Cognition 247 (2024) 105762

Contents lists available at ScienceDirect

Cognition

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

Oblique warping: A general distortion of spatial perception

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ARTICLE INFO

Keywords:
Oblique effect
Oblique warping
Prototype effect
Spatial representation
Vision

ABSTRACT

There are many putatively distinct phenomena related to perception in the oblique regions of space. For instance, the classic oblique effect describes a deficit in visual acuity for oriented lines in the obliques, and classic "prototype effects" reflect a bias to misplace objects towards the oblique regions of space. Yet these effects are explained in very different terms: The oblique effect itself is often understood as arising from orientation-selective neurons, whereas prototype effects are described as arising from categorical biases. Here, we explore the possibility that these effects (and others) may stem from a single underlying spatial distortion. We show that there is a general distortion of (angular) space in the oblique regions that influences not only orientation judgments, but also location, extent, and size. We argue that these findings reflect *oblique warping*, a general distortion of spatial representations in the oblique regions which may be the root cause of many oblique effects.

The oblique effect describes the phenomenon whereby observers are worse at discriminating oriented bars presented in the oblique (diagonal) regions of space compared to the cardinal (horizontal/vertical) regions. That is, a line oriented at, say, 3°, would be more readily discriminated from a line at 1° versus lines oriented at 48° versus 46° (Appelle, 1972; Bonds, 1982; Essock, 1980; see Fig. 1A). This phenomenon is well-replicated and exceptionally robust (see, e.g., Essock, 1980; Vogels & Orban, 1985; Furmanski & Engel, 2000). A range of related effects have been observed not just in orientation judgment tasks, but also in location judgment tasks (Yousif, Chen, & Scholl, 2020), location placement tasks (Huttenlocher, Hedges, & Duncan, 1991), various haptic/motor tasks (e.g., Baud-Bovy and Viviani, 2004; Gentaz & Hatwell, 1995; Gordon, Ghilardi, & Ghez, 1995; Gourtzelidis, Smyrnis, Evdokimidis, & Balogh, 2001; Mantas, Evdokimidis, & Smyrnis, 2008; Petersik & Pantle, 1982; Sainburg, Ghilardi, Poizner, & Ghez, 1995; Smyrnis, Gourtzelidis, & Evdokimidis, 2000; Smyrnis, Mantas, & Evdokimidis, 2007; Yousif, Forrence, & McDougle, 2023), and even some aesthetic judgment tasks (Latto, Brain, & Kelly, 2000; Latto & Russell-Duff, 2002; Plumhoff & Schirillo, 2009; Youssef, Juravle, Youssef, Woods, & Spence, 2015). Moreover, oblique-related effects come in several different forms: Some of these effects are about reduced visual acuity in the oblique regions of space (e.g., Appelle, 1972; Yousif et al., 2020), whereas others involve memory errors and mislocalizations towards the oblique regions. Some of these biases involve vision (Cecala & Garner, 1986; Huttenlocher et al., 1991; Latto et al., 2000; Luyat & Gentaz, 2002; Luyat, Gentaz, Corte, & Guerraz, 2001; Luyat, Mobarek, Leconte, & Gentaz, 2005; Yousif et al., 2020), while others are observed in the absence of visual input (e.g., Gentaz & Hatwell, 1995; Gordon et al., 1995; Smyrnis et al., 2007). Finally, some oblique-related effects are characterized as attraction to certain regions of space, whereas others are characterized as repulsion (see, e.g., Huttenlocher et al., 1991; Rademaker, Chunharas, Mamassian, & Serences, 2017; Wei & Stocker, 2015; see also Azañón, Tucciarelli, Siromahov, Amoruso, & Longo, 2020; Tucciarelli, Ferre, Amoruso, Azanon Gracia, & Longo, 2023).

Surprisingly, these distortions are often explained in radically different ways. While the standard visual oblique effect is explained by variance in neural representations across orientations (see, e.g., Furmanski & Engel, 2000; Li, Peterson, & Freeman, 2003; see also Nasr & Tootell, 2012), oblique biases in spatial localization tasks have traditionally been explained as categorical effects related to spatial cognition (Huttenlocher et al., 1991). Do these effects reflect one underlying phenomenon, or multiple?

1. Current study

Here, we aim to demonstrate that observed oblique-related effects might reflect a more general kind of distortion that is not limited to any

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https://doi.org/10.1016/j.cognition.2024.105762
Received 29 August 2023; Received in revised form 17 December 2023; Accepted 25 February 2024

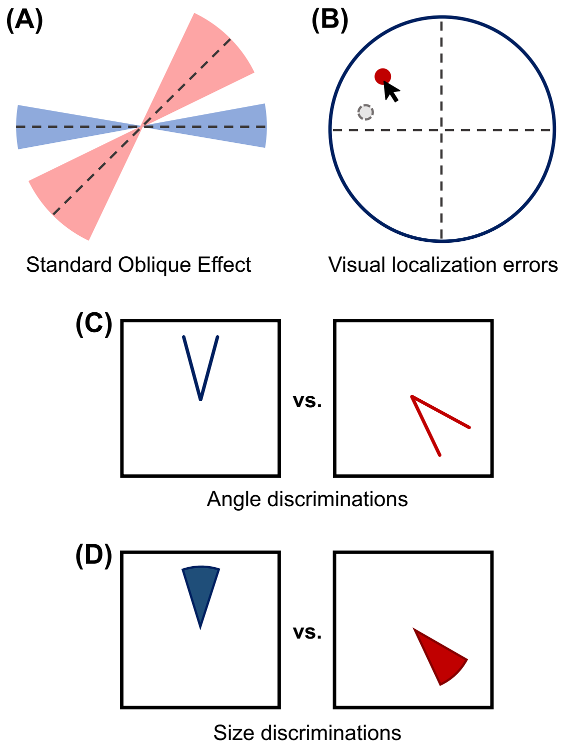

Fig. 1. Various oblique distortions. (A) A depiction of the classic oblique effect, whereby orientated lines/bars near the cardinal axes are perceived with greater acuity (e.g., Appelle, 1972). (B) A depiction of common localization errors whereby people are biased to remember items as having been closer to the oblique axes than they really were (e.g., Huttenlocher et al., 1991; Yousif et al., 2020). (C) A depiction of other plausible instances of 'oblique warping', such as differences in angular perception and (D) differences in size perception, which are investigated here.

one modality (see Yousif et al., 2023) nor any one spatial property. First, we explore oblique effects in *orientation* and *localization* tasks, as well as the relationship between them. To preview the results: We show that there are 'oblique effects' in both cases and that there is a strong correlation between them, suggesting that oblique distortions extend beyond orientation to other features (i.e., object location). Then, inspired by the thought that these oblique effects may stem from a general distortion of spatial representations, we explore the consequences of these effects on the perception of *angular extent* (Experiments 2a and 2b) and *perceived size* (Experiment 3). We show that objects spanning the cardinal regions of space are perceived as larger and/or having a greater angular extent. We discuss these findings in light of a general kind of *oblique warping* that affects a range of spatial tasks.

2. Experiment 1 — Oblique warping extends beyond orientation judgments

The canonical oblique effect reflects a deficit in acuity for oriented lines in the oblique regions of space. However, there are similar deficits in acuity for angular position that are not about orientation per se (see Yousif et al., 2020). Are these phenomena related? In a first experiment, we had participants complete both a location discrimination and an orientation discrimination task. We asked (1) whether there is an 'oblique effect' for both orientation and localization tasks, and (2) if those effects are related in some way (i.e., if oblique effects across the two are correlated).

2.1. Method

This experiment, and all subsequent experiments, were preregistered. Those pre-registrations, as well as raw data and analyses, can be accessed here: https://osf.io/7tcbh/

2.1.1. Participants

100 participants were recruited via Prolific. Participants were sampled exclusively from the United States. Here, and for all subsequent experiments in this paper, the sample sizes, primary dependent variables, and key statistical tests were chosen in advance and were preregistered (see link above). Likewise, for all experiments, the exclusion criteria we pre-registered were highly conservative, and thus no participants were excluded. This study was approved by the [REDCATED] Institutional Review Board.

2.1.2. Stimuli

There were two stimulus types: Dots for the location discrimination task and lines for the orientation discrimination task. Both sets of stimuli had similar properties. For the dot stimuli, a small black dot (10 pixels in diameter at default browser zoom distance) was presented relative to a central grey dot (10 pixels in diameter at default browser zoom distance). The black dots could initially appear at one of eight 'axes' around the central dot (0, 45, 90, 135, 180, 225, 270, or 315°), always 200 pixels away from the central dot. During the second presentation (see Procedure & Design), either the angle or distance of the black dot relative to the grey dot would change. Angle could change by +/− 4, 8, or 12°, or by 0 degrees (for a total of seven possibilities); distance could also change in seven increments, and the magnitude of the changes was set to match the difference of the angle changes in Euclidean distance (and so would change by either 0, 14, 28, or 42 pixels).

For the orientation discrimination task, the stimuli were similarly administered. Lines would initially appear along one of the same eight axes, and at second presentation would be altered by the same amounts in angular/distance increments as described above. For distance changes, the line would simply shift along the set axis away from or towards the central dot by that number of pixels.

Both the orientation task and the location task involved angle changes as well as distance changes. Distance changes were included to serve as a control. Including these changes made it possible to ask whether any relation observed between angular judgments across tasks is specific to orientation or is more general (i.e., extending to all spatial discriminations).

Each task had a total of 8 initial axes along which items could appear x 2 change types (angle, distance) x 7 increments (e.g., −12, −8, −4, 0, 4, 8, and 12°) for a total of 112 trials. Thus, across both tasks, there were a total of 224 trials. A visual depiction of the task design and trial types can be seen in Fig. 2.

2.1.3. Procedure & design

The trials were blocked such that half of the participants completed the orientation discrimination task first and the other half completed the location discrimination task first. In both tasks, the initial image was presented for 1000 ms before disappearing. After another 1000 ms, the second image would appear, at which point participants were prompted to press 's' if the second image was the same as the first and 'd' if the second image was different from the first. Throughout the trials, there was a thin black border (4px) around the stimuli (800 pixels wide; 680 pixels tall). During the response window, that border briefly turned green to signal to participants that they were able to respond. Between the blocks, there was a brief break during which participants were reminded that the stimuli were going to change but that the general task would remain the same. Prior to the first block, participants completed two representative practice trials (these data were not analyzed).

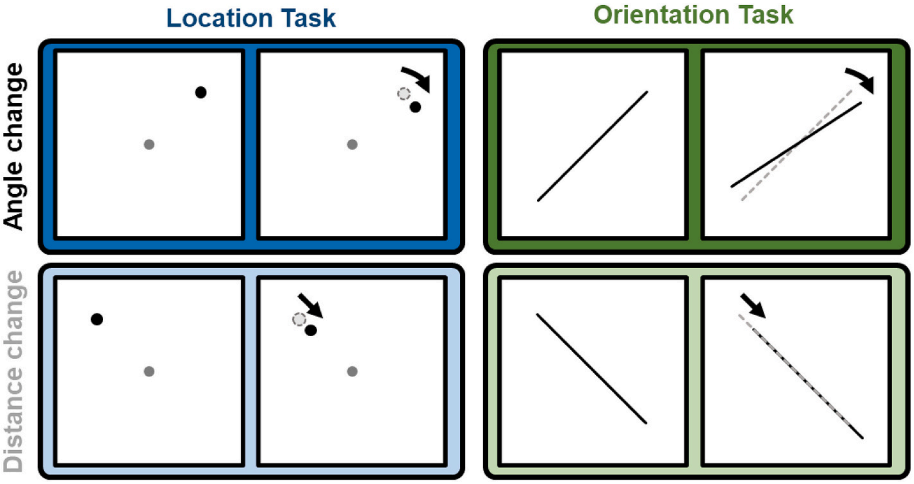

Fig. 2. Schematic of task and trial types for Experiment 1 (relative stimulus locations not to scale).

2.2. *Results and discussion*

First, we quantified the oblique distortions themselves. We separately calculated trial accuracy for each trial type for each region of space. Then, we calculated a difference score between those two accuracy values, leaving us with a single value for each trial type that indicates whether participants were more accurate for trials in the cardinal regions versus trials in the oblique regions (see Fig. 3A). To compare the cardinal and oblique regions, we simply collapsed across all cardinal angles (0, 90, 180, 270) and oblique angles (45, 135, 225, 315) and compared the two as part of a single *t*-test. We observed significant oblique distortions across both angle change detection conditions such that accuracy was generally higher in the cardinal regions (location-task-angle: cardinal axes: $M = 0.88$, $SD = 0.12$; oblique axes: $M = 0.66$, $SD = 0.19$; $t(99) = 13.95$, $p < .001$, $d = 1.40$; orientation-task-angle: cardinal axes: $M = 0.95$, $SD = 0.09$; oblique axes: $M = 0.65$, $SD = 0.18$; $t(99) = 16.20$, $p < .001$, $d = 1.620$). Interestingly, we also observed significant oblique distortions across both distance change detection conditions (location-task-distance: cardinal axes: $M = 0.61$, $SD = 0.20$; oblique axes: $M = 0.64$, $SD = 0.18$; $t(99) = 2.83$, $p = .006$, $d = 0.28$; orientation-task-distance: cardinal axes: $M = 0.50$, $SD = 0.22$; oblique axes: $M = 0.52$, $SD = 0.21$; $t(99) = 2.05$, $p = .04$, $d = 0.20$). Note however that these distortions for the distance changes were in the opposite direction (i.e., better change detection at the obliques), were significantly smaller than their angular equivalents ($ts > 10.00$, $ps < 0.001$, $ds > 1.00$), and are inconsistent with prior work (e.g., Yousif et al., 2020). Moreover, the distance condition differences in the orientation task did not survive Bonferroni correction. Thus, while there may be small differences in acuity for distance changes between the oblique and cardinal regions, our data do not provide strong evidence in support of that conclusion.

We also conducted the same between-region analysis for response time rather than accuracy. Participants were significantly faster to respond to angular differences on trials with items nearer to the cardinal axes in both the location (cardinal axes: $M = 849$ ms, $SD = 226$ ms; oblique axes: $M = 912$ ms, $SD = 337$ ms; $t(99) = 2.37$, $p = .020$, $d = 0.24$) and orientation tasks (cardinal axes: $M = 772$ ms, $SD = 215$ ms; oblique axes: $M = 894$ ms, $SD = 418$ ms; $t(99) = 3.13$, $p = .002$, $d = 0.31$), though the former result did not survive Bonferroni correction. Response time differences for judging cardinal versus oblique stimuli were not seen for distance change detection in either the location (cardinal axes: $M = 941$ ms, $SD = 391$ ms; oblique axes: $M = 897$ ms, $SD = 244$ ms; $t(99) = 1.15$, $p = .25$, $d = 0.11$) nor orientation task (cardinal axes: $M = 985$ ms, $SD = 483$ ms; oblique axes: $M = 966$ ms, $SD = 512$ ms; $t(99) = 0.30$, $p = .77$, $d = 0.03$). The results echo the accuracy findings, and also argue against an explanation of those findings based on a speed-accuracy-tradeoff.

To begin to examine relations between the tasks, we first calculated the accuracy for each of the trial types across tasks (i.e., the overall proportion of trials for which participants pressed 'same' when there was no change and 'different' when there was a change). We found that accuracy across all trial types was correlated (location-task-angle vs. orientation-task-angle: Pearson's $r = 0.63$, $p < .001$, Spearman's $r = 0.61$, $p < .001$; location-task-distance vs. orientation-task-distance: Pearson's $r = 0.54$, $p < .001$, Spearman's $r = 0.53$, $p < .001$; location-task-angle vs. location-task-distance: Pearson's $r = 0.77$, $p < .001$, Spearman's $r = 0.81$, $p < .001$; orientation-task-angle vs. orientation-task-distance: Pearson's $r = 0.71$, $p < .001$, Spearman's $r = 0.74$, $p < .001$). In other words, participants who did well in the task tended to do well across all conditions (see Fig. 3B-C).

The key question in this experiment, however, was whether there is a unique relationship in oblique distortions across location and orientation judgments. Using the above metrics of oblique distortions, we evaluated the same cross-task and cross-trial-type correlations we assessed before. Here, to ensure that these critical correlations were robust, we also ran bootstrapped correlations, resampling trials from each participant with replacement. The results of those bootstrapping analyses are shown as confidence intervals alongside the other correlation values. Unlike the overall accuracy correlations, we found that oblique distortions were reliably correlated only for angle discriminations (location-task-angle vs. orientation-task-angle: Pearson's $r = 0.43$, $p < .001$, bootstrapped 95% CI = [0.21, 0.44], Spearman's $r = 0.38$, $p < .001$, bootstrapped 95% CI = [0.19, 0.43]; see Fig. 3B). All other cross-task and cross-trial correlations were nonsignificant (location-task-distance vs. orientation-task-distance: Pearson's $r = 0.10$, $p = .31$, bootstrapped 95% CI = [−0.12, 0.22], Spearman's $r = 0.05$, $p = .60$, bootstrapped 95% CI = [−0.14, 0.21]; location-task-angle vs. location-task-distance: Pearson's $r = 0.16$, $p = .13$, bootstrapped 95% CI = [−0.09, 0.25], Spearman's $r = 0.15$, $p = .15$, bootstrapped 95% CI = [−0.10, 0.24]; orientation-task-angle vs. orientation-task-distance: Pearson's $r = -0.09$, $p = .40$, bootstrapped 95% CI = [−0.20, 0.09], Spearman's $r = -0.12$, $p = .23$, bootstrapped 95% CI = [−0.21, 0.10]; see Fig. 3C).

As predicted, there was a unique relationship between the magnitude of oblique effects across tasks. How should we interpret this correlation? One of the critical aspects of our design was the inclusion of distance changes as a control. These distance change trials allowed us to ask if the relationship we observed for the angular oblique effects was unique. Even though we did observe tiny oblique effects for the distance changes, those effects were unreliable, were not related across tasks, and

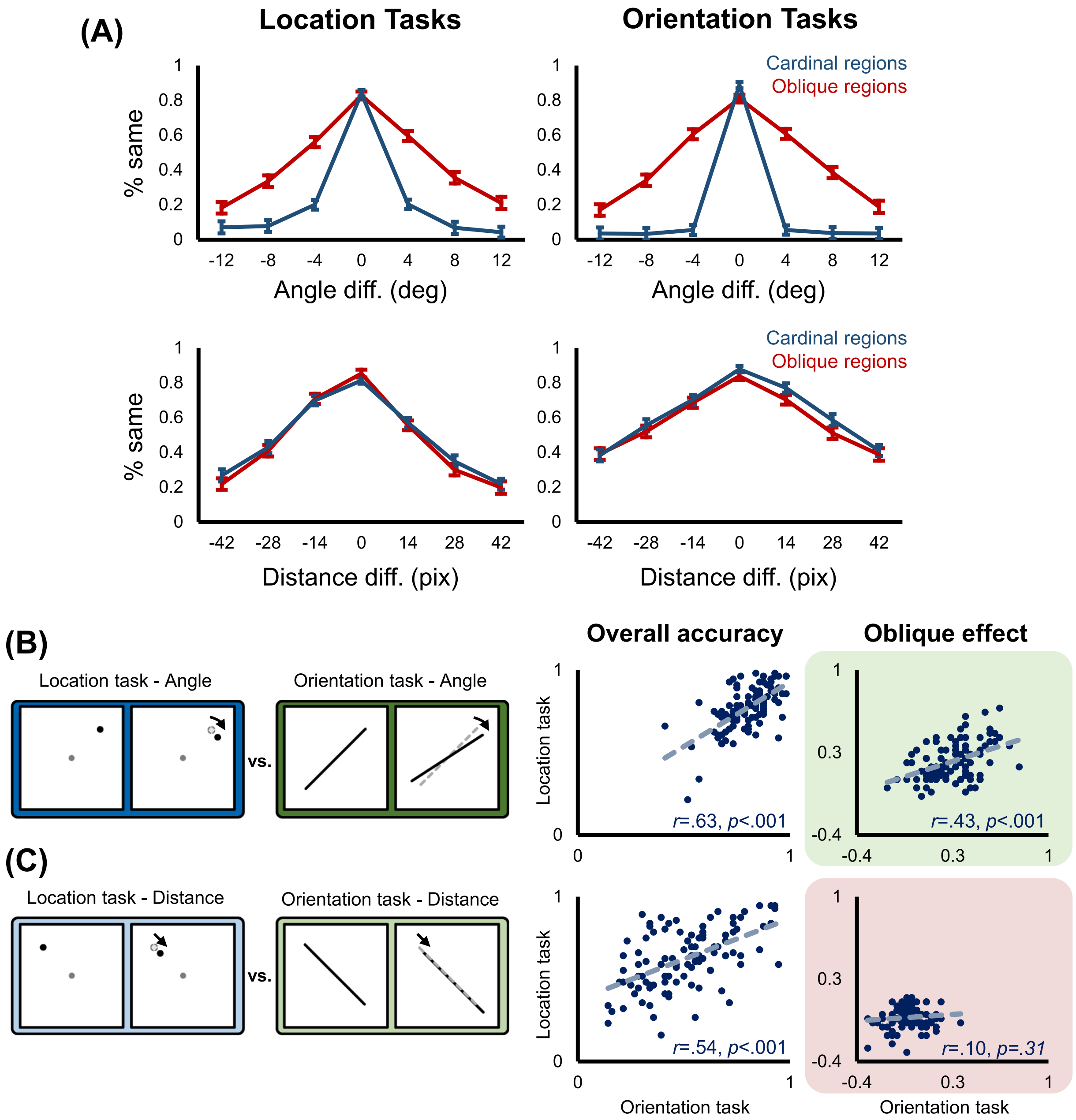

Fig. 3. Design and results of Experiment 1. (A) Results for the four different task/trial-type combinations. (B) Correlations for overall accuracy and oblique distortions between the location-angle discrimination trials and the orientation-angle discrimination trials. (C) Correlations for overall accuracy and oblique distortions between the location-distance discrimination trials and the orientation-distance discrimination trials. The key result here is that oblique distortions are correlated for angular discriminations only, indicating there are stable deficits in oblique acuity across tasks. (The depictions of the stimuli and distances between them shown here are not to scale; they are modified to increase readability of the figure.)

were in the opposite direction of typical oblique effects. Moreover, oblique effects for distance *within* each task were not related to the angular oblique effects in those same tasks. Thus, the only key effect that was reliably correlated across tasks was the angular oblique effect. We note that if this crucial correlation was due to some general factor (e.g., effort or attention) we would expect the control distance metrics to also be correlated. Thus, we think that this pattern reveals a unique, meaningful relationship between oblique distortions across these distinct tasks.

In short, the observed correlations point to two primary conclusions: (1) There are stable individual differences in visual acuity in the oblique regions of space that are not confined to orientation tasks, and (2) These distortions are specific to angular acuity (as opposed to a more general deficit in spatial acuity; see also Yousif et al., 2020). These results suggest that oblique effects may not be unique to orientation after all, and that the effect may be a product of a more general spatial distortion near the obliques.

3. Experiment 2a — Oblique warping explains other perceptual phenomena

What we have called *oblique warping* is not limited to one aspect of space (i.e., orientation). In Experiment 1, we showed not only that an oblique effect arises for location discriminations, but that the acuity with which individuals discriminate locations in the obliques is correlated with their ability to discriminate oriented lines in the oblique. But is it possible that the empty space of the oblique regions itself could be distorted? Here, we asked if observers perceive the empty space formed

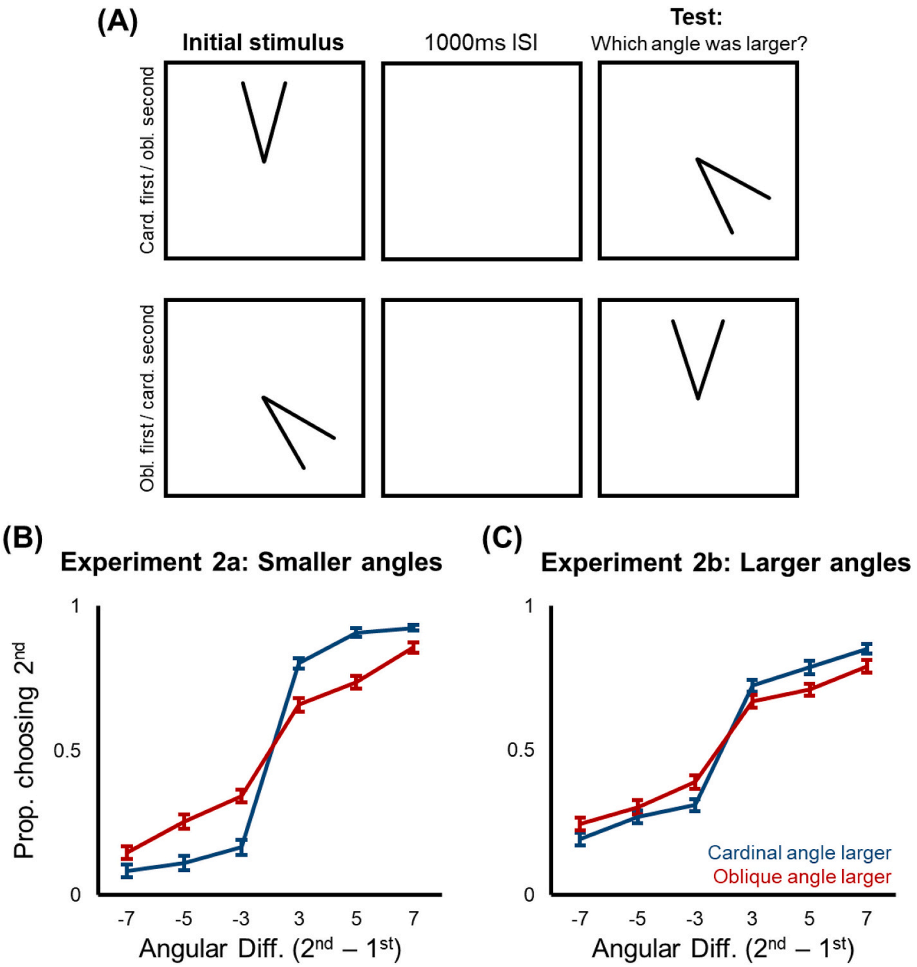

Fig. 4. Design and results of Experiment 2a and 2b. (A) A schematic of the design. (B) Proportion of responses selecting the second angle for each of the two trial types, broken down by angular difference, for Experiment 2a. (C) Proportion of responses selecting the second angle for each of the two trial types, broken down by angular difference, for Experiment 2b. The depictions of the stimuli shown here are not to scale; they are modified to increase readability of the figure.

by two oriented lines in the oblique regions as larger or smaller in magnitude than equivalent empty spaces in the cardinal regions (for a summary of the design, see Fig. 4A).

3.1. Method

This experiment was identical to Experiment 1, except as stated below.

3.1.1. Participants

50 participants were recruited via Prolific. The sample size and all analyses were pre-registered.

3.1.2. Stimuli

The stimuli consisted of angles subtended by two oriented lines, each of which originated in the center of the display, was 2 pixels wide, and was 200 pixels in length. One of the two angles was always presented centered on a cardinal axis (0, 90, 180, or 270°, randomly selected); the other was always presented centered on an oblique axis (45, 135, 225, or 315°, randomly selected). The size of the first angle was always either 20, 30, or 40°. The size of the second angle was always the size of the first angle +/− 3, 5, or 7°.

3.1.3. Procedure & design

There were 2 starting orientations (cardinal, oblique) x 3 base angle sizes (20, 30, 40°) x 3 possible size increments (3, 5, 7°) x 2 directions (size increases, size decreases), resulting in 36 unique trial types. Participants completed each trial type 4 separate times, resulting in a total of 144 trials. However, note that these 4 repeated trial types were not necessarily identical, as the specific axis that was chosen within the set of possible cardinal or oblique axes was random. All trials were completed within a single block. There were two representative practice trials before the beginning of the task. All other aspects of the design were identical to Experiment 1.

3.2. Results and discussion

The primary question of this experiment is whether empty spaces (i.e., angles subtended by two lines) in oblique regions are perceived as smaller or larger than those in cardinal regions. To that end, we conducted a repeated measures ANOVA with two factors (3 levels of angular change and 2 trial types [cardinal angle larger, oblique angle larger]). There was a main effect of angular change such that larger angles were better discriminated ($F[2,98] = 125.26$, $p < .001$, $\eta_p 2 = 0.72$), a main effect of trial type such that trials in which the cardinal angle was greater were better discriminated ($F[1,49] = 76.86$, $p < .001$, $\eta_p 2 = 0.61$), as well as an interaction between the two ($F[2,98] = 17.00$, $p < .001$, $\eta_p 2 = 0.26$; see Fig. 4). Moreover, this main effect of trial type — the critical result in this experiment — was consistent across all three base angle sizes (i.e., whether the initial angle was 20, 30, or 40°; all $ps < 0.001$). This main effect indicates that people generally perceive the empty space at the cardinals as larger than at the obliques. Thus, even the perception of empty space may be influenced by the sort of oblique warping we are studying here.

4. Experiment 2b — Perceived angle size differences are not a function of line orientation

The results of Experiment 2a may not be caused by a difference in perceived space in the oblique regions, as we originally hypothesized. There may be a simpler explanation: It could be that the results are driven not by the perception of space itself but by the percept of the oriented lines that form the angles in the first place. If lines near the oblique regions are perceived as closer to the oblique axes, for instance (as dots are; see Huttenlocher et al., 1991; Yousif et al., 2020), this distortion could cause those angles to be perceived as subtending a smaller area. Here we addressed this possibility by using larger angles. In this new experiment, the angles centered on a given axis were made up of oriented lines that were closer to the opposing set of axes, eliminating the possibility of an oblique effect driven by the lines themselves.

4.1. Method

This experiment was almost identical to Experiment 2a, with one notable difference: The base angle sizes were changed from 20, 30, and 40° to 80, 90, and 100°. The purpose of this change was to de-confound angle size and the axes with which the constituent lines were colinear (or near-colinear). 50 new participants were recruited via Prolific. The sample size, design, and analyses were pre-registered.

4.2. Results and discussion

As with the previous experiment, we conducted a repeated measures ANOVA with two factors (3 levels of angular change and 2 trial types [cardinal angle larger, oblique angle larger]). There was a main effect of angular change such that larger angles were better discriminated (F[2,98] $= 45.79$, $p < .001$, $\eta_{p}2 = 0.48$), a main effect of trial type such that trials in which the cardinal angle was larger were better discriminated (F[1,49] $= 12.76$, $p < .001$, $\eta_{p}2 = 0.21$), but no interaction between the two (F[2,98] $= 0.16$, $p = .85$, $\eta_{p}2 = 0.00$; see Fig. 4). However, the main effect of trial type — unlike the previous experiment — was not consistent across all three base angle sizes (i.e., whether the initial angle was 80, 90, or 100°). Observers were more accurate when the cardinal angle was larger for the 80-degree trials ($p < .001$) and the 90-degree trials ($p = .009$), but more accurate when the oblique angle was larger for the 100-degree trials ($p = .019$). Note that although this p-value is below 0.05, this value is not statistically significant after accounting for Bonferroni correction. Nevertheless, it may be interesting that this effect did not go in the opposite direction, as was the case with the other 5 angle sizes that were tested across both angle judgment experiments.

This one result may suggest an influence of the perception of each of the individual lines rather than a more abstract judgment of space. However, we think this single result cannot explain our results: First, it is important to note that the 100-degree trials are unlike the others, in that they are the only obtuse angles included in the study; it may be possible that this result is partially explained by other known categorical effects of angle perception (see Dillon, Duyck, Dehaene, Amalric, & Izard, 2019). More importantly, an explanation appealing to the percept of the individual lines cannot explain the predicted results observed in the 90-degree trials: Right angles are perceived with high acuity, and, because the placement of the constituent lines would always be centered on either an oblique or cardinal axis, there should be no distortions towards or away from any axis because each line is equidistant from the two nearest axes. Thus, while acknowledging that the 100-degree stimulus results do not fit our predictions, the 90-degree stimulus results provide a purer test — unexplainable by the individual lines — and thus provide strong support for our predictions.

5. Experiment 3 — Oblique warping influences perceived size

In Experiment 2a and 2b, we showed that perceived angular extent is greater in the cardinal regions of space (compared to the obliques), meaning that oblique warping may extend not only to location, but to perceived spatial extent. How general are these distortions? Might they influence not only angular extent but also perceived size? To test this, we had observers judge the relative size of different ‘pie slices’ spanning the cardinal or oblique regions of space. If there is a general warping of perceived space in the obliques, then one may expect that objects presented in the obliques are perceived as smaller (much like angular extent is reduced in Experiments 2a and 2b).

5.1. Method

This experiment was identical to Experiment 2a, except that (a) the stimuli consisted of filled-in pie slices instead of angles, and (b) observers were asked about surface area (rather than angular extent). 50 new participants completed the task.

5.2. Results and discussion

The results of Experiment 3 can be seen in Fig. 5. As with the previous experiment, we conducted a repeated measures ANOVA with two factors (3 levels of size change and 2 trial types [cardinal-centered shape larger, oblique-centered shape larger]). There was a main effect of size change such that larger differences in size were better discriminated (F

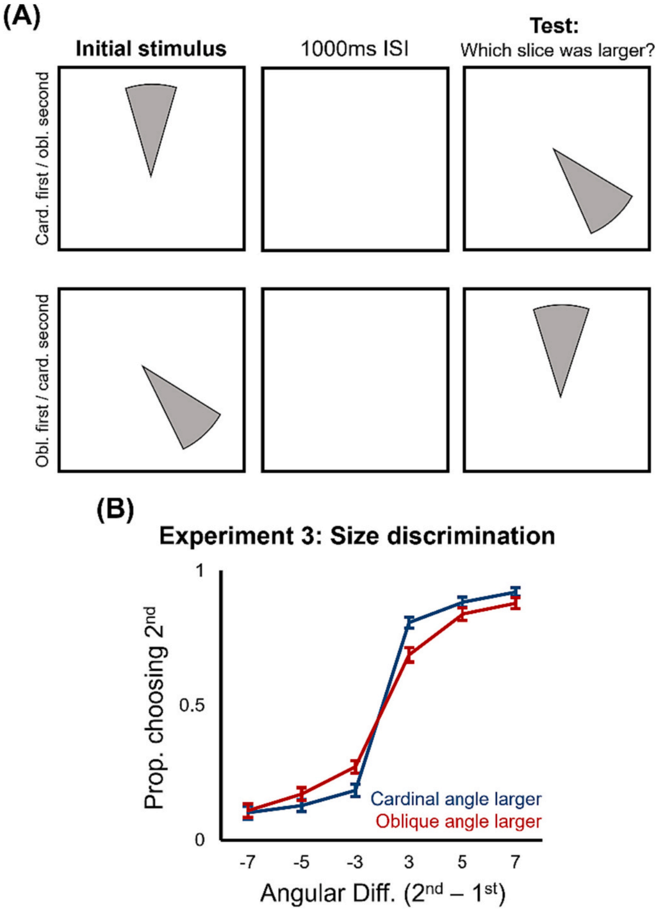

Fig. 5. Design and results of Experiment 3. (A) A schematic of the design. (B) Proportion of responses selecting the second slice for each of the two trial types, broken down by angular difference. The depictions of the stimuli shown here are not to scale; they are modified to increase readability of the figure.

$[2,98] = 99.41$, $p < .001$, $\eta_p2 = 0.67$), a main effect of trial type such that trials in which the cardinal-centered object was larger were better discriminated ($F[1,49] = 34.19$, $p < .001$, $\eta_p2 = 0.41$), and an interaction between the two ($F[2,98] = 8.50$, $p < .001$, $\eta_p2 = 0.15$) driven by the fact that the effects were larger for the smaller angle differences. The main effect of trial type was independently observed for all three base angle sizes (i.e., 20-, 30-, and 40-degree slices; $ps < 0.004$).

An advantage of this approach is that it also addresses limitations of Experiments 2a and 2b, for which it is hard to know for sure whether the observed results are caused by a change in perceived angular extent or a distortion in the perception of the individual lines composing the angles (but see the discussion of Experiment 2b). Here, however, no such concern arises: The presence of an entire pie slice de-emphasizes the individual radial lines, and, moreover, observers need not attend to them (as they are asked only to discriminate based on perceived area). Thus, the finding that objects located in the cardinal regions are perceived as larger provides additional strong support of our hypothesis and suggests that oblique warping may reflect a general distortion of perceived (angular) space.

6. General discussion

We explored the possibility that distinct oblique effects in visual perception reflect an *oblique warping* that generalizes to a range of spatial tasks. We showed that two unique distortions (for localization as well as orientation) were correlated across participants, providing a strong hint of a common source. In three additional experiments, we showed that this view may help to explain novel oblique-related effects that have not been observed before — namely, an expansion of ‘empty’ space in the cardinal versus oblique regions of space (Experiments 2a and 2b), as well as an increase in perceived size (Experiment 3).

6.1. ‘Oblique warping’: a general distortion?

The key suggestion here is that there exists a continuous distortion of space in the angular dimension (but *not* the distance dimension) between the cardinal and oblique axes that can account for a range of other distortions and biases (see Fig. 6 for a visual explanation). That there are angular distortions is incontrovertible: Reductions in angular acuity in the oblique regions of space, for orientation as well as location, are well-documented (see Appelle, 1972; Wei & Stocker, 2015; Yousif et al., 2020). At issue is whether these differences in angular acuity are related to the other oblique distortions discussed and demonstrated here. We think there are compelling reasons to believe that they might be.

One primary reason to believe that acuity differences and localization biases are related is because computational work has demonstrated a “lawful relation” between the two (see Wei & Stocker, 2015, 2017). For example, Wei and Stocker (2015) argue that efficient coding principles can explain how differences in orientation acuity lead to biases in orientation representation. The only difference here is that we are arguing that the relevant “acuity” may not be specific to orientation (though that may be the “original” form of warping via our experience

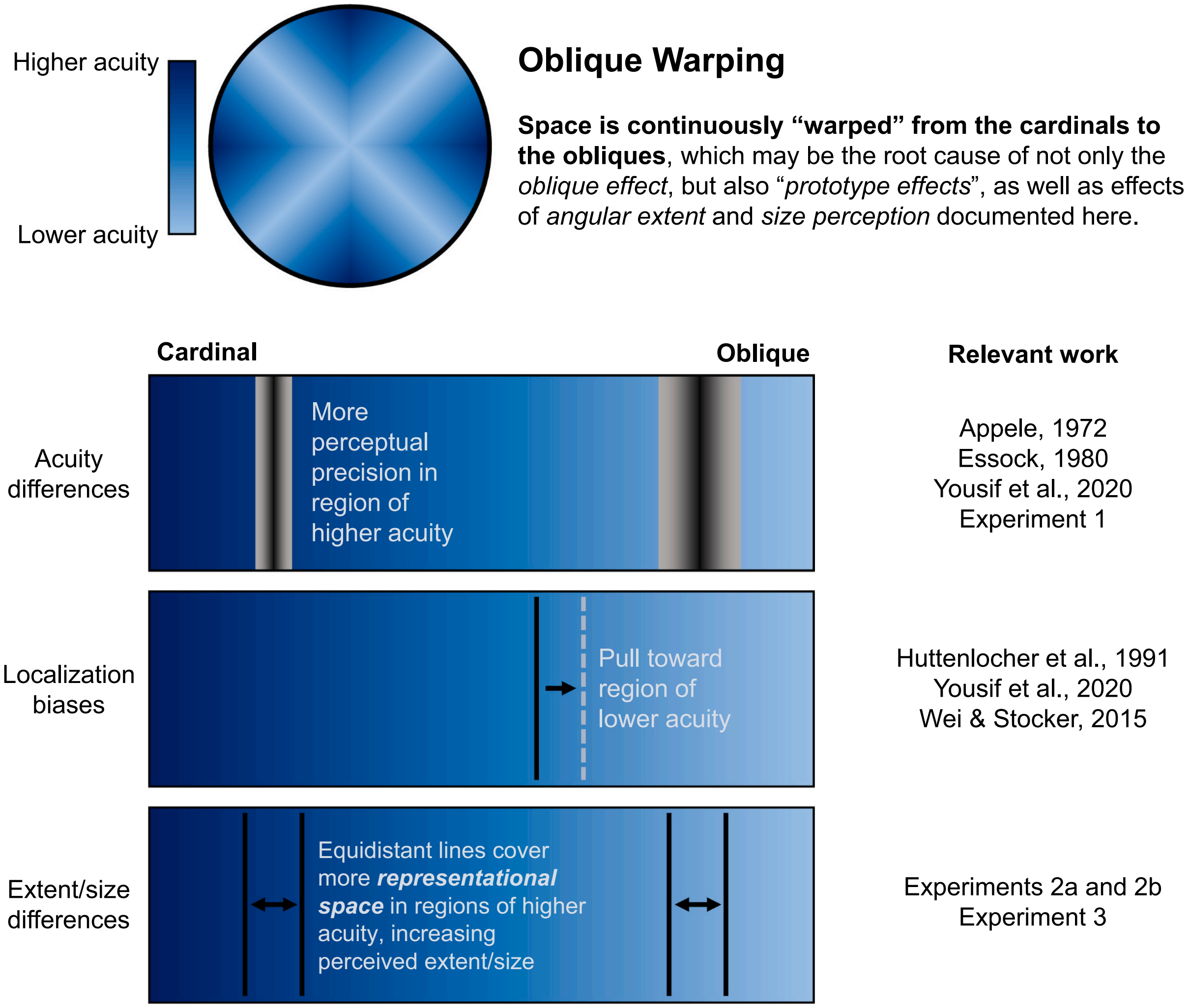

Fig. 6. A visual explanation of oblique warping and how it may explain known oblique distortions.

with the world) but instead encompasses a number of other spatial properties (e.g., location, extent, size; see Fig. 6).

Another reason to believe that these effects arise from a common, warped representation is that we have tested several key predictions of that view. Not only did we predict that distortions of orientation and location would be correlated (Experiment 1), we also guessed that, if there is indeed a general distortion of space, other spatial properties like extent and size should be affected by these distortions (predictions that, to our knowledge, have not been made or tested before). Our predictions were borne out: Perceived extent and size are increased in the cardinal regions of space.

It could be argued that the relation between orientation acuity and location acuity is not surprising, as the "location" task could be thought of as an orientation task (insofar as observers may imagine a particular coordinate reference frame, drawing a line between the target location and the central point). That is: The apparent differences in location acuity may reflect the fact that observers are treating the location task as an orientation task in disguise. We think this is an interesting possibility that opens doors to other novel questions. For instance: Are biases of localization (Huttenlocher et al., 1991; Yousif et al., 2020; Yousif et al., 2023) *also* a result of orientation processing? What about biases of angular extent and size (as in Experiments 2 and 3) ? We aren't sure how one would demonstrate that orientation processing explains these effects, but, if that were true, we would view it as consistent with the proposal offered here — that there exists a single distortion underlying a range of spatial phenomena.

Another reason to believe that observed oblique effects arise from a common, warped representation is that these distortions appear to be modality general: Yousif et al. (2023) have recently shown that oblique biases in visual localization tasks (akin to Huttenlocher et al., 1991; Yousif et al., 2020) are robustly correlated with oblique biases in a purely proprioceptive localization task (using a similar design). These cross-modal correlations make it hard to buy the argument that all of these effects are about orientation per se. If these effects all boil down to differences in orientation-selective neurons in visual cortex (see, e.g., Furmanski & Engel, 2000; Li et al., 2003), then how should we explain the presence of oblique biases during a motor task? It is plausible that motor processing is somehow co-opting visual cortex, but it seems equally (if not more) plausible that these distortions are specific neither to vision nor orientation.

In light of the cross-task correlations demonstrated here (Experiment 1), the cross-modal correlations shown in other work (Yousif et al., 2023), and the novel effects documented in Experiments 2 and 3, there is good reason to believe in a common spatial representation at the heart of these phenomena. We speculatively propose that all of them, from the "oblique effect" to "prototype effects" to distortions of size and angular extent, reflect a fundamental spatial phenomenon — a general oblique warping that transcends domain and modality.

One thing to note about oblique warping is that these effects are not categorical. We do not think that there is a rigid boundary between the oblique regions of space and the cardinal region of space. Instead, we think that there are continuous differences in acuity between the cardinal axes and the obliques (see Experiment 3c of Yousif et al., 2020, and Fig. 6 here). In this way, these effects are not about the oblique regions any more than they are about the cardinal regions (see also Rademaker et al., 2017). We use the term *oblique warping* to capture the fact that, historically, emphasis has been put on the reduction in acuity in the obliques rather than the increase in acuity along the cardinal axes.

Another important aspect of oblique warping is that it is *not* a general warping of all aspects of space: The acuity differences and biases discussed here are specific to the angular dimension of space (see Experiment 1; see also Yousif et al., 2020). This fact alone has some interesting implications. For instance, it means that classic 'prototype effects' (Huttenlocher et al., 1991) may be thought of not as biases towards a point in space, but as biases along a single angular dimension. The specificity of 'oblique warping' evokes the conclusion that angular information is being represented independently from other dimensions on some level, pointing to the possible use of polar coordinates as a primary means of spatial representation. This is consistent with other work providing evidence that spatial representations may spontaneously operate in a polar coordinate system (see Yousif, 2022; Yousif et al., 2023; Yousif & Keil, 2021).

Does the existence of oblique warping imply that canonical explanations for the oblique effect appealing to orientation-selective neurons (e.g., Furmanski & Engel, 2000; Li et al., 2003) are incomplete? Or that 'prototype effects' (Huttenlocher et al., 1991) and the 'Category Adjustment Model' (Holden, Curby, Newcombe, & Shipley, 2010; Holden, Newcombe, & Shipley, 2013) are misunderstood? We think not. While the present results suggest that a range of oblique distortions could arise from a single spatial representation, there could be effects that are domain- and modality-general and other effects that are domain- and modality-specific, meaning that different tasks may induce different effects or single tasks may induce multiple effects. For instance, it is possible that observed points are biased towards the 'prototype' of a category, and that, in addition to this categorical effect, there is an additional effect of angular acuity, as we have proposed here. It is also likely the case that some of the instances of oblique warping documented here do arise directly from differences in orientation-selective neurons in visual cortex, even if not all of them do. Finally, it may be the case that environmentally driven warping in visual cortex cascades to later visual areas and even brain areas involved with more abstract spatial cognition (see, e.g., Girshick, Landy, & Simoncelli, 2011). We believe that, in light of the cross-modal correlations observed in other work (Yousif et al., 2023), the parsimonious explanation for all these findings is likely neither a categorical explanation nor an explanation that appeals only to orientation-selective neurons in early visual cortex.

7. Conclusion

While prior work has offered multiple domain- and modality-specific explanations for many oblique-related phenomena, ranging from cognitive biases to physical limitations, we suggest that they might boil down to a single representational distortion: *Oblique warping.* Oblique warping describes a continuous decrease in spatial acuity from the cardinal axes to the obliques that is not limited to any one spatial feature (e.g., orientation) but applies more broadly (to orientation, location, extent, and size). This account is supported by the many replications of oblique-related effects across tasks and paradigms, as well as both cross-task and cross-modality correlations. These findings hint that beneath a range of oblique-related phenomena exists a common representational form.

CRediT authorship contribution statement

Sami R. Yousif: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Samuel D. McDougle:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest. All data and preregistrations are available here: https://osf.io/7tcbh/

Data availability

All of our data are available on an OSF page linked in the article

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