Corresponding author at: Department of Psychology, Georgia Southern University, P.O. Box 8041, Statesboro, GA 30460, USA.
E-mail address: bradleysturz@georgiasouthern.edu (B.R. Sturz).

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Given recent interest in biases in spatial perception (e.g., Jackson & Cormack, 2007; Lourenco, Longo, & Pathman, 2011; Vagnoni, Lourenco, & Longo, 2012), we questioned the extent to which the biases in spatial memory might be attributable to initial biases in spatial perception, but the extent to which implicit spatial boundaries bias spatial perception remains unknown. We drew from centuries of research on perceptual grouping principles and harnessed known biases in memory-based distance judgments in an attempt to detect the perception of illusory spatial boundaries. Specifically, we utilized knowledge of grouping principles such as *closure*, in which we complete the gaps in our perception to create unitary and distinct objects, and *continuity*, in which we differentiate between two or more intersecting objects by following the directions of their outlines or curves (for a review, see Wagemans et al., 2012) to predict that an opening into a room from a hallway formed by opposing corner projections appeared to promote perception of an illusory spatial boundary. We then utilized knowledge of systematic bias that occurs in memory-based distance judgments to infer the perception of illusory spatial boundaries. Specifically, when participants are presented with common objects in a spatial layout divided into regions by transparent spatial boundaries, systematic underestimations of remembered inter-object distances occur for objects occupying the same spatial region, and systematic overestimations of remembered inter-object distances occur for objects occupying different spatial regions (McNamara, 1986).

In the present experiment, we attempted to infer the perception of illusory spatial boundaries by probing the extent to which distances were overestimated across potential spatial boundaries. Participants made distance judgments from their current location to a colored wall on the far end of a room (i.e., egocentric judgments of distance) in static images of three simple virtual rectangular enclosures depicted from a first-person perspective (Fig. 1). The distance judgments in the rectangular enclosures served as base measures of within-boundary distance judgments (i.e., distance judgments that did not cross a potential boundary). We probed the perception of illusory spatial boundaries by presenting participants with an enclosure that contained opposing corner projections to create a hallway connecting two rooms. Participants also made distance judgments that were identical in length to the base enclosure judgments in this more complex enclosure. Importantly, the distance judgments in the more complex enclosure were identical in length to base enclosure distance judgements but occurred both within and across potential spatial boundaries (Fig. 1). To the extent that the opposing corner projections created the perception of illusory boundaries, distance judgments within a boundary should not differ from identical-length distance judgments in the base enclosures, but distance judgments across boundaries should be overestimated relative to identical-length distance judgments in the base enclosures.[1]

Given the possibility that simple two-dimensional cues can influence distance judgments that would be independent of illusory spatial boundaries (for a review, see Cutting, 1997), we included a control group that was presented with two-dimensional versions of the Testing Enclosure images that were devoid of illusory spatial boundaries. The number of vertices and wall projections in each control image were made equivalent to those of the Testing Enclosure images for the Experimental Group (Fig. 1). The absence of illusory spatial boundaries in the Testing Enclosure images for the Control Group should produce no differences in distance judgments from identical-length distance judgments in the Base Enclosures.

2. Method and materials

2.1. Participants

Two hundred thirty-six (236) undergraduate students (113 males; 123 females) participated in the experiment. Participants were assigned to one of two groups: Experimental (117; 57 males; 60 females) or Control (119; 56 males; 63 females). Twenty-nine (29) participants did not complete the protocol [Experimental Group = 11 (6 males; 5 females); Control Group = 18 (7 males; 11 females)] and were excluded from analyses. Fourteen (14) participants (5 males; 9 females) from the Experimental Group and 9 participants (3 males; 6 females) from the Control Group were also excluded because at least one of their distance judgment ratios (see Results) was greater than twice the standard deviation of their respective group means. We analyzed the data from the remaining 184 participants (46 males and 46 females in each the Experimental and Control Groups). The mean age of included participants was 19.93 years, 95% CI [19.46, 20.4]. Participants had normal or corrected-to-normal vision and received extra class credit or participated as part of a course requirement.

2.2. Apparatus

Experimental events were presented, controlled, and recorded using Qualtrics Online Survey Software (http://www.qualtrics.com/). Participants completed the experiment on devices ranging from desktop computers (23%), laptop computers (73%), tablets (2%), and smart phones (2%).

2.3. Stimuli

We constructed and rendered four three-dimensional virtual enclosures using Valve Hammer Editor. Dimensions are length $\times$ width $\times$ height and measured in virtual units (vu; 1 vu = $\sim$2.54 cm): Base Enclosure 1 (550 $\times$ 275 $\times$ 260 vu = $\sim$14 $\times$ 7 $\times$ 6.6 m), Base Enclosure 2 (1100 $\times$ 550 $\times$ 260 vu = $\sim$28 $\times$ 14 $\times$ 6.6 m), Base Enclosure 3 (2200 $\times$ 1100 $\times$ 260 vu = $\sim$56 $\times$ 28 $\times$ 6.6 m), and Testing Enclosure (I-Shape) [2200 $\times$ 1100 $\times$ 260 vu = $\sim$56 $\times$ 28 $\times$ 6.6 m]. We created 14 still images (8 within base enclosures; 6 within Testing Enclosure) from a first-person perspective using screen capture (see Fig. 1). Images were .jpegs (1024 $\times$ 768 pixels) with a field of view of 90°. Images depicted either Distance A (550 vu = $\sim$14 m) or Distance B (1100 vu = $\sim$28 m). For the Experimental Group, Testing Enclosure images depicted wall projections that created zero, one, or two potential boundaries. For the Control Group, flat tan shapes were placed in the location of the vertices and wall projections of the Experimental Group's Testing Enclosure images to create equivalent, two-dimensional, Testing Enclosure images devoid of illusory spatial boundaries. Except for two colored walls to serve as prompts for distance judgments (i.e., red and blue walls), and tan shapes in the Control Group's Testing Enclosure images, all surfaces were beige in color with the exceptions of the floors (gray) and ceilings (black). Fig. 1 provides images of the Base and Testing Enclosures for both Experimental and Control Groups.

2.4. Procedure

The online system first presented participants with an informed consent followed by a demographic form. Participants indicated sex,

[1] There is considerable variability in individual distance judgments, and distances are often underestimated in virtual environments (see Kuhl, Thompson, & Creem-Regehr, 2009; Zhang, Nordman, Walker, & Kuhl, 2012). Importantly, we are not concerned with judgment accuracy. Given our use of a measure of perception that is relative to each participant's distance judgment, the extent to which an individual (or group) overestimates or underestimates (or the extent to which distance judgments are collectively underestimated) becomes irrelevant for detecting bias in spatial judgments.