Cognition 146 (2016) 371–376

Contents lists available at ScienceDirect

Cognition

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

Short Communication

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

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ARTICLE INFO

Article history:
Received 26 April 2015
Revised 14 October 2015
Accepted 17 October 2015
Available online 9 November 2015

Keywords:
Illusory spatial boundaries
Spatial boundary perception
Spatial perception
Distance judgments
Bias

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.

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http://dx.doi.org/10.1016/j.cognition.2015.10.015
0010-0277/

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.

[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.

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,

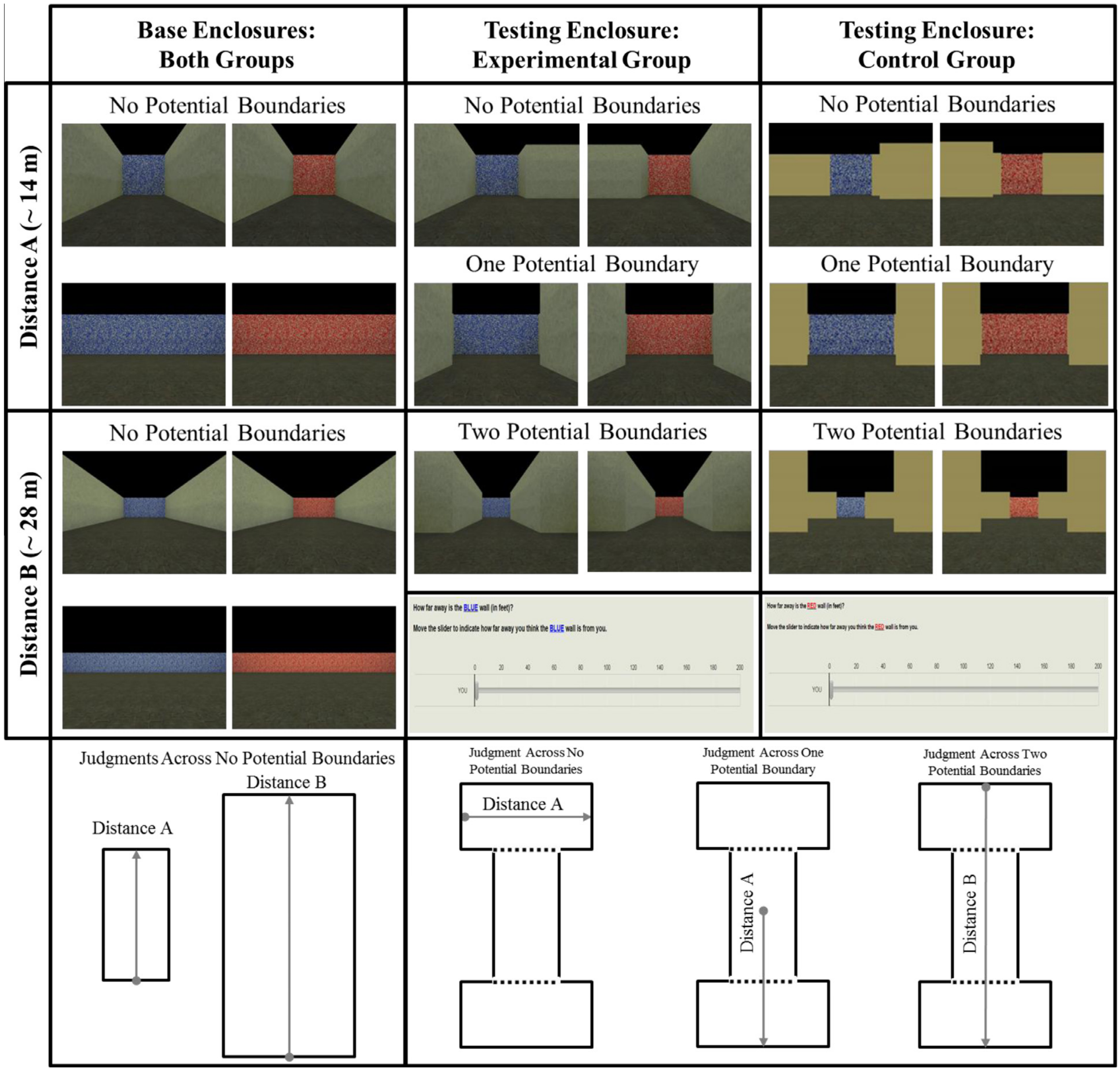

Fig. 1. *Top and middle panels.* First-person perspective screen shots of the Base Enclosures (*left*) and Testing Enclosure for the Experimental (*middle*) and Control (*right*) Groups. Images were presented to participants for egocentric distance judgments of Distance A (*top panel*) and Distance B (*middle panel*). Participants judged the distance from the vantage point of the images to the colored walls. For illustrative purposes, two sample prompts with slider responses are shown (*middle and right panels*). Also shown, an overhead view of two of the Base Enclosures with distance judgments indicated by arrows (*bottom left*) and the three Distance Judgment Types in the Testing Enclosure (*bottom right*) for No Potential Boundaries, One Potential Boundary, and Two Potential Boundaries. For illustrative purposes, dashed lines represent potential spatial boundaries.

age, existence of visual impairments, and device type on which they were completing the experiment. Participants then experienced one of 14 images (8 Base Enclosure, 6 Testing Enclosure) of a virtual enclosure from a first-person perspective with a slider (minimum value 0; maximum value 200 in increments of 1 with labels at every 20) positioned below each image (Fig. 1, middle panels). Instructions prompted participants to move the slider to indicate how far away they thought the colored wall depicted in the image was from them in feet. As participants moved the slider, the current distance judgment was indicated to the right of the slider. Participants repeated this process until they viewed and responded to all 14 images. Image order was randomized across participants.

All participants judged Distance A four times in the Base Enclosures (twice in reference to red, twice in reference to blue). All participants also judged Distance B four times in the Base Enclosures (twice in reference red, twice in reference to blue). In the Testing Enclosure, all participants judged Distance A four times (twice in reference to red, twice in reference to blue). Two of these judgments (one red, one blue) were across No Potential Boundaries, and two of these judgments (one red, one blue) were across One Potential Boundary. Participants also judged Distance B twice in the Testing Enclosure (once in reference to red, once in reference to blue), and both of these judgments were across Two Potential Boundaries (refer to Fig. 1).

3. Results

3.1. Raw distance judgments

We converted raw distance judgments (in feet) to meters and computed the average distance judgments for each Base Enclosure distance for each participant for each group, and computed the average distance judgments for each Testing Enclosure Distance Judgments Type for each participant for each group. Table 1 summarizes the means (in meters) and 95% CI for both the Experimental and Control Groups for all Base and Testing Enclosure Distance Judgment Types.

3.2. Distance judgment ratios

To standardize judgments and make meaningful comparisons across all three conditions despite differences in distances [No Potential Boundaries (Distance A), One Potential Boundary (Distance A), Two Potential Boundaries (Distance B)] as well as to maintain consistency with prior distance judgment research (e.g., Sinai, Ooi, & He, 1998), we calculated a distance judgment ratio by dividing each participant's average Testing Enclosure distance judgment by his/her average Base Enclosure distance judgment for each Distance Judgment Type for each group. This judgment ratio value provided an a priori referential value by which to detect biases in distance judgments. Specifically, a value of one represented no difference between a judgment in the Testing Enclosure and its identical-length distance judgment in the Base Enclosures while values less than one represented underestimations and values greater than one represented overestimations.

Table 1
Means and 95% confidence intervals (in meters) for raw distance judgments by group and Distance Judgment Type.

	Group			
	Experimental		Control	
	M	95% CI	*M*	95% CI
Distance Judgment Type				
Base: Distance A	10.43	[8.98, 11.88]	15.29	[13.11, 17.47]
Base: Distance B	24.97	[22.50, 27.44]	29.00	[26.15, 31.85]
Testing: No Potential Boundaries	9.29	[8.05, 10.53]	15.18	[13.17, 17.19]
Testing: One Potential Boundary	11.22	[9.65, 12.79]	14.86	[12.67, 17.05]
Testing: Two Potential Boundaries	26.51	[23.64, 29.38]	28.90	[25.63, 32.17]

Note: There is considerable variability in individual distance judgments, and distances are often underestimated in virtual environments (see Kuhl et al., 2009; Zhang et al., 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 (see Distance Judgment Ratios), 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.

Fig. 2 shows mean distance judgment ratios plotted for each Testing Enclosure Distance Judgment Type for both the Experimental and Control Groups. For the Experimental Group, the mean distance judgments in the No Potential Boundaries condition did not differ from mean identical-length distance judgments in the Base Enclosures, but mean distance judgments in the One Potential Boundary and Two Potential Boundaries condition were greater than the mean identical-length distance judgments in the Base Enclosures. In contrast, for the Control Group, the mean distance judgments across potential boundary conditions did not differ from the mean identical-length distance judgments in the Base Enclosures. These results suggests that participants in the Experimental Group overestimated distances in the potential boundary conditions while participants in the Control Group neither underestimated nor overestimated distances in the potential boundary conditions.

We confirmed these results with a three-way mixed analysis of variance (ANOVA) on distance judgment ratio with Group (experimental, control), Gender (male, female), and Testing Enclosure Distance Judgment Type (no potential boundaries, one potential boundary, two potential boundaries) which only revealed a significant Group × Testing Enclosure Distance Judgment Type interaction, $F(2, 360) = 9.95$, $p < .001$, $\eta_p^2 = 0.052$. None of the other main effects or interactions were significant, $Fs < 1.9$, $ps > .15$. The interaction resulted from differences in mean judgment ratios across Testing Enclosure Distance Judgment Types for the Experimental but not the Control Group as confirmed by two separate two-way repeated measures ANOVAs on distance judgment ratios with Gender (male, female) and Testing Enclosure Distance Judgment Type (no potential boundaries, one potential boundary, two potential boundaries) as factors. For the Experimental Group, there was a main effect of Testing Enclosure Distance Judgment Type, $F(2, 180) = 10.26$, $p < .01$, $\eta_p^2 = 0.1$. Neither the effect of Gender nor the interaction was significant, $Fs < 0.8$, $ps > .4$. Fisher's least significant difference (LSD) post hoc tests on the Testing Enclosure Distance Judgment Type factor revealed that the mean distance judgment ratio in the No Potential Boundaries condition was significantly less than the mean distance judgment ratios in the One Potential Boundary and Two Potential Boundaries conditions ($ps < .01$), but mean distance judgment ratios in the One Potential Boundary and Two Potential Boundaries conditions were not significantly different from each other ($p = .42$). In addition, the mean distance

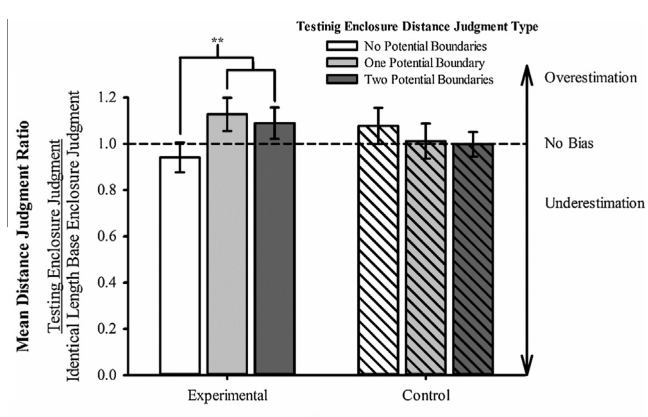

Fig. 2. Mean distance judgment ratio (Testing Enclosure Judgment/Identical Length Base Enclosure Judgment) plotted by Testing Enclosure Distance Judgment Type for both the Experimental (unhashed) and Control (hashed) Groups. For reference, the dashed line at one represents no biases in distance judgments whereas values above one represent overestimations, and values below one represent underestimations. Error bars represent 95% confidence intervals of the means. *Note:* ** represents significant differences at the $p < .01$ level.

judgment ratio for the No Potential Boundary condition was not significantly different from one (i.e., no bias), one-sample t-test, $t(91) = 1.8$, $p = .07$, whereas mean distance judgment ratios for the One Potential Boundary and Two Potential Boundaries conditions were significantly greater than one, one-sample t-tests, $t(91) = 3.54$, $p < .01$, and $t(91) = 2.6$, $p < .05$, respectively. In contrast, for the Control Group, there were no significant main effects or interactions, Fs < 1.9, $ps > .16$. In addition, the mean distance judgment ratios for the No Potential Boundary, One Potential Boundary, and Two Potential Boundaries conditions were not significantly different from one, one-sample t-tests, $ts(91) < 1.98$, $ps > .05$.

3.3. Slope analyses

To provide converging evidence of the analyses of distance judgment ratios reported above, we also calculated slopes for individual participants on their mean distance judgment ratios across No Potential Boundaries, One Potential Boundary, and Two Potential Boundaries conditions. For the Experimental Group, 70% of participants had positive slope values whereas for the Control Group, 45% of participants had positive slope values, and these proportions were significantly different from each other, binomial test, $z = 3.54$, $p < .001$. We assumed equivalence in the probability of positive and negative slope values (i.e., .5), and the number of participants in the Experimental Group with positive slope values (64) was greater than would be expected by chance (i.e., 46), χ^2 (1, $N = 92) = 14.09$, $p < .001$. In contrast, the number of participants in the Control Group with positive slope values (41) was not greater than would be expected by chance, (i.e., 46), χ^2 (1, $N = 92) = 1.09$, $p = .29$. In addition, the mean slope value of the Experimental Group [0.07, 95% CI (0.03, 0.11)] was significantly greater than zero (i.e., no relationship), one-sample t-test, $t(91) = 3.49$, $p < .001$. In contrast, the mean slope value of the Control Group (−0.04, 95% CI (−0.09, 0.01)] was not significantly greater than zero, one-sample t-test, $t(91) = 1.7$, $p = .09$. Moreover, these mean slope values for the Experimental and Control Groups were significantly different from each other, independent samples t-test, $t(182) = 3.6$, $p < .001$. These results suggest that only distance judgments in the Experimental Group increased across illusory spatial boundaries [by an average of 7% (±4%)].

4. Discussion

Results in the present distance judgment task indicate that participants in the Experimental Group overestimated distances across but not within potential spatial boundaries. Coupled with the lack of such an effect in the Control Group, results collectively suggest that participants in the Experimental Group perceived the potential boundaries as illusory spatial boundaries. Such biases in spatial perception are consistent with known biases in spatial memory and open the possibility that biases in spatial memory may be attributable to initial biases in spatial perception (Holden et al., 2010; Hutcheson & Wedell, 2012; Huttenlocher et al., 1991, 2000; McNamara, 1986; Stevens & Coupe, 1978; Tversky, 1981).

The lack of difference in the Experimental Group between the One Potential Boundary and Two Potential Boundaries conditions is worth noting because it seems reasonable to suspect that distance estimations across two potentially boundaries would result in a bias greater than that of estimations across one potential boundary. Extant literature appears to be silent with respect to the relationship between judgment bias and number of real or implicit boundaries. One possibility is that the lack of difference between the conditions indicates that the bias in distance judgments across illusory boundaries may be binary rather than linear. Such a binary relationship may be sufficient for time-sensitive and biologically-relevant decisions regarding the approximate distance of an object to self. Another possibility is that the Experimental Group images utilized in the Two Potential Boundary condition were only sufficient to invoke the perception of an illusory boundary at the close but not the far wall projections due to differences in the directionality of the wall projections themselves (i.e., toward versus away from the participant's point of view, respectively). Although these two issues remain open questions, our obtained perceptually-based biases in distance judgments across illusory spatial boundaries are consistent with known memory-based biases in distance judgments across implicit spatial boundaries (McNamara, 1986; Stevens & Coupe, 1978; Tversky, 1981).

The novel method by which to detect the perception of illusory spatial boundaries reported here may assist in predicting and refining conditions under which memory-based biases occur. As importantly, such a method by which to detect the perception of illusory spatial boundaries via distance judgments should also serve to assist in delineating other environmental features capable of promoting illusory boundary perception and allow the determination of the extent to which illusory boundaries function like and activate the same brain regions as actual spatial boundaries. Ultimately, biases in spatial perception resulting from illusory spatial boundaries should assist in illuminating the nature of spatial memory and spatial perception while advancing theoretical and empirical approaches to the study of object perception, spatial navigation, spatial judgments, and the relationship between our perceptions, our memories, and our actions.

Acknowledgments

This research was conducted following the relevant ethical guidelines for human research. We are grateful to Ty W. Boyer, Jonathan W. Kelly, John F. Magnotti, and three anonymous reviewers for helpful comments on a previous version of this manuscript.

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