2D location biases depth-from-disparity judgments but not vice versa

Nonie J. Finlayson* and Julie D. Golomb+

Department of Psychology, Center for Cognitive & Brain Sciences, The Ohio State University, Columbus, OH 43210, USA

* Correspondence should be addressed to Nonie Finlayson (nonie.j@gmail.com). This author's current affiliation is Experimental Psychology, 26 Bedford Way, University College London, WC1H 0AP, UK.

+ golomb.9@osu.edu

Abstract

Visual cognition in our 3D world requires understanding how we accurately localize objects in 2D and depth, and what influence both types of location information have on visual processing. Spatial location is known to play a special role in visual processing, but most of these findings have focused on the special role of 2D location. One such phenomena is the *spatial congruency bias* (Golomb, Kupitz, & Thiemann, 2014), where 2D location biases judgments of object features but features do not bias location judgments. This paradigm has recently been used to compare different types of location information in terms of how much they bias different types of features. Here we used this paradigm to ask a related question: whether 2D and depth-from-disparity location bias localization judgments for each other. We found that presenting two objects in the same 2D location biased position-in-depth judgments, but presenting two objects at the same depth (disparity) did not bias 2D location judgments. We conclude that an object's 2D location may be automatically incorporated into perception of its depth location, but not vice versa, which is consistent with a fundamentally special role for 2D location in visual processing.

Keywords: depth perception, space perception, 3D space, 2D space, spatial congruency bias

Acknowledgements: This work was supported by research grants from the National Institutes of Health (R01-EY025648) and Alfred P. Sloan Foundation (BR-2014-098). We thank members of the Golomb Lab for assistance with data collection.

Introduction

It has been suggested that location information plays a special role in visual cognition, influencing visual processing and the perception of object features in several ways (Cave & Pashler, 1995; Chen, 2009; Golomb et al., 2014; Treisman & Gelade, 1980; Tsal & Lavie, 1988, 1993). A classic example is Treisman's *feature integration theory* (Treisman & Gelade, 1980), which theorized that spatial attention is required to bind features into a coherent object. Another classic study by Tsal and Lavie (1993) found that when instructed to report one of two targets based on the color of a cue, participants were unable to ignore the location of the cue, even though it was irrelevant and detrimental to performance, supporting an automatic encoding of 2D location information. More recently, Golomb et al. (2014) demonstrated a *spatial congruency bias*, where two objects are more likely to be judged as the same identity if they appeared in the same spatial location.

The unique role of location information in visual perception is in line with the ubiquitous nature of spatial representation throughout visual cortex and beyond. Both neurophysiology and functional neuroimaging studies reveal a large number of regions in the brain sensitive to visuo-spatial information (Felleman & van Essen, 1991; Grill-Spector & Malach, 2004). Human visual cortex is organized into topographic maps of spatial location (Engel et al., 1994; Sereno et al., 1995; Silver & Kastner, 2009; Wandell, Dumoulin, & Brewer, 2007), and location information can be decoded from fMRI response patterns in early, ventral, and dorsal visual areas (Golomb & Kanwisher, 2012; Kravitz, Kriegeskorte, & Baker, 2010; Schwarzlose, Swisher, Dang, & Kanwisher, 2008).

Critically, while the above studies have focused on 2D spatial information, we live in a 3D world, and visual cognition requires understanding how we accurately represent and localize objects in 2D and depth, and what influence both types of location information have on visual processing. A number of studies have looked at how depth information is perceived and represented in the brain (Backus, Fleet, Parker, & Heeger, 2001; Ban, Preston, Meeson, & Welchman, 2012; DeAngelis & Newsome, 1999; Hubel & Wiesel, 1970; Preston, Li, Kourtzi, & Welchman, 2008; Tsao et al., 2003), including a recent fMRI study from our group directly comparing representations of 2D location and position-in-depth across the visual hierarchy (Finlayson, Zhang, & Golomb, 2017).

A related question is how 2D location and position-in-depth compare in terms of their influences on visual perception. This is important because accurate visual perception and action require integrating information about objects' features and their locations, which may be processed separately in the brain, e.g. the "binding problem" (Treisman, 1996). During this binding process, is depth information treated more like an object feature such as color, shape, and texture, or is position-in-depth part of an integrated 3D representation of space?

From a theoretical perspective, this question is particularly notable because a number of studies have posed a special role for location information. Are certain types of location information more "special" in this context? Depth is a unique case because it is fundamentally important for real-world object localization, but it must be extracted from 2D retinal information, e.g. differences in retinal positions between the two eyes (binocular disparity). The *spatial congruency bias* (Golomb et al., 2014) -- which demonstrates that location information is innately tied to representations of object features -- is particularly well-suited for examining the role of depth-from-disparity in the binding process. This paradigm has previously been used to compare different types of location information in terms of how much they bias different types of features (Bapat, Shafer-Skelton, Kupitz, & Golomb, 2017; Finlayson & Golomb, 2016; Shafer-Skelton, Kupitz, & Golomb, 2017). The spatial congruency bias demonstrates that participants are automatically biased to judge the features of two objects as more similar when the objects appeared in the same location, despite location information being irrelevant to the task. Location has been shown to bias a variety of feature/object judgments, including orientations, colors, shapes, and faces (Golomb et al., 2014; Shafer-Skelton et al., 2017). Critically, this *spatial congruency bias* appears to be unique to location: object features do not induce a bias – either on each other, or on location judgments (Golomb et al., 2014). Where does depth information fit into this asymmetry? In comparing position-in-depth and 2D location, we can ask (1) whether both types of location information bias feature judgments, and (2) whether the two types of location bias judgments of each other. The first question was addressed in a recent paper

(Finlayson & Golomb, 2016), finding no reliable effects of position-in-depth on color perception. The second question is the focus of this report.

The spatial perception literature tells us a great deal about localization in 2D, including how various parameters and contexts affect our ability to localize (Adam, Davelaar, Van der Gouw, & Willems, 2008; Adam, Ketelaars, Kingma, & Hoek, 1993; Tsal & Bareket, 2005). There is also considerable research on distance perception, with particular focus on how this information arises from the 2D properties of visual angle and visual direction (Gajewski, Philbeck, Wirtz, & Chichka, 2014; Gajewski, Wallin, & Philbeck, 2014; Harris & Mander, 2014). In terms of their influences on each other, depth information is known to affect a range of processes including attention (Finlayson & Grove, 2015; Nakayama & Silverman, 1986) and early visual processes such as size perception (Murray, Boyaci, & Kersten, 2006), but it is unknown whether depth location information might influence 2D localization per se.

In terms of whether 2D location information might bias depth localization, a classic psychophysics phenomenon called the *equidistance tendency* (Gogel, 1965; Wist & Summons, 1976) has shown that objects that are presented closer to each other in 2D space tend to be perceived as more similar in depth (i.e., distance from the viewer). The *equidistance tendency* may reflect a default principle that nearby objects are often similar in depth distance as well, which may be helpful for perception, especially when reliable depth information is not available. Interestingly, a similar explanation has been posed for the *spatial congruency bias* – that our visual systems might rely on a default assumption that two objects are likely to be the same identity if they share the same location. Similar to how the equidistance tendency has a stronger influence on distance judgments when stimulus support for distance and depth cues are weaker (Gogel, 1965), the *congruency bias* is strongest when the feature differences between the stimuli are less obvious; i.e. when the task is perceptually difficult (Golomb et al., 2014). The *equidistance tendency* suggests that 2D location information will likely bias depth judgments in the *congruency bias* paradigm, but it will still be important to test in the context of this paradigm and the other types of *congruency bias* effects. More interesting is the direct comparison of the two conditions using the same paradigm: to what extent does 2D location information bias depth judgments, and depth information bias 2D location judgments?

Note that this is a different question than whether depth discrimination is weaker than 2D discrimination (e.g., Gilinsky, 1951), since our emphasis is on whether the different types of location information *influence* each other. Just because one type of information is more discriminable doesn't necessarily mean it will influence judgments of other dimensions. E.g., in the Golomb et al. (2014) paper, even very small (near threshold) location differences were found to bias identity judgments, whereas very large, highly discriminable color differences did not. Thus the spatial congruency bias seems to tap into something special about location with important theoretical consequences, in that it influences judgments of other features, even when the location information is not highly salient.

The focus of the current study is comparing how depth-from-disparity and 2D space influence perception of each other in the context of the *spatial congruency bias*. We focus on binocular disparity because it is one of the most compelling depth cues (Finlayson, Remington, & Grove, 2012; McKee & Taylor, 2010), and importantly, because it allows for manipulation of depth position with minimal 2D location differences, compared to alternative (monocular) depth cues such as size and occlusion. Of particular interest is whether depth-from-disparity and 2D location exert symmetric or asymmetric effects on each other. A number of studies have demonstrated similar perceptual and attentional effects for depth as for 2D space, suggesting that depth may be a fundamental part of location representations. For example, Caziot and colleagues (2015) demonstrated that depth from binocular disparity is perceived very quickly and on a similar timescale to luminance changes. They suggested that binocular disparity might contribute to early visual processing more than has generally been appreciated. There is also considerable support for priming effects in depth: Just as we see for 2D location (Posner, 1980), presenting stimuli at the same depth results in faster responses than stimuli at different depths, indicating a depth-aware attention system (Atchley, Kramer, Andersen, & Theeuwes, 1997; Downing & Pinker, 1985; Finlayson, Remington, Retell, & Grove, 2013; Nakayama &

Silverman, 1986). Binocular disparity has also been shown to be advantageous for object recognition (Caziot & Backus, 2015).

However, other studies have shown that the perceptual and attention effects of depth are weaker or delayed compared to those effects seen for 2D space (Finlayson et al., 2013; Gilinsky, 1951; Kasai, Morotomi, Katayama, & Kumada, 2003; Loomis et al., 2008; Moore, Hein, Grosjean, & Rinkenauer, 2009), and depth did not seem to bias color judgments as strongly as 2D location did in a recent paper from our group (Finlayson & Golomb, 2016). Kasai and colleagues (2003) found that although attention to depth location modulates early ERP signals, these effects were weaker than those seen for 2D spatial attention. Furthermore, while our recent fMRI study found both depth-from-disparity and 2D representations across multiple brain regions (Finlayson et al., 2017), these more balanced 3D representations were restricted to later visual areas, whereas early visual cortex was predominantly 2D in nature. Likewise, a recent report found that 2D visual images from the two eyes are not transformed into a cyclopean representation of space until area V2 at the earliest (Barendregt, Harvey, Rokers, & Dumoulin, 2015). If the *spatial congruency bias* stems from very low-level visual processes, we might expect a more asymmetric interaction, where 2D location biases depth-from-disparity judgments but depth-from-disparity does not bias 2D location judgments.

To test these hypotheses, we conducted two experiments utilizing the *spatial congruency bias* paradigm. In Experiment 1 we tested what effect irrelevant 2D location information has on the perception of depth-from-disparity location. In Experiment 2 we tested the influence of irrelevant depth-from-disparity information on 2D (vertical) location. In each experiment, participants were presented with two sequential stimuli in the periphery and performed a two-alternative forced-choice same/different depth (Experiment 1) or vertical (Experiment 2) location judgment. Because past research has shown that depth discrimination is weaker than 2D discrimination (Gilinsky, 1951), differences in the relevant location dimension (depth for Experiment 1 and vertical location for Experiment 2) were set near the discrimination threshold (individually staircased to target 75% accuracy), while the differences in irrelevant location dimensions were set well above the discrimination threshold.

Method

Participants

Sample size was chosen based on a power analysis of the original spatial congruency experiment reported in Golomb et al. (2014), which had a *Cohen's d* = 1.01 and statistical power (1 - β) of 0.96 with $N = 16$. Experiment 1 had 16 participants (10 female; mean age = 19 years; range: 18-27), with five additional participants excluded for poor task performance (accuracy < 55%, pre-defined criteria). Experiment 2 had sixteen participants (10 female; mean age = 20 years; range: 18-23). All participants reported normal or corrected-to-normal color and binocular vision, and were screened for stereovision. Informed consent was obtained for all participants, and the Ohio State University Behavioral and Social Sciences Institutional Review Board approved the study protocols. All participants were compensated with course credit.

Stimuli

Stimuli were generated with the Psychtoolbox extension (Brainard, 1997) for MATLAB (MathWorks). Depth from binocular disparity was achieved using a Wheatstone stereoscope, with two 24" flat screen LCD monitors facing each other with mirrors set between and reflecting an image from each monitor to each eye of the observer. The viewing distance was 60 cm, with the observer sitting at a chinrest 90° to the monitors.

Stimuli for both experiments were random dot stereograms (RDS) with black and white dots (100% contrast), sized 0.4° × 0.4°, on a white background. Masks were an array of straight lines at random orientations covering the whole display (8° × 8°). Subjects fixated at the center of the screen on a small RDS patch of light and dark gray dots (18% contrast), sized 0.2° × 0.2°, always presented at the central screen depth (zero disparity). Stimuli were presented peripherally and could vary in horizontal, vertical, and depth location.

Procedure & Design

For both experiments, participants began each trial by fixating in the center for 500 ms, after which the first stimulus appeared in a peripheral location for 500 ms (Figure 1). This was followed by a blank screen (50 ms), and a mask (100 ms). Following another 1000ms fixation period, a second stimulus appeared. The second stimulus was presented for the same duration and masked as the first. Trial timing was chosen to match previous spatial congruency bias paradigms (Golomb et al, 2014). The 500ms presentation time should enable sufficient time to process the depth cue and accumulate accurate information for depth perception from binocular disparity[1] (Adam et al., 1993; Gajewski, Philbeck, et al., 2014; Sanocki & Sulman, 2009; Uttal, Davis, & Welke, 1994). Masks were included to ensure visual afterimages were not used to help with the same/different location task.

In Experiment 1 (same/different depth judgment), the second stimulus could appear in one of eight locations relative to the first stimulus: same or different depth location (relevant dimension) by same or different horizontal location (irrelevant dimension) by same or different vertical location (irrelevant dimension). These eight conditions were counterbalanced and equally likely. Horizontal, vertical, and depth location of the first stimulus were randomly assigned for each trial. The horizontal and vertical locations were 2° to the left or right of fixation, and 2° above or below fixation. Depth position was jittered between 0 to 64 arcmin (1.06°) in front of or behind fixation. When the second stimulus differed in depth, it differed by a small amount determined by each individual's discrimination threshold. The depth difference for each individual was determined by staircasing to 75% accuracy during practice trials, and then was adjusted further between runs if necessary. The average difference was 25.2 arcmin (0.42°) between the two stimuli. The horizontal and vertical locations of the second stimulus were chosen such that the two stimuli were 25% same horizontal same vertical (x1y1),

---

[1] Note that because we did not systematically vary presentation time, we cannot be certain that depth information accumulation had asymptoted by 500ms in this paradigm, but previous studies (cited above) have shown that depth from disparity information takes about 200ms to fully accumulate, and the RT data from Experiment 2 (and ability to perform the Experiment 1 task) suggest that subjects were indeed sensitive to the depth differences here. See also Discussion.

25% same horizontal different vertical (x1y0), 25% different horizontal same vertical (x0y1), and 25% different horizontal different vertical (x0y0).

In Experiment 2 (same/different 2D judgment), the vertical location was the task-relevant dimension. The first stimulus was jittered between 0° to 1.06° above or below fixation. When the second stimulus differed in vertical location, it again differed by a small amount determined by each individual's discrimination threshold. The vertical difference was staircased individually as described above, with an average difference of 0.39° above or below the first stimulus. The horizontal and depth locations (irrelevant dimensions) were positioned 2° to the left or right of fixation, and 18 arcmin (0.3°) in front of or behind fixation (36 arcmin distance between the two stimuli – well above discriminability threshold) and were chosen such that the two stimuli were 25% same horizontal same depth (x1z1), 25% same horizontal different depth (x1z0), 25% different horizontal same depth (x0z1), and 25% different horizontal different depth (x0z0). It should be noted that we chose to use vertical and not horizontal location for the relevant dimension in this experiment, because by using binocular disparity (i.e. small horizontal location differences in each eye) to vary the irrelevant depth location of a stimulus, we would be confounding depth location with horizontal location judgments.

In both experiments***,*** participants were instructed to judge whether the two objects were in the same location, along the relevant location dimension. In Experiment 1, they compared the two stimuli's depth locations; horizontal and vertical location was irrelevant to the task. In Experiment 2, they compared the two stimuli's vertical locations; horizontal and depth location was irrelevant to the task. Participants responded by keyboard press, and to ensure they were doing the task correctly, they were presented with visual feedback (green or red dot) informing them whether their response was correct. They were also provided with feedback if they broke fixation at any point during the trial, and the trial was aborted and re-run later in the block.

After a 500 ms feedback screen, the next trial began. Participants completed 80 trials per block, comprising 10 trials per each of the eight relevant-location × irrelevant-location conditions, in randomized order. Each participant completed one practice block and four main blocks.

Eye position was monitored with an EyeLink 1000 eye-tracking system, recording monocular pupil and corneal reflection position. Fixation was monitored for both experiments. If at any point the participant's fixation deviated greater than 1.5°, the trial was aborted and repeated. Ensuring accurate fixation was critical both to ensure accurate depth perception and fusion, and to ensure participants were not looking directly at the stimuli, which would defeat the purpose of exploring different 2D visual field locations.

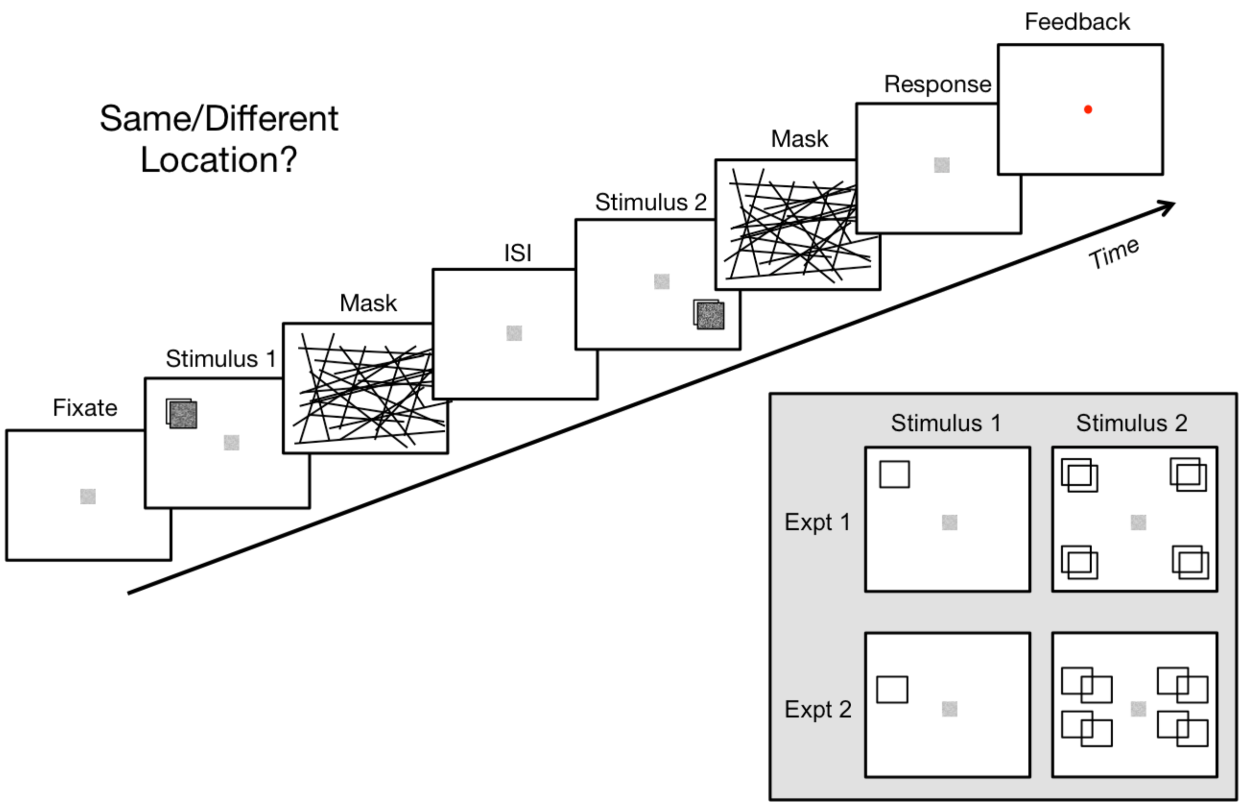

Figure 1. Schematic illustration of the task and stimuli locations for Experiments 1 and 2. For Experiment 1, the task was to indicate whether the relevant spatial dimension, depth, was the same or different across the two stimuli, while ignoring the irrelevant horizontal and vertical positions. For Experiment 2, the task was to indicate whether the relevant spatial dimension, vertical location, was the same or different across the two stimuli, while ignoring the irrelevant horizontal and depth positions. The inset shows a schematic sample stimulus 1 location, and the eight possible locations of stimulus 2. Distances between stimuli along the relevant dimension were subtle (adjusted to 75% accuracy threshold), while distances along the irrelevant dimensions were much larger.

Analyses

Our primary measure for all experiments was the Spatial Congruency Bias (Golomb et al., 2014). For each participant, we first calculated hit and false alarm rates for each location condition. For Experiment 1, we defined a "hit" as a "same depth location" response when the stimuli were in the same depth location, and a "false alarm" as a "same depth location" response when the stimuli were in different depth locations. For Experiment 2, hits and false alarms were defined analogously for vertical location instead of depth location. Using the hit rate and false alarm rate, we used signal detection theory to calculate bias (criterion) for each location condition.

For all experiments we focus on the bias measure because our main goal was to assess the *spatial congruency bias* (Golomb et al., 2014) for position-in-depth compared to 2D location. As secondary analyses we also report other standard behavioral measures, namely reaction time and d-prime, to assess whether the bias results were also accompanied by differences in response facilitation (priming and sensitivity, respectively). Values for each of these measures, as well as raw proportion of "same" responses, and alternate ways of calculating bias (normalized c and likelihood ratio β), can be found in Table 1.

$$\text{Bias (criterion)} = -(z(\text{hit rate}) + z(\text{false-alarm rate})) / 2$$

$$d' = z(\text{hit rate}) - z(\text{false-alarm rate})$$

$$\text{Normalized } c = \text{bias} / d'$$

$$\text{Likelihood ratio } (\beta) = e^{(z(\text{false-alarm rate})^2 - z(\text{hit rate})^2)/2}$$

Values for all measures were averaged separately for each participant and condition and submitted to repeated-measures ANOVAs, with effect size calculated with partial eta squared. Trials on which participants failed to respond, or responded with RTs greater than 2.5 standard deviations of the participant's mean RT, were excluded (less than 2.9% of trials for each experiment). We also excluded participants who had an overall task accuracy of less than 55% -- although some degree of uncertainty in responses is intentional for the near-threshold task (an important part of the Spatial Congruency Bias; Golomb et al., 2014), we wanted to ensure that subjects were not performing completely at chance (*only* guessing, or non-compliant). This criterion was set in advance at 55% consistent with prior studies using this paradigm (Finlayson & Golomb, 2016; Shafer-Skelton et al., 2017), but the same pattern of results below holds with stricter or looser cutoffs.

Results

Experiment 1

Figure 2A illustrates the proportion of "same depth location" responses broken down by hits and false alarms for each irrelevant location condition. We focus primarily on the bias measure, since our main goal was to assess interactions between spatial dimensions in terms of whether they influence judgments of each other, as measured by the *spatial congruency bias* (Golomb et al., 2014).

Does 2D location information bias depth-from-disparity judgments? Figure 2B illustrates the response bias as a function of the irrelevant location conditions; a negative bias indicates a greater tendency to respond "same depth". We found that irrelevant 2D location information biased depth judgments, such that when the two objects were in the same horizontal and/or vertical location, participants were more likely to report that the objects were at the same depth. (As can be seen from Figure 2A, the bias to judge the objects as the same can be seen as an increase in both hits and false alarms.) A two-way repeated-measures ANOVA with factors horizontal location (same/different) and vertical location (same/different) revealed that both horizontal and vertical locations elicited a significant main effect on response bias (X; $F_{1,15} = 15.23$, $p = .001$, $\eta_p^2 = .50$, Y; $F_{1,15} = 20.76$, $p < .001$, $\eta_p^2 = .58$ respectively). There was no significant two-way interaction ($F_{1,15} = 2.24$, $p = .156$, $\eta_p^2 = .13$).

Other effects. As noted above, our primary measure of interest was the congruency bias. Because the congruency bias is sometimes accompanied by priming effects such as RT and d' (see Discussion), these other measures are listed in Table 1. There was a significant influence of horizontal location on *d'* ($F_{1,15} = 6.77$, $p = .020$, $\eta_p^2 = .31$). This effect was in the same direction but not quite significant for vertical location ($F_{1,15} = 0.4.47$, $p = .052$, $\eta_p^2 = .09$), with no significant interaction ($F_{1,15} = 1.50$, $p = .240$, $\eta_p^2 = .09$). RT priming was significant for vertical location ($F_{1,15} = 7.04$, $p = .018$, $\eta_p^2 =$

.32) and in the same direction but not significant for horizontal location ($F_{1,15}$ = 2.08, p = .115, η_p^2 = .16), also with no significant interaction ($F_{1,15}$ = 0.89, p = .361, η_p^2 = .06).

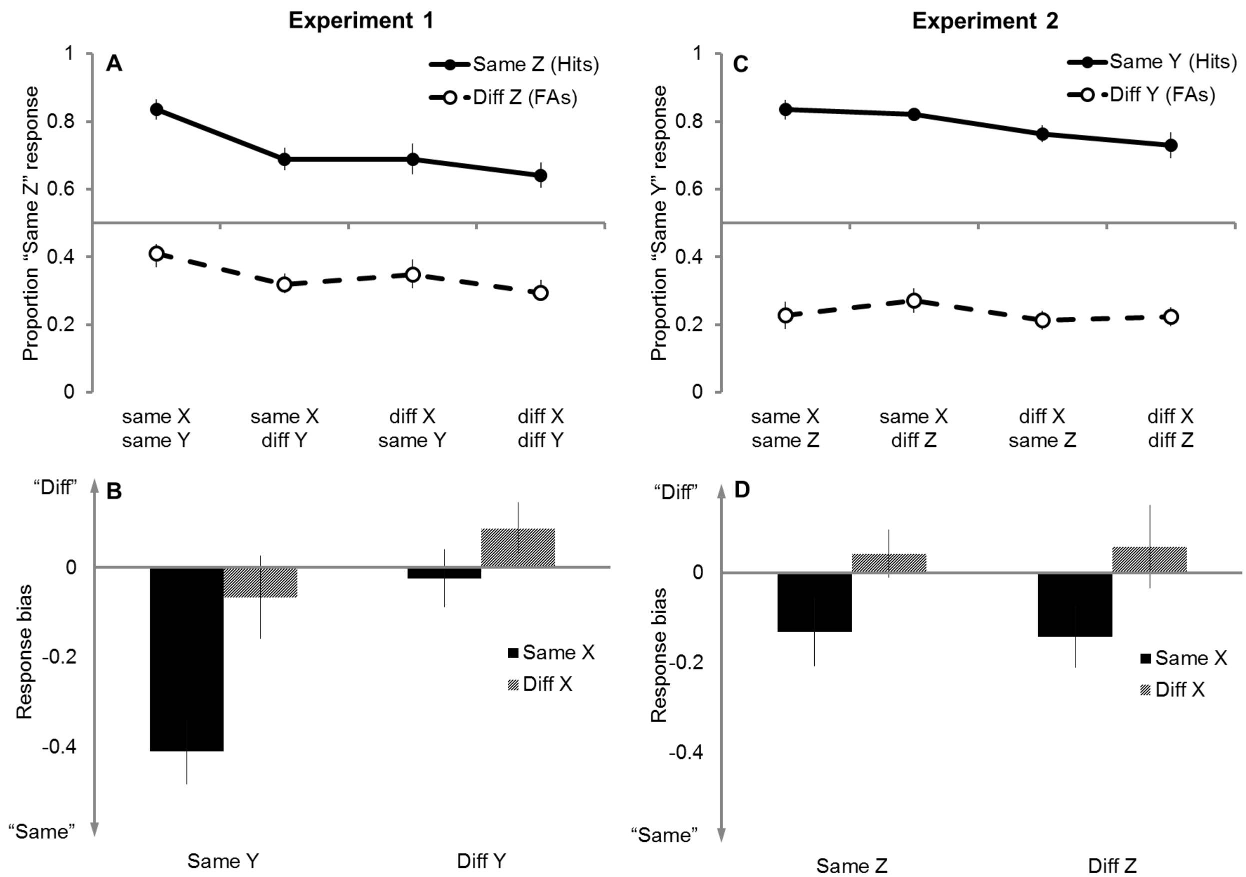

Figure 2. Experiments 1 (A & B) and 2 (C & D) results. (A) Proportion of "same depth" responses and (B) response bias plotted for each of the four irrelevant horizontal (X) and vertical (Y) location conditions in Experiment 1. (C) Proportion of "same vertical location" responses and (D) response bias plotted for each of the four irrelevant horizontal (X) and depth (Z) location conditions in Experiment 2. Negative response biases indicate greater likelihood to report "same". Error bars show SEM (N=16).

Experiment 2

Figure 2C illustrates the proportion of "same vertical location" responses broken down by hits and false alarms for each irrelevant location condition.

Does depth-from-disparity location information bias 2D judgments? Figure 2D illustrates the response bias as a function of the irrelevant location conditions. There was no significant effect of depth location on response bias ($F_{1,15}$ = 0.002, p = .969, η_p^2 < .01), nor was the two-way interaction significant ($F_{1,15}$ = 0.07, p = .795, η_p^2 = .01).

Other effects. Depth effects: There was also no significant effect of depth location on d' ($F_{1,15}$ = 2.70, p = .122, η_p^2 = .15). However, RT priming was significant for depth location ($F_{1,15}$ = 5.97, p = .027, η_p^2 = .29), suggesting that the irrelevant depth information was discriminable enough that participants were sensitive to it on some level. Horizontal effects: There was a small numerical bias to respond "same vertical location" when horizontal position was the same, although this effect did not reach significance ($F_{1,15}$ = 3.86, p = .068, η_p^2 = .21). There were no significant influences of horizontal location on *d'* or RT (see Table 1: $F_{1,15}$ = 2.85, p = .112, η_p^2 = .16, and $F_{1,15}$ = 2.21, p = .158, η_p^2 = .13, respectively).

Comparison of Experiment 1 and 2

Taken individually, the results of Experiment 1 demonstrate that 2D location significantly biases depth-from-disparity judgments, while Experiment 2 demonstrates that depth-from-disparity does not significantly bias 2D location judgments. To directly test this asymmetry we next conducted a mixed-effects ANOVA comparing the bias found in each experiment. For a more straightforward comparison we averaged across horizontal location, so that we could conduct a more symmetrical comparison of the effect of vertical location on depth judgments in Experiment 1 and the effect of depth location on vertical judgments in Experiment 2. We conducted a 2x2 ANOVA on the bias scores, with a between-subjects factor of Experiment and a within-subjects factor of same/different location (for the irrelevant dimension: i.e. same/different Y for Experiment 1 and same/different Z for Experiment 2). We found a significant interaction ($F_{1,30}$ = 15.31, p < .001, η_p^2 = .34). Thus, our results indicate that vertical locations bias depth-from-disparity judgments, depth-from-disparity locations do not bias vertical judgments, and the difference between these effects (i.e. the 2D-depth asymmetry) is significant.

General Discussion

We investigated the perceptual interactions between position-in-depth and 2D space. Specifically, we investigated the *spatial congruency bias* paradigm (Golomb et al., 2014) to ask if 2D location and depth-from-disparity bias one another during perceptual judgments. In Experiment 1 we found that 2D space biased position-in-depth judgments, such that participants were more likely to judge two stimuli as having the same depth location when they appeared in the same 2D location, even though that location was irrelevant to the task and its influence could be detrimental to performance. These results align with the *equidistance tendency*, in which objects located closer to each other in 2D space tend to be perceived as more similar in distance (Gogel, 1965; Wist & Summons, 1976). Critically, in Experiment 2 we found that the opposite was not true: depth-from-disparity did not bias 2D location judgments -- and the across-experiment interaction was significant.

Our finding of a 2D-depth asymmetry in the *spatial congruency bias* is consistent with past literature showing weaker or delayed effects of depth compared to 2D spatial effects (Finlayson et al., 2013; Kasai et al., 2003; Loomis et al., 2008; Moore et al., 2009), and that depth differences are less discriminable than 2D location differences (Gilinsky, 1951). However, as noted in the introduction, just because one type of information is more discriminable doesn't necessarily mean it will influence judgments of other dimensions. For example, in the Golomb et al. (2014) study, even very small (near threshold) location differences were found to bias identity judgments, whereas very large, highly discriminable color differences did not. Here our approach was to use highly discriminable differences for both 2D location and depth when each was the irrelevant dimension. Of course, it is possible that the "highly discriminable" depth differences in Experiment 2 were still not as discriminable or salient as the 2D differences in Experiment 1, but we can at least be confident that the depth differences were salient enough to be processed on some level, given the significant RT priming effect in Experiment 2, with faster responses to stimuli presented at the same depth than different depth.

It is important to note that the *spatial congruency bias* reflects a different type of effect than response facilitation or attentional effects measured by reaction time or sensitivity. Both RT and d' measure facilitation; that is, an increase in performance when an irrelevant dimension is repeated. The congruency bias, on the other hand, is a shift in responses; sometimes it is accompanied by RT and/or d' effects, but not always (Finlayson & Golomb, 2016; Golomb et al., 2014; Shafer-Skelton et al., 2017). This shift in responses has been argued to reflect something more fundamental about the role of location in object perception (Golomb et al, 2014). In this sense the congruency bias could be seen as similar to the Simon or Stroop tasks (Lu & Proctor, 1995; Simon, 1990; Stroop, 1935), such that when the irrelevant location is the same, participants might be unable to suppress a response to that feature, even though it is task irrelevant. However, while the Simon and Stroop tasks are typically understood as response interference effects, Golomb et al. (2014) argued that the congruency bias reflects more of a perceptual-level shift. Although the bias (criterion) measure is traditionally associated with changes in response, bias effects can in fact result from either perceptual or response processes (Mack, Richler, Gauthier, & Palmeri, 2011; Wixted & Stretch, 2000), and may reflect a perceptual-level effect even when there is no effect on d-prime/sensitivity (Morgan, Hole, & Glennerster, 1990; Witt, Taylor, Sugovic, & Wixted, 2015). Although the current experiments cannot differentiate between perceptual versus decision-level effects, in the original *spatial congruency bias* report, Golomb et al (2014) reported that even when judgments were made using a sliding scale that eliminated the response conflict, participants were more likely to rate two objects as more similar when location was the same, and this effect was only present for perceptually difficult discriminations (Golomb et al., 2014).

Thus, the *spatial congruency bias* carries different theoretical implications than a sensitivity effect, even though both may be perceptual in nature. Moreover, it is possible for the two effects to co-exist. Sensitivity effects have been reported previously for both 2D and depth location cues, and here we found some sensitivity effects in Experiment 1, although the experiments were not designed to maximize these measures. Our focus was on the *spatial congruency bias*, which seems an ideal measure to compare interactions between the different spatial dimensions. The congruency bias is consistent with an account of location as a privileged feature, suggesting that irrelevant location information is automatically encoded with other object features, biasing their perceptual judgments, with location serving as an index to group or bind features of an object together, or as an important cue for object "sameness" (Golomb et al., 2014; Kahneman, Treisman, & Gibbs, 1992). Importantly, prior studies only demonstrated that 2D location is special compared to other features; here we demonstrate that 2D spatial information is similarly prioritized over depth-from-disparity information. The *spatial congruency bias* demonstrated a clear difference between Experiments 1 and 2, suggesting that an object's 2D location may be automatically incorporated into perception of its depth location, but not vice versa.

It is important to note that our lack of a depth-from-disparity bias suggests that depth information is not *automatically* incorporated into the judgment of an object's 2D location. However, it is possible that under other specific experimental manipulations, depth information might be able to bias 2D localization (though this would imply a depth influence that is cue- or parameter-specific, rather than generalizable). For example, as noted earlier, stimulus timing may influence the results. Here we chose a single stimulus duration (500ms) that has been shown to reliably induce a 2D location bias (Finlayson & Golomb, 2016; Golomb et al., 2014; Shafer-Skelton et al., 2017), and should be sufficient to allow accumulation of disparity information (Adam et al., 1993; Gajewski, Philbeck, et al., 2014; Sanocki & Sulman, 2009; Uttal et al., 1994). While this duration was clearly sufficient to evoke some depth effects in our study (RT priming), it remains possible that with longer stimulus durations, we might begin to see a congruency bias for depth as well. For example, Gajewski et al. (2014) found that distance perception improved when allowed a 15 sec preview of the scene. Another possibility is that under reduced attention conditions, 2D localization might be impaired (Adam et al., 2008; Fortenbaugh & Robertson, 2011; Tsal & Bareket, 2005), and there might be a greater influence of position-in-depth information on 2D location judgments. Finally, depth information was cued here with binocular disparity, which is one of the more compelling cues for depth perception (Finlayson et al., 2012; McKee & Taylor, 2010), but it is possible that other depth cues may interact differently with 2D location. We did not use any monocular cues in this experiment, because monocular cues could produce actual changes in 2D location that could confound the task. However, a related investigation from our lab investigating whether depth biases feature judgments (Finlayson & Golomb, 2016) included experiments with different depth cues, and found that monocularly-cued position-in-depth (size and occlusion cues) did not bias feature judgments. It is an interesting question for future research whether a more real-world "full cue" (disparity plus other depth cues) scenario might result in an increased influence of depth on 2D localization judgments. Nonetheless, the fact that we did not find a depth-from-disparity bias here implies that depth information does not *generally* bias 2D localization, but at best would be cue-specific.

The fact that salient depth-from-disparity location information did not bias 2D location judgments here, combined with the recent finding that depth (from multiple cues) did not bias color judgments (Finlayson & Golomb, 2016), reveals a strong contrast with 2D location. These findings are consistent with the idea that depth information may not play as special a role in visual processing as 2D location, which could have important consequences for real-world object localization. This asymmetry suggests that position-in-depth may be processed more like an object feature than part of its location, though it is also possible that depth is simply a less salient spatial dimension than 2D space. As noted above, while it is possible that depth might bias 2D judgments under different experimental manipulations, this would still be a notable contrast to the 2D bias, which is robust to manipulations such as timing, task, and salience (Golomb et al., 2014). Regardless, it seems that depth-from-disparity is failing to exert the same automatic, fundamental influence that we see from 2D location with effects like the *equidistance tendency* (Gogel, 1965; Wist & Summons, 1976) and *spatial congruency bias* (Golomb et al., 2014).

Our results suggest that the effects measured by the *spatial congruency bias* are very low-level, perhaps stemming from processing occurring in early visual cortex where spatial representations have not yet been integrated into balanced 3D (Finlayson et al., 2017) or cyclopean (Barendregt et al., 2015) representations. Although binocular disparity information is present in neurons as early as V1 (Hubel & Wiesel, 1968), the *percept* of depth from disparity, as well as the integration of depth cues, is not thought to occur until intermediate or later visual areas (Backus et al., 2001; Preston et al., 2008; Tsao et al., 2003). Thus, while it may seem more ecologically relevant for objects to be bound to their 3D locations, the spatial congruency bias suggests that the special role of location information in object recognition may be occurring at too low of a level for depth-from-disparity to be integrated. The finding that the *spatial congruency bias* also remains in retinotopic, eye-centered coordinates after eye movements, rather than updating to spatiotopic, world-centered locations (Shafer-Skelton et al., 2017), is similarly consistent with this low-level, automatic spatial influence.

Conclusions

We demonstrated that irrelevant 2D location biases position-in-depth judgments, but disparity cued depth location does not bias 2D location judgments. We conclude that 2D space influences the perception of depth information, but this relationship is asymmetric, suggesting that the *spatial congruency bias* arises early in visual processing, before 2D images from each retina are combined to form a coherent perception of 3D space.

Table 1. Summary of all measures for Experiments 1 and 2.

Expt.	Stimuli locations: Irrelevant	Stimuli locations: Relevant	p("Same")	RT (ms)	Bias (c)	d-prime	Normalised c	Likelihood ratio (β)
1	**Same X Same Y**	**Same Z**	0.84	956	-0.41	1.31	-0.39	0.64
		Diff Z	0.41	976				
	Same X Diff Y	**Same Z**	0.69	1010	-0.02	1.03	0.01	0.97
		Diff Z	0.32	991				
	Diff X Same Y	**Same Z**	0.69	986	-0.07	0.99	-0.07	0.97
		Diff Z	0.35	990				
	Diff X Diff Y	**Same Z**	0.64	994	0.09	0.95	0.41	1.09
		Diff Z	0.30	990				
2	**Same X Same Z**	**Same Y**	0.83	956	-0.13	1.90	-0.13	0.89
		Diff Y	0.23	946				
	Same X Diff Z	**Same Y**	0.82	948	-0.14	1.62	-0.13	0.90
		Diff Y	0.27	986				
	Diff X Same Z	**Same Y**	0.76	958	0.04	1.61	-0.001	1.16
		Diff Y	0.21	960				
	Diff X Diff Z	**Same Y**	0.73	992	0.06	1.51	0.08	1.21
		Diff Y	0.22	1002				

References

Adam, J. J., Davelaar, E. J., Van der Gouw, A., & Willems, P. (2008). Evidence for attentional processing in spatial localization. *Psychological Research*, *72*(4), 433–442.

Adam, J. J., Ketelaars, M., Kingma, H., & Hoek, T. (1993). On the time course and accuracy of spatial localization: Basic data and a two-process model. *Acta Psychologica*, *84*(2), 135–159.

Atchley, P., Kramer, A. F., Andersen, G. J., & Theeuwes, J. (1997). Spatial cuing in a stereoscopic display: Evidence for a "depth-aware" attentional focus. *Psychonomic Bulletin & Review*, *4*(4), 524–529.

Backus, B. T., Fleet, D. J., Parker, A. J., & Heeger, D. J. (2001). Human Cortical Activity Correlates With Stereoscopic Depth Perception. *Journal of Neurophysiology*, *86*(4), 2054–2068.

Ban, H., Preston, T. J., Meeson, A., & Welchman, A. E. (2012). The integration of motion and disparity cues to depth in dorsal visual cortex. *Nature Neuroscience*, *15*(4), 636–643. https://doi.org/10.1038/nn.3046

Bapat, A. N., Shafer-Skelton, A., Kupitz, C. N., & Golomb, J. D. (2017). Binding object features to locations: Does the "spatial congruency bias" update with object movement? *Attention, Perception, & Psychophysics*, 1–13. https://doi.org/10.3758/s13414-017-1350-5

Barendregt, M., Harvey, B. M., Rokers, B., & Dumoulin, S. O. (2015). Transformation from a Retinal to a Cyclopean Representation in Human Visual Cortex. *Current Biology*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0960982215006685

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*(4), 433–436.

Cave, K. R., & Pashler, H. (1995). Visual selection mediated by location: Selecting successive visual objects. *Perception & Psychophysics*, *57*(4), 421–432.

Caziot, B., & Backus, B. T. (2015). Stereoscopic Offset Makes Objects Easier to Recognize. *PloS One*, *10*(6), e0129101.

Caziot, B., Valsecchi, M., Gegenfurtner, K. R., & Backus, B. T. (2015). Fast perception of binocular disparity. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(4), 909–916.

Chen, Z. (2009). Not all features are created equal: Processing asymmetries between location and object features. *Vision Research*, *49*(11), 1481–1491. https://doi.org/10.1016/j.visres.2009.03.008

DeAngelis, G. C., & Newsome, W. T. (1999). Organization of Disparity-Selective Neurons in Macaque Area MT. *The Journal of Neuroscience*, *19*(4), 1398–1415.

Downing, C., & Pinker, S. (1985). The spatial structure of selective attention. In M. Posner & O. Marin (Eds.), *Attention and performance XI: Mechanisms of attention and visual search.* (p. 171â€“187). Hillsdale, NJ: Erlbaum.

Engel, S. A., Rumelhart, D. E., Wandell, B. A., Lee, A. T., Glover, G. H., Chichilnisky, E.-J., & Shadlen, M. N. (1994). fMRI of human visual cortex. *Nature*. Retrieved from http://psycnet.apa.org/psycinfo/1995-00647-001

Felleman, D. J., & van Essen, D. C. (1991). Distributed Hierarchical Processing in the Primate. *Cerebral Cortex*, *1*(1), 1–47. https://doi.org/10.1093/cercor/1.1.1

Finlayson, N. J., & Golomb, J. D. (2016). Feature-location binding in 3D: Feature judgments are biased by 2D location but not position-in-depth. *Vision Research*, *127*, 49–56.

Finlayson, N. J., & Grove, P. M. (2015). Visual search is influenced by 3D spatial layout. *Attention, Perception, & Psychophysics*, 1–9. https://doi.org/10.3758/s13414-015-0924-3

Finlayson, N. J., Zhang, X., & Golomb, J. D. (2017). Differential patterns of 2D location versus depth decoding along the visual hierarchy. *NeuroImage*, *147*, 507–516.

Finlayson, Remington, R. W., & Grove, P. M. (2012). The role of presentation method and depth singletons in visual search for objects moving in depth. *Journal of Vision*, *12*(8), 13–13. https://doi.org/10.1167/12.8.13

Finlayson, Remington, R. W., Retell, J. D., & Grove, P. M. (2013). Segmentation by depth does not always facilitate visual search. *Journal of Vision*, *13*(8). https://doi.org/10.1167/13.8.11

Fortenbaugh, F. C., & Robertson, L. C. (2011). When here becomes there: attentional distribution modulates foveal bias in peripheral localization. *Attention, Perception, & Psychophysics*, *73*(3), 809–828.

Gajewski, D. A., Philbeck, J. W., Wirtz, P. W., & Chichka, D. (2014). Angular declination and the dynamic perception of egocentric distance. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 361.

Gajewski, D. A., Wallin, C. P., & Philbeck, J. W. (2014). Gaze direction and the extraction of egocentric distance. *Attention, Perception, & Psychophysics*, *76*(6), 1739–1751.

Gilinsky, A. S. (1951). Perceived size and distance in visual space. *Psychological Review*, *58*(6), 460–482.

Gogel, W. C. (1965). Equidistance tendency and its consequences. *Psychological Bulletin*, *64*(3), 153.

Golomb, J. D., & Kanwisher, N. (2012). Higher level visual cortex represents retinotopic, not spatiotopic, object location. *Cerebral Cortex*, *22*(12), 2794–2810.

Golomb, J. D., Kupitz, C. N., & Thiemann, C. T. (2014). The Influence of Object Location on Identity: A "Spatial Congruency Bias." *Journal of Experimental Psychology: General*, Advance Online Publication. https://doi.org/10.1037/xge0000017

Grill-Spector, K., & Malach, R. (2004). The human visual cortex. *Annu. Rev. Neurosci.*, *27*, 649–677.

Harris, L. R., & Mander, C. (2014). Perceived distance depends on the orientation of both the body and the visual environment. *Journal of Vision*, *14*(12), 17–17.

Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *The Journal of Physiology*, *195*(1), 215–243.

Hubel, D. H., & Wiesel, T. N. (1970). Stereoscopic vision in macaque monkey: cells sensitive to binocular depth in area 18 of the macaque monkey cortex. *Nature*, *225*, 41–42.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: object-specific integration of information. *Cognitive Psychology*, *24*(2), 175–219.

Kasai, T., Morotomi, T., Katayama, J., & Kumada, T. (2003). Attending to a location in three-dimensional space modulates early ERPs. *Cognitive Brain Research*, *17*(2), 273–285. https://doi.org/10.1016/S0926-6410(03)00115-0

Kravitz, D. J., Kriegeskorte, N., & Baker, C. I. (2010). High-Level Visual Object Representations Are Constrained by Position. *Cerebral Cortex*, *20*(12), 2916–2925. https://doi.org/10.1093/cercor/bhq042

Loomis, J. M., Klatzky, R., Rieser, J. J., Ashmead, D. H., Ebner, F. F., & Corn, A. L. (2008). Functional equivalence of spatial representations from vision, touch, and hearing: Relevance for sensory substitution. *Blindness and Brain Plasticity in Navigation and Object Perception*, 155–184.

Lu, C., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*(2), 174–207. https://doi.org/10.3758/BF03210959

Mack, M. L., Richler, J. J., Gauthier, I., & Palmeri, T. J. (2011). Indecision on decisional separability. *Psychonomic Bulletin & Review*, *18*, 1–9. https://doi.org/10.3758/s13423-010-0017-1

McKee, S. P., & Taylor, D. G. (2010). The precision of binocular and monocular depth judgments in natural settings. *Journal of Vision*, *10*(10), 5.

Moore, C. M., Hein, E., Grosjean, M., & Rinkenauer, G. (2009). Limited influence of perceptual organization on the precision of attentional control. *Attention, Perception, & Psychophysics*, *71*(4), 971–983.

Morgan, M. J., Hole, G. J., & Glennerster, A. (1990). Biases and sensitivities in geometrical illusions. *Vision Research*, *30*(11), 1793–1810. https://doi.org/10.1016/0042-6989(90)90160-M

Murray, S. O., Boyaci, H., & Kersten, D. (2006). The representation of perceived angular size in human primary visual cortex. *Nature Neuroscience*, *9*(3), 429–434.

Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, *320*(6059), 264–265. https://doi.org/10.1038/320264a0

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Preston, T. J., Li, S., Kourtzi, Z., & Welchman, A. E. (2008). Multivoxel Pattern Selectivity for Perceptually Relevant Binocular Disparities in the Human Brain. *The Journal of Neuroscience*, *28*(44), 11315–11327. https://doi.org/10.1523/JNEUROSCI.2728-08.2008

Sanocki, T., & Sulman, N. (2009). Priming of simple and complex scene layout: Rapid function from the intermediate level. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(3), 735.

Schwarzlose, R. F., Swisher, J. D., Dang, S., & Kanwisher, N. (2008). The distribution of category and location information across object-selective regions in human visual cortex. *Proceedings of the National Academy of Sciences*, *105*(11), 4447–4452. https://doi.org/10.1073/pnas.0800431105

Sereno, M. I., Dale, A. M., Reppas, J. B., Kwong, K. K., Belliveau, J. W., Brady, T. J., … Tootell, R. B. (1995). Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. *Science*, *268*(5212), 889–93.

Shafer-Skelton, A., Kupitz, C. N., & Golomb, J. D. (2017). Object-location binding across a saccade: A retinotopic spatial congruency bias. *Attention, Perception, & Psychophysics*, 1–17.

Silver, M. A., & Kastner, S. (2009). Topographic maps in human frontal and parietal cortex. *Trends in Cognitive Sciences*, *13*(11), 488–495. https://doi.org/10.1016/j.tics.2009.08.005

Simon, J. R. (1990). The effects of an irrelevant directional cue on human information processing. In R. W. Proctor & T. G. Reeve (Eds.), *Stimulus-Response Compatibility: An Integrated Perspective*. Elsevier.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Tsal, & Lavie, N. (1988). Attending to color and shape: The special role of location in selective visual processing. *Perception & Psychophysics*, *44*(1), 15–21. https://doi.org/10.3758/BF03207469

Tsal, & Lavie, N. (1993). Location dominance in attending to color and shape. *Journal of Experimental Psychology. Human Perception and Performance*, *19*(1), 131–139.

Tsal, Y., & Bareket, T. (2005). Localization judgments under various levels of attention. *Psychonomic Bulletin & Review*, *12*(3), 559–566.

Tsao, D. Y., Vanduffel, W., Sasaki, Y., Fize, D., Knutsen, T. A., Mandeville, J. B., … Van Essen, D. C. (2003). Stereopsis activates V3A and caudal intraparietal areas in macaques and humans. *Neuron*, *39*(3), 555–568.

Uttal, W. R., Davis, N. S., & Welke, C. (1994). Stereoscopic perception with brief exposures. *Perception & Psychophysics*, *56*(5), 599–604.

Wandell, B. A., Dumoulin, S. O., & Brewer, A. A. (2007). Visual field maps in human cortex. *Neuron*, *56*(2), 366–383.

Wist, E. R., & Summons, E. (1976). Spatial and fixation conditions affecting the temporal course of changes in perceived relative distance. *Psychological Research*, *39*(2), 99–112.

Witt, J. K., Taylor, J. E. T., Sugovic, M., & Wixted, J. T. (2015). Signal detection measures cannot distinguish perceptual biases from response biases. *Perception*, *44*(3), 289–300. https://doi.org/10.1068/p7908

Wixted, J. T., & Stretch, V. (2000). The case against a criterion-shift account of false memory. *Psychological Review*, *107*(2), 368–376. https://doi.org/10.1037/0033-295X.107.2.368