Bias in Spatial Memory: Prototypes or Relational Categories?

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Abstract

Two experiments examined participants' use of independent and relational category structures in a spatial memory task. When estimating the locations of dots presented on a rectangular display, many participants appeared to divide the space into left and right relational categories, biasing estimates away from the center of the screen and toward the outer edges, in contrast to prior work showing biases toward centrally located prototypes. More participants showed this relational pattern at short interstimulus intervals than at long ones. The results suggest that participants flexibly make use of different types of spatial structure under different task demands. **Keywords:** spatial memory; categorization.

Introduction

Categories profoundly affect our interpretation of situations. But how are categories constructed, and how do particular situations impact this construction? Recent studies distinguish between categories defined in isolation and those that are defined in relation to other categories (see Chin-Parker & Ross, 2004; Genter & Kurtz, 2005; Goldstone, 1996; Yamauchi & Markman, 1998). This distinction between relational and non-relational category structures comes out of the literature on categories of objects. To our knowledge, there has been little discussion of this issue in the spatial domain, despite the large literature on spatial category effects. Thus it is not known what factors might influence the kinds of category structure people use to organize space. To the extent that categories of objects and of space serve similar functions, the distinction between relational and independent categories may emerge in the spatial domain as well.

Research on categories of objects has shown that when a category is construed as independent, the category center is generally treated as the prototype, leading to fast, accurate classification and high typicality ratings for central values (e.g., Goldstone, 1996; Posner & Keele, 1968; Rosch, 1975). However, when categories are established in a contrasting relation to one another, the values that show advantages in classification and higher typicality ratings tend to be more extreme than the central values (e.g., Atran, 1999; Barsalou, 1985; Goldstone, Steyvers, & Rogosky, 2003; Davis & Love, 2010). That is, the best exemplars of contrasting categories are idealized caricatures that exaggerate the differences between the categories, rather than the most typical values. These different category structures have also been shown to influence how individual category members are remembered. When items within a single category vary along a continuous dimension such as size or hue, estimates of individual items are biased toward the central value of the presented set (e.g., Huttenlocher, Hedges, & Vevea, 2000), but when that set is divided into two distinct categories, estimates may be biased away from the value corresponding to the category boundary (Goldstone, 1995, but see also Sailor & Antoine, 2005).

Patterns of bias in estimates have also been used to investigate categorization in the spatial domain. A common finding is that when participants reproduce the location of a stimulus within a bounded spatial frame, their location estimates are systematically biased toward some locations and away from others. A prominent model explains these biases as category effects that arise during reconstructive memory (Huttenlocher, Hedges, & Duncan, 1991). In a process likened to Bayesian estimation, the model posits that people use the category information as a prior distribution in order to adjust for the inexactness of fine-grained memory, leading to systematic biases toward the center of the prior distribution. As predicted by this account, when fine-grained memory is worsened by adding a delay, bias becomes more extreme, suggesting that the category is given more weight during memory reconstruction. This model offers an account of the large literature on how categories influence memories of stimulus features and suggests that bias in estimates can reveal the category structure that people impose on space.

The categories that are revealed by bias in spatial memory tend to be consistent across many variations in experiment procedures. In general, estimates are biased away from outer edges and internal axes of symmetry and toward centrally located prototypes. For example, within a circle, estimates are biased toward the centers of mass of the four quadrants bounded by the horizontal and vertical axes of symmetry (Huttenlocher, et al., 1991; Huttenlocher, Hedges, Corrigan, & Crawford, 2004). Stretching the circle along one dimension so that it becomes an ellipse moves the prototypes accordingly (Wedell, Fitting, & Allen, 2007). Stimuli within a rectangular frame, such as sandbox or a rectangle drawn on paper (Huttenlocher, Newcombe, &

Sandberg, 1994), or shown on a computer screen (Crawford & Duffy, 2010) are shifted away from the rectangle's outer edges and away from the midpoint, suggesting that the categories used are the left and right halves of the rectangle.[1]

A primary goal of the current work is to explore whether the distinction between relational and independent category structure can inform our understanding of spatial categories. Based on studies of object categories, these two category structures would be expected to produce different bias patterns in memory for the locations within a rectangle. An independent construal would divide the rectangle into two subregions, place prototypes at the center of each region, and lead estimates to be biased toward those two prototypes and away from the outer edges and internal boundary. Alternatively, a purely relational approach to dividing the rectangle would lead to overall outward bias, as items on the left would be estimated as further leftward and items on the right as further rightward. This would be comparable to the caricature effect by Goldstone (1995) in work on hue estimates. Prior studies that have tested memory for locations within a rectangular frame have been interpreted as supporting assimilation toward prototypes, but examination of aggregate data seems to show something in between. For example, data reported by Crawford & Duffy (2010) show a pattern of estimates that is similar to what the prototype account would predict, but with greater bias away from the center than would be predicted if estimates were biased toward centrally located prototypes.

Another goal for this work is to examine the possibility that participants might take different approaches (or a combination of approaches) to structuring a given space. Rather than combining participants and fitting their collective data, which presumes that the collective well represents individuals, we model individual participants separately. We also examine factors that may encourage the use of relational versus independent category structures, such as the time between stimulus presentation and response. Experiment 1 examines whether people's reliance on relational or independent categories depends on how long they must hold a stimulus in memory. Finding especially strong evidence of relational coding at short intervals, Experiment 2 replicates the finding and examines whether a certain aspect of our response methodology may have contributed to that result.

Experiment 1

Method

Participants 51 undergraduates at the University of Richmond participated in exchange for course credit.

Procedure Participants were seated in front of a computer with a 21" (diagonal) display set to resolution of 1920 by 1080 pixels. On each trial, they viewed a white dot (12 pixels diameter) on a black background for 900 ms. The dot was followed by an interstimulus interval, during which the screen went gray. Then the screen went black again and a response dot appeared near the top of the screen in its horizontal center. Using the mouse, participants moved the response dot to the location where they remembered seeing the stimulus dot and then clicked to register their response. There were 90 unique stimulus dots, all at the same central vertical position (540) and evenly spaced across the horizontal dimension of the screen approximately every 21 pixels. Each dot was shown twice, once with an interstimulus interval of 300 ms and once with an interval of 3000 ms, for a total of 180 trials. Trial order was randomized for each participant.

Results and Discussion

Models. Errors more than three standard deviations from the mean by participant were culled. Data from each participant and each time delay was fitted separately, using two models. The first model instantiated a simple version of the category adjustment model, assuming two symmetrically located categories with Gaussian distributions. The distance of the prototypes from the screen center and the variance in the prototypes was fitted to the data as free parameters, as was the relative weighting of input from memory and the categories. The second model was intended to capture the relational comparison account: bias is assumed to linearly increase with distance from a centrally located boundary. Although truncation at the edges is predicted in both models, neither model included this as a factor directly.

Resulting model fits were obtained using the R function optim (R Development Core Team, 2008); since the models were not nested, they cannot be compared using a likelihood ratio test. We compared them using BIC; each participant's data was then summarized with two values: the best fitting model at 300ms, and the best-fitting model at 3000ms.

Results.

The overall pattern of bias is shown in Figure 1 for each interstimulus interval. Positive values indicate rightward bias and negative values leftward bias.

At 300 ms, the relational model was a better fit than the prototype model for 66% of participants. At 3000ms, only 49% were better fit by the relational model, a significant shift by McNemar's test (p~0.03). Space precludes the display of the per-subject data, but Figure 2 displays the mean bias of participants who were better fit by each model, for each interstimulus interval, and Figure 3 displays data from two participants who illustrate each the two different strategies.

[1] Although a different pattern is found in young children (Huttenlocher et al., 1994)

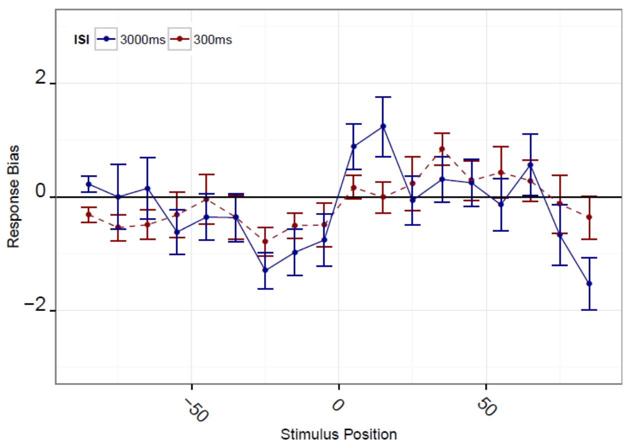

Figure 1: Mean bias at each ISI. Positive bias indicates a rightward shift in memory, negative bias a leftward shift.

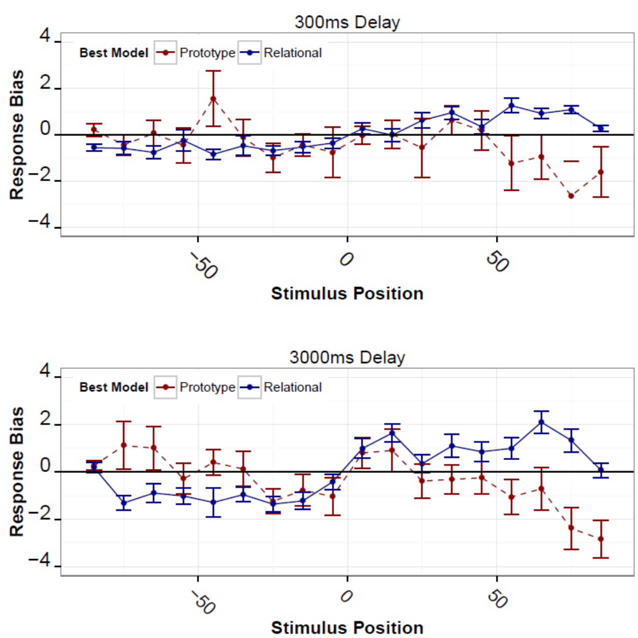

Figure 2: Mean bias at each delay for those best fit by each model.

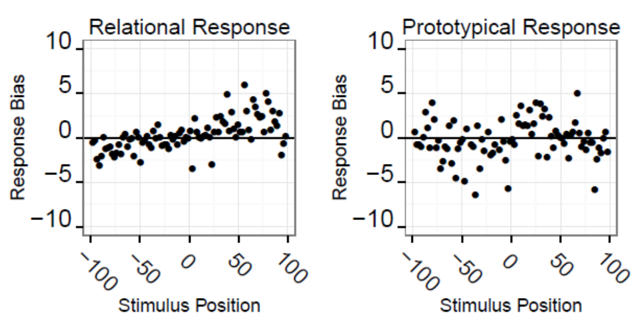

Figure 3: Estimates from two participants to illustrate the relational and prototype patterns of bias

The overall pattern shows bias outward much more than inward, and looks like caricature effect found in work on contrasting categories of objects (Goldstone, 1995). This suggests that many participants are coding location as left or right of center. Indeed, if we assumed participants were all biasing toward some shared prototype, that prototype would have to be located off of the screen's edges at short delays to account for the observed pattern.

This extreme outward bias is especially pronounced at the shorter delays. This differs from prior work (e.g., Huttenlocher et al., 1991) that has shown similar bias forms that are more extreme for longer delays. Here we find that the bias changes qualitatively. It appears that types of boundaries, perceptible and subjectively imposed, operate differently.

Experiment 2

The results of Experiment 1 show a much stronger outward bias than has been found in previous studies of immediate spatial memory. This raises the question of which methodological differences might give rise to the difference in results. Experiment 2 examines one possible factor: the starting location of the response dot. In Experiment 1, the response dot appeared horizontally centered near the top of the screen. It is possible that this contributed to the observed effects by imposing an immediate relational structure on the task and by increasing the salience of the screen's horizontal center.

A variety of different responses have been used in previous studies of category effects on spatial memory. Some used a digital stylus (Huttenlocher, et al., 1991) or pencil and paper versions of this task (Crawford & Duffy, 2010). In versions that have used a computer mouse, the response dot has been implemented in several ways – sometimes appearing at the center of the bounded region (Wedell et al., 2007; Huttenlocher, Hedges, Corrigan Crawford), sometimes it appears outside of the bounded region (Sampaio & Wang, 2009), and sometimes at a random location within the bounded space (Crawford & Duffy, 2010). To our knowledge no studies have examined what effect the starting location of the response dot might have on spatial memory. In study two, we manipulated the location of the response dot to examine whether estimates might be affected by an initial relational comparison between the stimulus dot and response dot locations.

Method

Participants Twenty four undergraduates at the University of Richmond who participated in exchange for course credit.

Procedure The materials and stimulus distribution were the same as in Experiment 1. All 180 trials used the short (300ms) interstimulus interval. On each trial, the response dot appeared near the top of the screen and either in the center of the left half of the screen (480 pixels from the left edge) or in the center of the right half of the screen (1440 pixels from the left edge). Each stimulus dot was shown twice, once followed by the left response dot and once with the right. Order of trials was randomized.

Results and Discussion

The same two models used in Experiment 1 were fitted to individual participant's responses in Experiment 2, with one difference. In order to investigate the influence of the cursor position, the models were each assigned a parameter that shifted the effective midpoint in the direction of the cursor. The prototypes were then placed proportionally symmetrically around this midpoint (say, 40% of the way from the estimated midpoint to the screen edges on both sides, although this might not be the same physical distance). For simplicity, the midpoint bias was assumed to be symmetric for trials on which the cursor was on the left or on the right.

Replicating Experiment 1, estimates were strongly biased away from the screen's center, even for stimuli near the outer boundaries of the display, and the relational model was the better-fitting model (by a BIC criterion) for 21 of 24 participants (83%). In addition, data from all participants, presented in Figure 4, indicated a bias in estimates due to cursor position, especially in the region between the cursors, for which categorical information (left vs. right) would be predicted to differ depending on cursor position. To evaluate this influence, we analyzed the fitted shift of the category boundary away from the midpoint in response to the cursor position for each participant (excluding the participants fit by the category adjustment model did not impact the conclusions reached here). The mean of these parameters was estimated with a bootstrap procedure (using 10,000 replications via the boot package; the data were significantly non-normal by a Shapiro-Wilks test, W=0.8, p~0.0004). The 95% confidence interval on the mean excluded zero (CI=[1.25%, 23.8%]), indicating that the apparent midpoint was shifted in the direction of the starting cursor position, but not shifted all the way out to the starting cursory position, as would be expected if the starting position alone produced the outward bias. This observed shift reveals an additive effect of biasing away from the screen's center and biasing away from the starting cursor value, although it is not clear if these effects combine within a trial or if different relational structures apply from trial to trial. To our knowledge, this is the first study to show that the starting position of the response cursor influences estimates of spatial location. The findings suggest that, although placing the response dot at the screen's center may have contributed to the outward bias found in Experiment 1, it does not fully account for it.

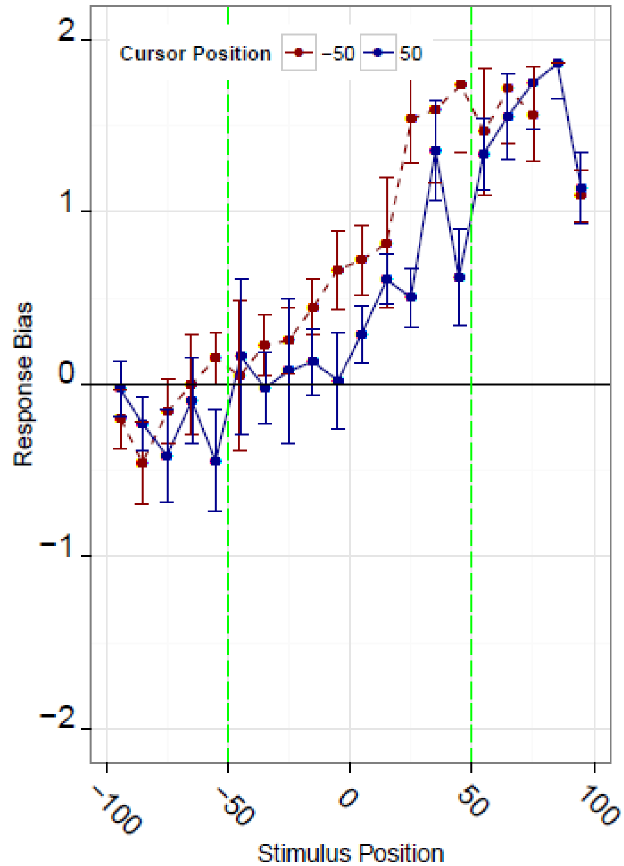

Figure 4. Bias for each of the response dot's starting locations.

General Discussion

We report two experiments showing that, when estimating the locations of horizontally distributed objects in a rectangular display, a substantial number of participants produce biases outward from the center, such that items on the left are remembered as having appeared further leftward than they were and items on the right as further rightward. For these participants, estimates effectively exaggerate the distance between stimuli on the left versus the right, an effect comparable to biases observed in memory for non-spatial object attributes when a contrasting relation exists between two adjacent categories (Goldstone, 1995). In addition, the results indicate that more participants show this relational pattern at short time delays (300 ms) than long ones (3000 ms). Finally, we find that estimates are affected by the response dot starting location, but this effect does not account for the general outward bias we observed.

We used a modeling strategy that classifies individual participants according to whether they are better fit by a relational or prototype strategy. This approach does not tell us how well the data from each participant was fitted, and some participants' estimates were not well described by either model. What the approach provides is compelling evidence that combining participants and fitting their collective data misses an important aspect of behavior by obscuring the fact that individuals apply different strategies to the task. Collapsing across these strategies can lead researchers to draw conclusions about cognition that do not actually apply to individual minds. Had we collapsed across participants, we likely would have concluded that participants bias toward prototypes and that the prototype locations depend on ISI. Instead, our analysis shows that many participants are not well described by a prototype model at all, and that very few fit a prototype account when time delays are especially short. This suggests that rather than taking a single, fixed approach to spatial categorization, participants may fluidly switch strategy under different task demands.

It is not clear why a relational strategy might dominate at shorter time delays. Huttenlocher and colleagues (e.g., Huttenlocher et al., 1991; Crawford, Huttenlocher, & Engebretson, 2000) have argued that because longer delays increase memory uncertainty, people should (and do) give more weight to category-level information. However in the present case, the delay manipulation has a different effect: it leads people to adopt different category structures. Building on the idea from Huttenlocher's category effects model that people rely on category structure to reduce variability of estimates, we suggest that when uncertainty is low (i.e., at short delays), the vertical axis of symmetry may provide a coarse and adequate preliminary structure, and that only as memory becomes more uncertain do other structural elements (i.e., outer boundaries, centrally located prototypes) provide enough additional information to be worth using.

A possible interpretation of the results would be that the time delays differentially tap into perception and memory, and that the caricature effect we've shown is due to perceptual processes. However, this is untenable because if the bias operates in perception, it should affect both the stimulus and response dots (cf., Firestone & Scholl, 2014). In that case, the biases would cancel out, leading to unbiased reports.

Given that many prior studies have described spatial memory as being biased toward category prototypes, it is striking that our results show such a strong relational pattern. In addition to the participant-level modeling employed here, our study introduced additional variations – we used a larger screen than other computerized tasks have used, distributed the dots in a horizontal row rather than across the whole screen, and did not draw a bounded shape on the screen but allowed the computer screen itself to provide the boundaries. It is not yet clear which of these factors, individually or in combination, may explain our findings. By establishing a situation that produces a caricature-like pattern of results in the spatial domain, the present study suggests several avenues for future research.

The present study raises questions about the nature of spatial category boundaries. As noted above, the stimuli shown here were presented on a large rectangular computer display but not within a geometric shape drawn on the screen. The screen's edges might be expected to have powerful effects on memory because they necessarily constrain the possible locations of the stimuli, which cannot appear off of the screen. It is striking that the center of the screen, which is not marked by any perceptible features and provides no necessary constraints on possible dot position, appears to have a much more pronounced effect on memory than do the readily perceptible and functionally necessary screen edges.

We return to the opening questions that motivated these studies: how do people construct categories? When external structure supports either prototype-like categories or relational categories, how do people choose which construal to employ? This study provides initial evidence that people adopt different approaches to categorizing the same spatial display, and demonstrates one factor, the amount of time a stimulus is held in memory, that influences which strategy is used. This suggests that representational structures may themselves be highly tuned to the situation at hand.

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