Bayesian priors in estimates of object location in virtual reality

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Abstract

We investigated the category bias in spatial memory, which reveals the influence of a region (i.e., a spatial category) on memory for specific locations within the region's bounds. The standard approach to investigating the category bias employs a static dot-in-circle task, in which observers indicate the location of a single dot from memory after a brief interval. The agreement in the literature is that these location estimates result from Bayesian principles; however, the priors in the dot-in-circle task are geometric prototypes (the central angular value of each quadrant and two-thirds of the radius from the center of the circle to its circumference). These geometric prototypes are not "true" priors in that they are not pre-existing statistical likelihoods of a target's location before other evidence is considered. In this paper, we tested the category bias with items for which informative priors exist (e.g., a vase, which is expected to be in the center of a table) and found that people favor them over geometric prototypes for estimating angular but not radial target positions. Our work contributes to the literature by showing that localizing common everyday objects in a circular space is not restricted to the use of cues intrinsic to the space. This is important because the majority of the empirical data on the category bias derives from locating targets that have little to no semantic information.

Keywords Spatial memory · Category-adjustment model · Category bias · Spatial memory bias · Spatial cognition · Virtual environment

Introduction

Remembering locations is fundamental for numerous tasks in life. Nonetheless, systematic biases exist in spatial memory. In this paper, we focus on the category bias, which reveals that a general region influences memory judgments for specific locations within that region's bounds. The standard approach to investigate the bias follows Huttenlocher, Hedges, and Duncan's (1991) Category Adjustment Model and employs a dot-in-circle task: on each trial, observers see one dot in a circle; the dot disappears, and individuals indicate its location after a brief interval. Angular responses in the dot-in-circle task are predictably distorted towards the centroid of the quadrant where the dot appears, suggesting that people impose onto the space mental sections demarcated by Cartesian axes and combine the dot's metric position with its region. Radial values are also biased, with remembered locations pulled

towards two-thirds the distance from the center of the circle to its circumference.

The agreement in the literature is that these location estimates result from Bayesian principles. In general terms, Bayes' theorem describes the probability of an event (*posterior probability*) based on prior knowledge of the likelihood of the event before new information is observed (*prior probability*). The theorem hence provides a method for individuals to revise their estimates in light of new relevant data. Applied to spatial memory, the posterior probability for a given location is based on the combination of prior knowledge of the likely position for the target and the memory trace of its specific location (Crawford, Huttenlocher, & Engebretson, 2000; Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Hedges, & Vevea, 2000). This widely accepted view is appealing, as reconstructed memories in numerous areas have been shown to indeed be mixtures of episodic information with general knowledge acquired through experience.

The *priors* in the dot-in-circle task are geometric prototypes; that is, the priors are the central angular value of each region (the 45° line of each quadrant) and the two-thirds mark of the radius from the center of the circle to its circumference. However, strictly speaking, geometric prototypes are not "true" Bayesian priors, which are the pre-existing statistical likelihood of a target's location before other evidence is

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considered. In Bayes' theorem, a prior refers to the knowledge an individual has acquired in the world through experience. Hence, there is no combination of a genuine prior with the metric information in the dot-in-circle task; instead, individuals rely on values defined by the geometry of the circle. In other words, people do not hold a pre-experimental expectation of where a dot ought to be within a circular space. We think that this typical experimental setup may not reflect how people truly remember locations in real life. In this paper, we will refer to priors used in the standard dot-in-circle task as *geometric prototypes* as they are based on the physical characteristics of the space; thus, we will refer to two types of geometric prototypes: the angular prototype located at the 45° line and the radial prototype located at the two-thirds point from the center to the edge of the circle.

The aim of this paper was to test the category bias with items for which Bayesian priors exist, such as a vase that is expected to be in the center of a table. In quotidian life, the most reasonable basis for spatial judgments from memory lies in that object's expected location gained through experience. Indeed, research shows that people utilize pre-existing expectations about an object's location to help clarify metric traces (e.g., Hemmer & Steyvers, 2009). Eckstein, Drescher, and Shimozaki (2006), for example, found that when people searched for a target chimney in a scene containing a house, the target was found faster and more accurately when it was in its expected position. Even when the target was absent, people used its expected location, suggesting that a target's identity provides information regarding its prototypical location within a space. We will refer to these likely locations obtained from accumulated experience as *priors*.

We note that in the dot-in-circle task, the effect of the Cartesian boundaries as categories is strong and has defied many attempts to refute it. Consequently, the effect of the geometric prototypes on location estimates has proven to be quite resistant to manipulation. Huttenlocher, Hedges, Corrigan, and Crawford (2004), for example, presented uneven distributions of dots within the circle to encourage the creation of an alternative categorization scheme. In four experiments, they were unable to change how people carved the circular space: people continued to use the default categories. The same categorization scheme and bias have been found in locating 3D geometric shapes on a round table in a virtual room (Sampaio, Walsh, Williams, & Engelbertson, 2017).

To our knowledge, only a few papers have reported that an alternative categorization in a circular space is possible, and only under certain circumstances (Crawford & Jones, 2011; Sampaio & Wang, 2010, 2012). Other research has found that categories can be flexible and based on cues other than those based on the geometry of the space. Hund and Plumert (2005), for example, proposed that spatial categories are created by the individual to perform a given task. They suggest that people combine information from memory, perceptually available

information, and task goals to carve up the space. Research in spaces without strong default categorization (natural environments, Hirtle & Jonides, 1985; geography, Friedman & Brown, 2000) moreover confirms that people may rely on sources of information other than the geometry of the space to categorize targets.

In this paper, we introduced priors into a three-dimensional (3D) version of the dot-in-circle paradigm and investigated how these priors may influence estimates. The use of meaningful targets (as opposed to dots) presents another source of information in the Bayesian combinatory process. Given the robust effect of the geometric values in estimates of location in circular spaces, it is not completely clear how the various sources (the geometric prototypes, which are values based on the physical properties of the space; priors, which are likely positions based on experience; and metric information, which are the exact coordinates of a target) will interact to generate an estimate of location in a circular space. Sources may be selected over one another or be completely combined in the process (Cheng, Shettleworth, Huttenlocher, & Rieser, 2007).

We believed that in environments that contain meaningful information, individuals would combine metric information with priors rather than with geometric prototypes to estimate locations from memory. This is because priors provide the most reliable source for estimation: people have beliefs about where familiar objects in an everyday setting are likely to be, and these beliefs serve to inform judgments of location from memory. For example, we see vases in the center of our own table and also on tables we have never seen before; remembering where a specific vase is on a specific table will be influenced by a generic vase's prototypical position on tables. Thus, people rely on a prior, the target's likely position, which is highly informative and relevant in everyday behaviors, rather than on cues intrinsic to the shape of the space itself.

To that end, our research strategy was to use targets whose likely locations in real life contradict those established by default geometric prototypes. To examine angular bias, we selected objects that are typically found on a dinner table either directly in front of the viewer at 0°, such as a dessert plate (*proximal* items), or off to the side of the viewer, such as a spoon (*tangential* items). If people used the geometric angular prototype, both proximal and tangential objects would be biased toward the 45° line (Fig. 1a). However, if people used priors, then proximal objects would be biased towards the 0° line or the proximal prior (Fig. 1b). For tangential objects, if people used priors, then they would be biased towards their expected location based on past experience or the tangential prior, a positive value away from the zero line (see Fig. 1c).

We moreover included radial targets. Williams and Sampaio (2017) found that individuals do not use priors or likely positions for everyday objects in radial estimations of shapes that represent objects from a top-down view. Specifically, participants in Williams and Sampaio
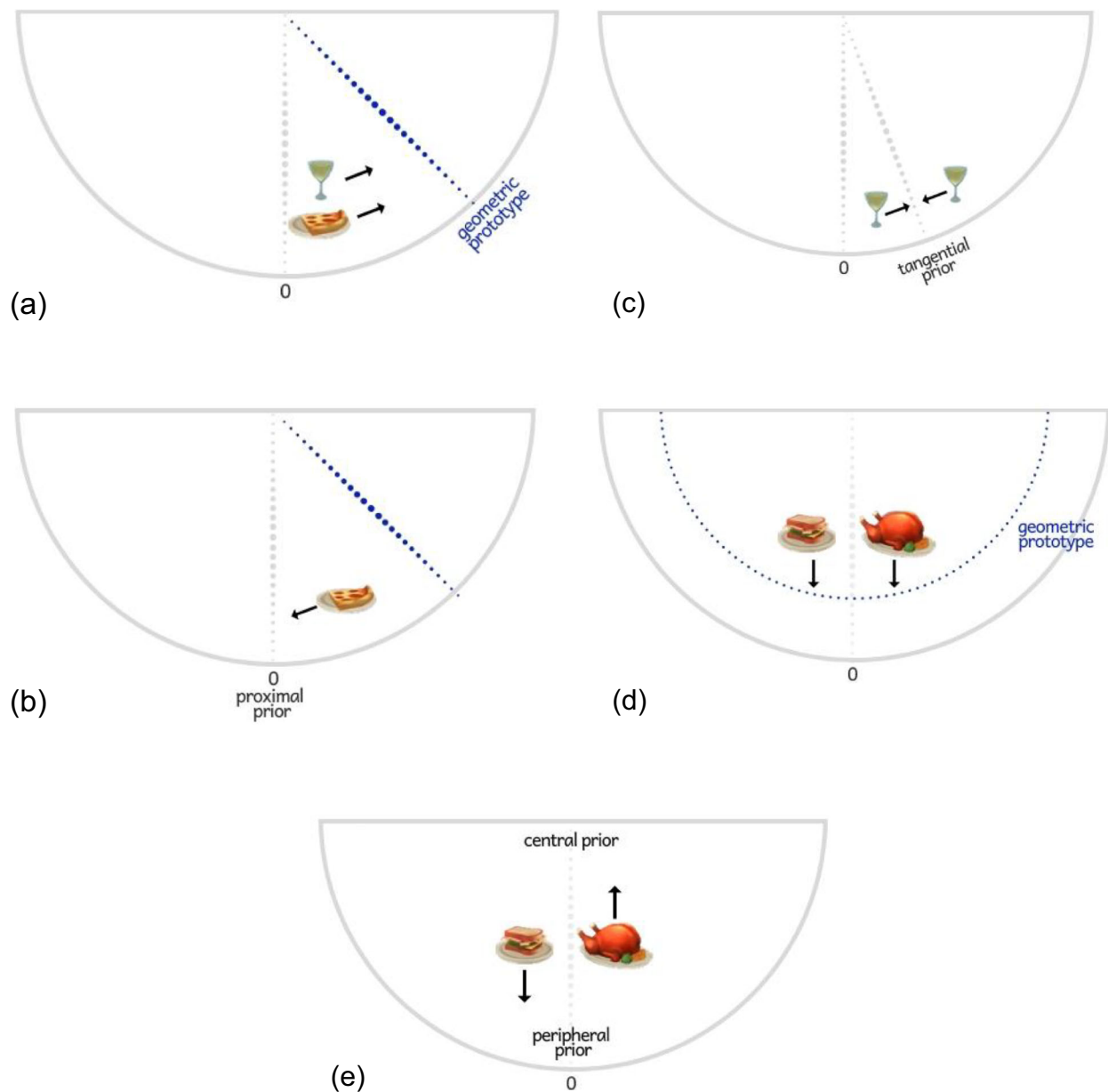
Fig. 1 Predictions: (**a**) shows predictions for angular items if participants use geometric prototypes, with the expected bias toward the 45° line regardless of item type; (**b**) shows the predictions for proximal items if participants used the priors instead, with the bias being towards the 0° line; (**c**) shows the predictions for tangential items if participants used the priors, with the bias towards the tangential prior; (**d**) shows predictions for radial items if participants use geometric prototypes, with the expected radial bias toward the two-thirds point regardless of item type; (**e**) shows predictions for the radial items if participants used priors

reproduced the positions of shapes within a circle displayed on a computer screen; each shape represented both an object that was likely to be found at the center of a table and another that was likely to be found towards its edge (e.g., a circle represented a vase and a bowl of cereal). The authors found that all recalled locations were biased towards the geometric prototype, irrespective of the objects' identity and thus their prototypical positions in real life. While we use these data to make predictions in the current paper, we acknowledge that there are

major differences between the two experiments in terms of the visual richness of the environment, observer's perspective, type of response, target objects, and nature of space.

We hypothesized that people would use the geometric radial prototype in their estimates, and therefore all remembered locations would be biased toward the two-thirds radial point (Fig. 1d). If people used priors, then memory for central and peripheral objects would show different patterns, with estimates for central objects being biased towards the central prior

(i.e., the center of the table) and estimates for peripheral objects being biased towards the peripheral prior (i.e., a point close to the edge of the table, Fig. 1e).

Method

Participants

Participants were 31 undergraduate psychology students at Western Washington University, who participated to fulfill a course requirement. Only individuals who never had a seizure, loss of awareness, or other symptoms linked to an epileptic condition were eligible to participate. Consent was obtained for all participants before their inclusion in the experiment, and their privacy rights were observed.

Materials

Rendering software and hardware The virtual environment was created using the Unity game engine, version 2017.3.1. The environment was run on a desktop computer, supported by an Intel Xeon E5-1607 3.1 GHz processor and a NVIDIA GeForce GTX 970 4 GB GPU.

VR hardware Participants experienced the virtual environment (VE) in high resolution through the Oculus Rift. This head mounted display (HMD) creates a stereoscopic 3D image via a pair of 960 x 1,080-pixel screens for a total resolution of 1,920 x 1,080. The HMD weighed 440 g, and its head strap was adjusted to fit each participant comfortably before each session. Participants interacted with the VE using the Leap Motion controller. Leap Motion uses two monochromatic infrared (IR) cameras and 3 IR LEDs to track hand gestures and movement. Mounted to the front of the HMD, the Leap Motion sensor tracked the movement and positioning of participants' hands and digits, allowing them to pick up and move objects within the virtual environment.

Target objects For our target items, we selected virtual replications of everyday objects that are commonly found on a dinner table top. We aimed to use objects with which participants would likely have experience and therefore knowledge of their typical locations on a round dinner table top. The objects were mostly food items and eating utensils. Items were grouped comparatively along one of two experimental axes, and each experimental axis contained two categories. Objects measured on the radial axis included *central* and *peripheral* objects and were expected to be found either at the center of a table (e.g., a whole pizza) or towards its edge (e.g., a dinner plate). Objects measured on the angular axis were either *proximal* or *tangential* and expected to be found either directly in front of the observer at 0° (e.g., a dessert plate), or laterally

displaced from the observer, away from the 0° line (e.g., a fork). Twenty pairs of radial items and 17 pairs of angular items were utilized to test the two types of category bias. In total, we used 74 items. See Fig. 2b for sample target objects.

We collected norming data with a separate group of subjects to validate the expected locations of the objects. In the norming study (N = 35), we gave subjects the names of each target object and asked them to choose whether (1) each *radial* object was most likely to be found in the middle, towards the edge, or another location on a dinner table ("other"); and (2) each *angular* object was most likely to be found right in front of the observer, off to the side, or another location ("other"). "Other" responses were not recorded for any of the radial objects, and three were recorded for the angular objects. These "other" responses were unrelated to the object's angular position and instead referred to its radial position; thus, they were excluded from the analyses. We found that 99% of the responses indicated that the central items are most likely to be found in the middle of the table, and 91% of the peripheral items are most likely to be found around the edge. For the angular targets, 93% of the responses for the proximal items confirmed that these are most likely to be found in front of the observer. Eighty-three percent of the responses to tangential items indicated that these are most likely to be off to the side from the observer.

Confidence scale After participants finished placing each object, a 7-point Likert-type virtual number pad appeared over the placement location for the participant to rate their confidence of the object placement. The confidence scale ranged from 1 (not at all confident) to 7 (totally confident). Participants selected their confidence level by touching its corresponding number on the dial.

Test environment Using Unity, we created a square virtual room with a white, circular table at its center. The table was designed to emulate Huttenlocher et al.'s (1991) dot-and-circle paradigm in 3D. The room was similar to Sampaio et al.'s (2017) in size, level of realism, and overall structure. The table had a diameter of 178 cm, and each target item on it was sized to be realistically proportional to its real-world counterpart. For example, a glass of water had a virtual diameter of 6.5 cm and a height of 11.5 cm, while a plate of spaghetti had a diameter of 23 cm and a height of 10 cm. The 34 angular objects were presented at random locations between 5° and 40° on the table; we used this range to maximize the standard angular bias toward 45° (Huttenlocher et al., 1991). All angular objects were presented at a constant radius extending 60 percent away from the center of the table and to the right of the participant. The 40 radial objects were presented at random locations along the 0° line, ranging from one-third to two-thirds down the radius of the table to the participant. The table was white with no markings or texture that could be used

(a)
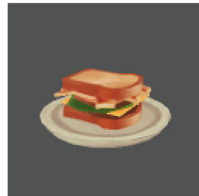
(b)

Fig. 2 (a) Overview of the virtual room; participants faced the green wall throughout the experiment, (b) sample target items

to aid in location memory. Three out of the four walls in the room were gray, and the wall behind the table was blue-green to provide orientation. The floor was gray (see Fig. 2a).

Post-experiment surveys After completing the experiment, participants filled out a Virtual World Feedback survey designed to ensure that participants were able to move and place the objects where they intended (e.g., "Were you able to place the objects EXACTLY where you wanted to place them?"). This survey also asked participants about their interaction with the virtual environment (e.g., "How easy was it to learn by looking around the virtual environment?"), as well as their overall experience with the virtual world (e.g., "Overall, how natural was your experience with the virtual world?"). The second survey, Video Game Experience (Terlecki & Newcombe, 2005), was used to ensure that participants indeed had experience playing video games (i.e., interacting with the apparatus of the study) and included questions about playing frequency (e.g., "How often do you currently play video games?"), perceived skill level (e.g., "How good do you think you are at playing video games?"), game types (e.g., puzzle, open-world role-playing games, first-person shooters, racing games, etc.), and their experience with the Oculus Rift (e.g.,

"How much time have you spent using the Oculus Rift VR headset, not including this study?").

Procedure

Participants were tested individually. After signing a consent form, participants were directed to a small room with a single computer. All participants reported having an unimpaired sense of balance and motion at the beginning of the experiment. They were told that the experiment was about memory in a virtual environment and were given verbal instruction on how to interact with it. Specifically, the experimenter told participants that they would use their bare hands to interact with the objects in the virtual environment via a sensor mounted to the front of the headset. This sensor would track their hand gestures as follows: (1) to pick up objects in the VE, participants would use a pinching motion towards the center of each object; and (2) to place objects in specific positions, they would open their fingers to drop them, as they would in real life. All participants were asked to replicate the required pinching motion before putting on the HMD. Participants were reminded that accuracy was important to the research and to be as accurate in object placement as possible. The

headset strap was then adjusted until the participant was comfortable. Participants were told to notify the experimenter immediately if they felt any discomfort such as dizziness or blurred vision in the virtual environment (none reported discomfort), and the experimenter began the program.

Thirty-one participants completed 74 trials. In each trial, participants were told to observe and memorize the location of an object as it appeared on the round table in front of them, and then they were directed to place the object exactly where it had appeared using their hands. In each trial, participants were presented with a target object for 5 s, after which the scene faded to a black screen for 2 s. After the delay, the object reappeared directly in front of the participant, on the edge of the table at the 0° line (see Fig. 2a). To place the object, participants used the same motions as they would in the physical environment: they grabbed the object to pick up it, moved their hand while holding it, and dropped the object in the desired location. Upon dropping the object on the table, participants were asked if their placement was final. Participants could either select "cancel" and restart the trial or rate their confidence in their placement, which ended the trial. There was no limit to the number of times participants could reposition each object. A 2-s inter-trial delay followed each trial, during which the participant saw a black screen displaying the trial number. After the delay, the next trial began, and a new object appeared on the table. The order of object presentation was random and therefore different for all participants.

The position of the player remained fixed at the bottom edge of the table for all trials. Participants could not walk around the table, but they could lean forward and back, and side to side as they moved their hands and virtual objects through the environment. All participants remained seated for the duration of the experiment. Upon experimental completion, participants filled out two surveys and then were debriefed.

Results

The data from our post-experiment surveys confirmed that all participants had experience with playing video games and were able to use Leap Motion to manipulate targets. We excluded errors that were larger than 45°. For the analyses, we set the bottom-most point of the circular table at 0° and proceeded counterclockwise.

We calculated the angular bias as the difference between the reported target angle and the actual angle, thus negative biases reflected underestimation of angles while positive biases reflected overestimation. We predicted that individuals would favor the use of priors over geometric prototypes to estimate locations from memory for the angular items. If individuals used the geometric prototype, then all responses would be biased towards the 45° line, regardless of item type

(see Fig. 1a). That is, both *proximal* objects (e.g., a plate with a slice of pizza) and *tangential* objects (e.g., a spoon) would be remembered toward the center of the quadrant. However, we expected a different pattern of bias for *proximal* and *tangential* items if individuals used priors: people would underestimate the angle of *proximal* objects (e.g., a plate with a slice of pizza) toward the 0° degree line (negative sign) rather than towards the diagonal line, as shown in Fig. 2b. For the *tangential* items, we expected that memory would be biased toward the tangential prior. We followed the standard procedure to empirically determine the position of the tangential prior. The procedure, first employed by Huttenlocher et al. (1991), identifies the point of zero bias within a category by regressing angular bias on actual target angle and using the regression line to calculate the prior. Our analysis indicated that the tangential prior was located at the 12.6° point in this experiment.

Our analysis showed a negative bias for proximal objects ($M = -4.41$, $SD = 3.23$, $t(18) = -5.94$, $p < .0001$), confirming that people moved these objects toward the center line. Using the empirical tangential prior, we divided the target angles into two bins, with the logic that angles smaller than the prior would be overestimated toward the prior while angles greater than the prior would be underestimated toward the prior. Targets classified into the upper bin therefore included angles greater than 12.6°, and targets classified into the lower bin included angles smaller than 12.6°.

The data indeed showed a negative bias for the tangential targets in the upper bin ($M = -4.73$, $SD = 3.5$, $t(18) = -5.95$, $p < .0001$), indicating that these angles were underestimated, and a non-significant positive bias for those in the lower range, ($M = 0.38$, $SD = 2.0$, $t(18) = 0.95$, $p = .20$). The pattern indicates that participants favored the use of the prior over the geometric prototypes (at the 45° line) in their estimations. That is, people misplaced common objects on a virtual dining room table toward prototypical locations from their experience with the objects rather than the centroid of the quadrant in which the object had appeared. The nonsignificant bias is consistent with the category-adjustment model, as targets close to the Cartesian coordinates or prototypes are expected to show little, if any, distortion (Huttenlocher et al., 1991). In fact, it is customary to not place targets close to these reference points. We acknowledge the restricted range in our data; nonetheless, these data are inconsistent with the use of the 45° geometric prototype.

Next, we conducted analysis for radial items. We calculated radial bias by subtracting the recalled radial position from the actual position. A negative bias would indicate that participants moved their estimates towards the center of the space while a positive bias would indicate that participants moved their estimates towards the edge of the table. Overall, our analysis revealed the same radial bias (magnitude and direction) for central and peripheral items (paired-sample t-test, $p = .56$), with the mean value of 0.05 or 5% of the radius of the table for both

central (SD = 0.04; one-sample t-test against zero t(18) = -6.0, p < .0001) and peripheral items (SD = 0.03; t(18) = -6.4, p < .0001). These findings indicate that participants slightly misjudged the distance of the targets from the center to the circumference, generally moving objects closer to the edge of the table regardless of type. These data are consistent with those of Williams and Sampaio (2017), who found that individuals do not use pre-existing expectations of everyday objects positions (i.e., priors) in radial estimations of line drawings representing objects in a 2D space. Together, these data indicate that the geometry of the space influenced radial judgments despite pre-existing expectations: radial responses were biased away from the center for objects expected to be found either at the center or the periphery of the table.

Discussion

We examined the role of experience-based priors on the category bias and found that individuals favor them over geometric priors for estimating angular but not radial positions. Our work contributes to the literature by showing that localizing common everyday objects in a circular space is not restricted to the use of cues intrinsic to the space. This is important because the majority of the empirical data on the category bias derives from locating targets that have little to no semantic information (i.e., dots in 2D circles instead of real-world objects in 3D spaces). However, in everyday life, as people interact with objects, they form expectations about their locations (Brewer & Treyens, 1981; Carlson-Radvansky, Covey, & Lattanzi, 1999; Hirtle & Mascolo, 1986; Hollingworth, 2005; Palmer, 1975) and their functions within that space (Castelhano & Witherspoon, 2016). Research has shown, for instance, that objects whose use is congruent with their placement in a scene are more easily found (Castelhano & Witherspoon, 2016; Eckstein, Drescher, & Shimozaki, 2006; Oliva & Torralba, 2007; Palmer, 1975), especially when people are exceedingly familiar with the objects (Brockmole, Hambrick, Windisch, & Henderson, 2008). People develop prototypical locations for everyday objects based on their experience (e.g., people expect a vase to go in the center of a table as opposed to the edge), and this spatial prototype in turn informs the likely location for a given object before any other evidence is provided and/or considered. Our findings are consistent with recent research showing that people are more accurate in visual searching tasks when objects are imbued with a purpose congruent with their position in the scene and when objects are located in that position in space (Castelhano & Witherspoon, 2016). Along the same lines, we found that people remembered the location of objects that would typically be found on a common household dining room table using their past experience with these objects.

To test the category bias in memory for locations for objects that have prototypical locations based on past experience

(i.e., priors), we used a virtual 3D version of the dot-in-circle task in which individuals had active control over the objects in space using their bare hands. Our virtual 3D task was interactive, mimicking real life, and individuals used everyday actions to manipulate the objects during the task: they picked up, moved, and dropped objects in similar ways they do in the physical world. We believe that this 3D VE technology provides an ideal tool to spatial research, in that environments hold fidelity to real life while still under rigorous experimental control (e.g., Loomis, Blascovich, & Beall, 1999).

Our finding that angular biases were based on the experience-based priors is consistent with the category literature. Categories provide reliable information about basic properties of its members and serve as tools to make inferences. A category functions to classify, understand, predict, reason, and communicate information about its members. As an object's frequency of instantiation within a particular set increases, the object becomes more familiar within that context over time (Barsalou, 1985). Therefore, experience with an object increases the degree of association between the object and the category. Consequently, it seems natural that people would use information about where an object should be in space to later estimate its location from memory. For example, if one frequently sees a vase in the center of tables, then the individual would more likely use a general vase's prototypical location to make a spatial judgment about a particular vase.

Radial bias

We found that the radial biases were based on the geometric prototype. That is, objects were estimated to generally be closer to the edge than they actually were. The finding is consistent with recent work (Williams & Sampaio, 2017) that revealed the robustness of the geometric radial prototype in estimates of shapes representing everyday objects in a two-dimensional circular space. It appears that the geometry of the table is difficult to overcome as people make radial judgments, even when there exist pre-existing expectations about locations.

We are not certain, however, whether the radial bias was towards the geometric prototype or the observer. Specifically, while it is possible that individuals used the typical exocentric frame of reference to form the two-thirds prototype onto the virtual 3D round table, it is also possible that instead they used an egocentric reference frame. Sargent, Dopkins, and Philbeck (2011), for example, found that people can define categories using an egocentric (body-based) rather than allocentric (space-based) frame of reference in a single room. Our data do not provide insight into whether the environment was encoded from an egocentric or an allocentric frame of reference. Future research is needed to address the question of whether people use allocentric or egocentric reference frames in this more ecologically valid task (e.g., to manipulate learned viewpoint angles).

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