# Object-based warping: An illusory distortion of space within objects

Timothy J. Vickery and Marvin M. Chun

Department of Psychology, Yale University

Corresponding author:

Timothy J. Vickery
Dept. of Psychology
Yale University
2 Hillhouse Ave.
New Haven, CT 06520
Ph: 617-671-9079
Email: tim.vickery@gmail.com

**Abstract**

Visual objects are high-level primitives that are fundamental to numerous perceptual functions, such as guiding attention. We report that objects warp visual perception of space, such that spatial distances within objects appear to be larger than in ground regions. When two dots were placed inside of a rectangular object, they appeared farther apart from one another than two dots with identical spacing outside of the object. To investigate whether this effect was object-based, we measured the distortion while manipulating the structure surrounding the dots. Object displays were constructed with a single object, multiple object, a partially occluded object, and an illusory object. Non-object displays were constructed to be comparable to object displays in low-level visual attributes. In all cases, the object displays resulted in a more powerful distortion of spatial perception than comparable non-object-based displays. These results suggest that perception of space within objects is warped.

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High-level visual functions, such as recognition and attention, depend on 'perceptual organization' processes, which provide the fundamental structural representations (objects and groups) on which these functions operate. Object perception itself depends on perceiving the spatial relationships among features in a scene to determine figure-ground perception and the assignment of visual regions to different objects. Given the dependence of object perception on spatial perception, it seems unlikely that objects could subsequently alter those very same spatial percepts. Nevertheless, we report an illusory distortion of perceived space within objects, which suggests that object perception alters the perception of space.

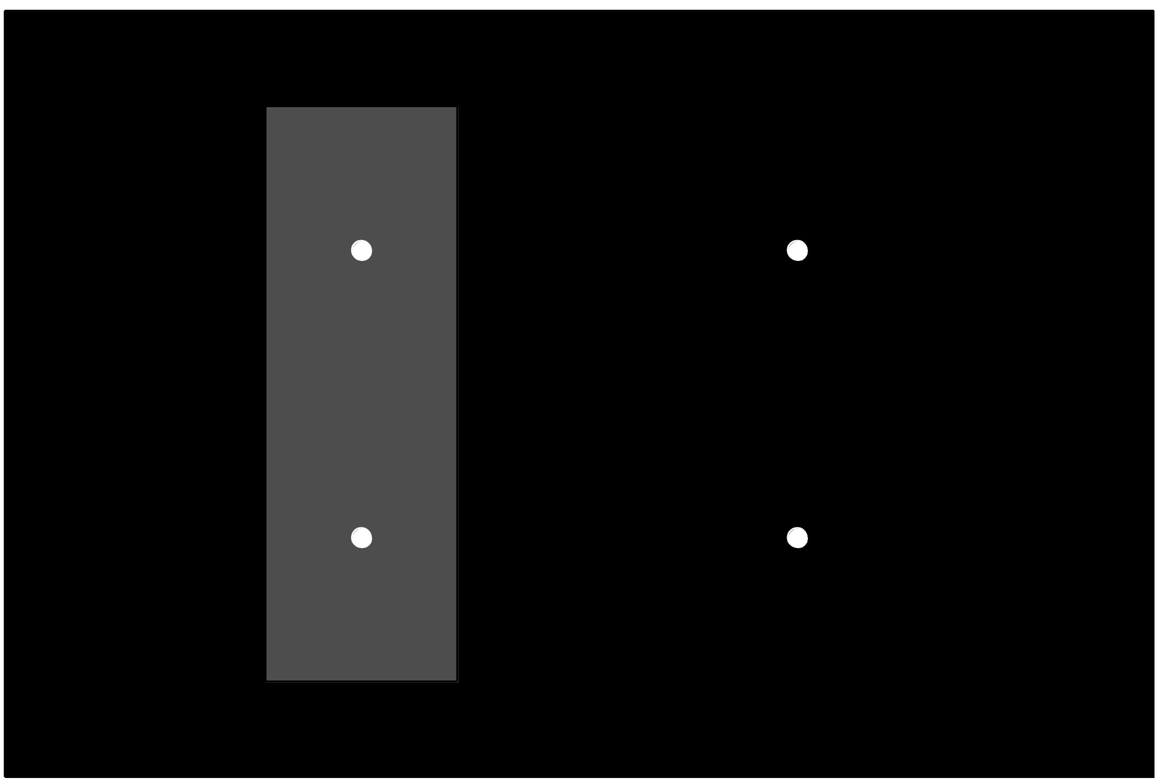

**Figure 1.** The dot-pair inside the gray rectangle has the same spacing as the dot-pair outside the rectangle, yet most observers report that the dot-pair within the rectangle appears to have greater spacing.

When the distance between two dots inside an object was compared to the distance between equivalently spaced dots outside an object, those inside the object were perceived as farther apart. This illusion, which we term "object-based warping," can be observed in Figure 1. Most informally-polled observers reported that the dots inside the object appear farther apart than the two dots outside the object.

Why would the inner area of an object show such a salient expansionary distortion? Many distortions of distance and size are due to depth perception – things that are perceived as more distant are perceived as greater in size or spacing. Intriguingly, object-based warping runs counter to a depth explanation. The dots overlaid on the object should be perceived as closer to the observer than the dots placed in empty space; thus, a depth account would effect the opposite distortion, with contracted space within the object.

One potential cause of object-based warping is attention, which involuntarily spreads across or arbitrarily selects entire surfaces of incidentally selected regions belonging to objects (e.g., Duncan, 1984; Egly, Driver, & Rafal, 1994). Attention has wide-ranging influences on perception; for instance, transient attention enhances both contrast sensitivity and apparent contrast (Carrasco, Ling, & Read, 2004), and it increases apparent gap size and spatial frequency (Gobell & Carrasco, 2005). Objects may arbitrarily attract attention (Kimchi, Yeshurun, & Cohen-Savransky, 2007), and attended patterns may be perceived as larger than equivalently-sized unattended patterns (Anton-Erxleben, Henrich, & Treue, 2007). Thus, attending to the dots on the object may cause incidental selection of the object during spatial judgment, which may in turn cause an expansion of perceived space within the object.

On the other hand, object-based warping may reflect a fundamental property of visual representation. Activity in early visual cortex is enhanced for figural compared to ground regions (e.g., Marcus & Van Essen, 2002), and contrast sensitivity is enhanced within closed contours (Kovacs & Julesz, 1994). It is possible that the visual system also devotes an exaggerated cortical representation to visual regions perceived as belonging to a figure's surface, due to the primacy of objects in perceptual computations. Devoting a finer-grained representation to parts of visual space may facilitate perception of the properties of that object. This explanation and one based on attention may not be mutually exclusive, with attention potentially bearing the responsibility for the overrepresentation in the first place.

We have strongly implied that this spatial warping is “object-based,” but our demonstration leaves open the possibility that the illusory distortion is unrelated to objecthood, and is actually due to low-level visual properties that define the object. For instance, the dots in the object are closer to a contour than the dots in the ground region – the contours could serve as an “anchor” that distorts perception. We hypothesized that this distortion was object-based, such that the spatial distortion would depend on the strength of evidence that dots were part of the same object structure. To investigate whether this effect was object-based, we measured distortion while manipulating the structure surrounding the dots. Object displays were constructed with a single object, multiple objects, a partially occluded object, and an illusory object. Non-object displays were constructed to be comparable to object displays in low-level visual attributes. If object-based warping is really due to objects, then the effect should be greater for object manipulations than similar, non-object manipulations.

## Methods

### *Participants*

Thirteen naive observers with normal or corrected vision from the Yale community completed the experiment for pay.

### *Stimuli and Procedure*

Participants viewed stimuli on a monitor, at an unconstrained distance of approximately 57 cm; thus 1 mm on the monitor subtended approximately 0.1 degrees of visual angle.

On each trial, participants viewed scenes containing two red *stationary dots* (2 mm x 2 mm) on a gray background in the upper-left of a monitor, and two red *adjustment dots* in the lower-right. Participants made smooth, unspeeded adjustments using the mouse, which moved the bottom of the two adjustment dots up and down. They were asked to adjust the position of the dot such that the adjustment dot spacing matched their perceived spacing of the stationary dots. Clicking the mouse froze the dot, at which point the participant was able to either proceed or correct their choice. Trials were separated by a 1 s blank gray screen.

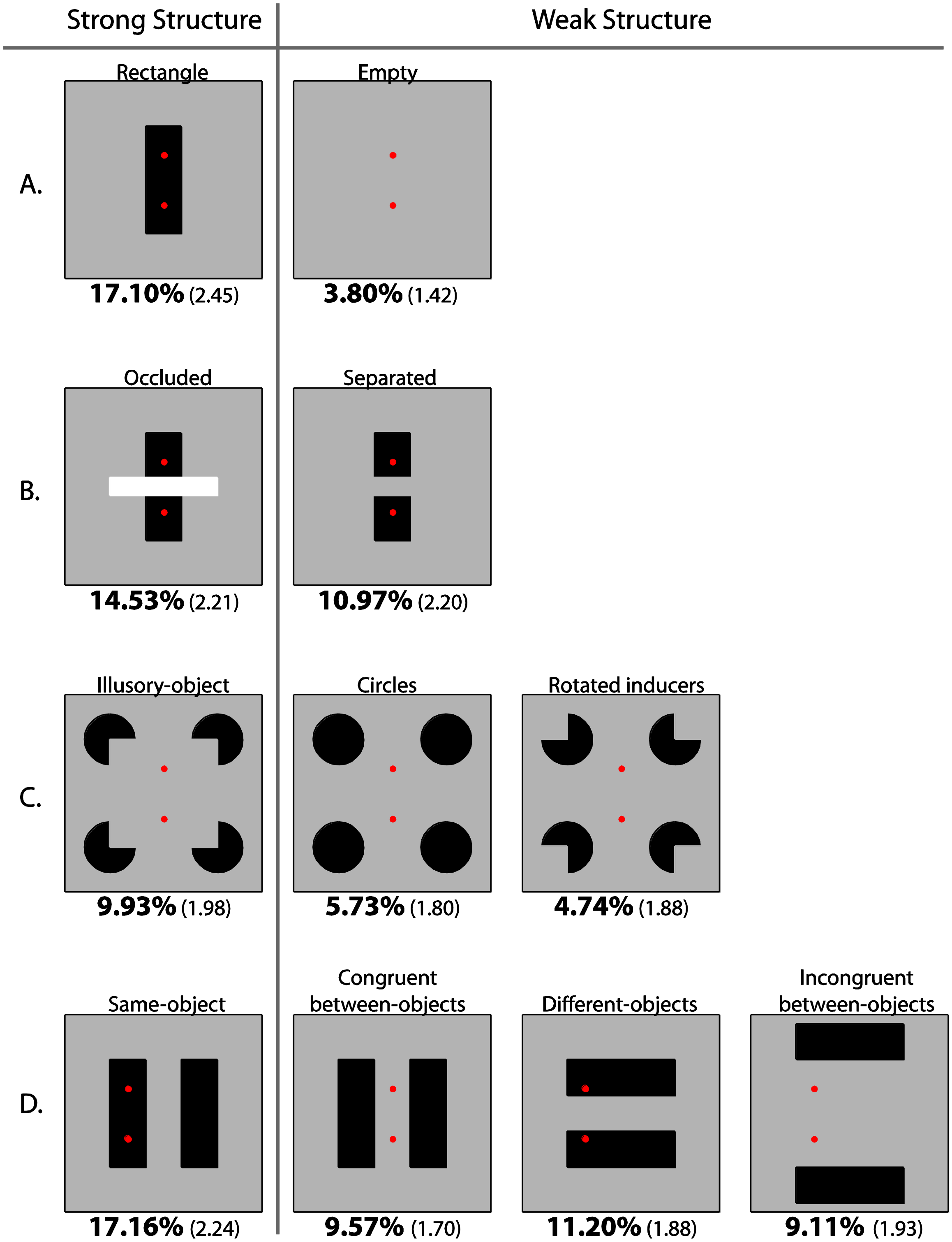


**Figure 2.** Depiction of all conditions (smaller of two dot separation lengths shown), drawn to scale with exception of exaggerated dot size for visibility. Strong-structure conditions are presented in the left-most column, with corresponding weak-structure conditions to the right of each. Mean estimated distance between dots and S.E.M. are presented below each condition.

From trial-to-trial, we manipulated displays to include either strong or weak evidence that the stationary dots were placed on the same object. We term these *strong-structure* and *weak-structure* conditions, respectively, because these terms do not rule out the likelihood that the distortion effect is due to perceived structure broadly construed (including perceptual grouping), rather than specific to objects, a particularly strong type of perceived structure. There were four *strong-structure* conditions and seven *weak-structure* conditions, which included comparable low-level attributes (e.g., contour proximity) to *strong-structure* counterparts.

Figure 2 and the following list describe each *strong-structure* condition, along with corresponding *weak-structure* conditions.

A. Object Manipulation: The *strong-structure* manipulation centered the stationary dots within a 25 mm x 75 mm black rectangle (*object* condition). This was contrasted with a *baseline* condition with no objects, to quantify the basic effect.

B. Occlusion Manipulation: The *strong-structure* condition (*occlusion*) placed the dots inside a black rectangle bisected by an occluding white rectangle (75 mm x 12.5 mm). The corresponding *weak-structure* condition (*separated*) was identical except the occluder was the same color as the background, implying that the dots were placed on two separate objects.

C. Illusory-Object Manipulation: The *strong-structure* condition (*illusory-object*) placed the dots within a "Kanizsa" square (75 mm x 75 mm), which was induced by 35 mm elements centered on its corners. The corresponding *weak-structure* displays were a *circles* condition where the inducers were solid circles in the same positions as the inducers in the *illusory-object* condition, and a *rotated-inducers* condition, where the inducers were identical, but rotated by 180 degrees to destroy the percent of a rectangle.

D. Same-Different Manipulation: The *strong-structure* condition (*same-object*) placed the dots inside the leftmost of two 25 mm x 75 mm (vertically-oriented) black rectangles, separated by 25 mm edge-to-edge. Dots were centered on the leftmost object for the *same-object* condition. Corresponding *weak-structure* conditions centered the dots in the space between the two objects (*congruent-between-objects*), within two different horizontally-oriented objects (*different-objects*), and between two widely spaced, horizontally-oriented rectangles (*incongruent-between-objects*). In the *different-objects* condition, the configuration was identical to the *same-object* condition, but with the two objects horizontally oriented. The stationary dots were each in a different object, on the left-hand side. In the *incongruent-between-objects* condition, the horizontally-oriented bars were separated by 75 mm edge-to-edge, with the dots centered in the space between them.

We measured judged distance as a percentage of actual separation for each trial. For all conditions, the stationary dots were presented in two spacings (vertically separated by 35 or 40 mm), and the adjustment dots were initialized at two spacings (2.5-mm or 87.5-mm spacings). Stationary and adjustment dot spacings were crossed, with each of the four possible combinations appearing once in every block for each condition, resulting in a total of 44 trials per block. The experiment was divided into 10 blocks with invisible boundaries. Within each block, trials were randomly interleaved.

## Results

Percent distortions in each condition were averaged after responses were trimmed if they exceeded 2.5 s.d. from the cell mean, eliminating 1.2% of trials. Averages were collapsed over stationary and adjustment dot spacings.

Planned comparisons were designed to demonstrate the existence and extent of the distortion based on differences between *strong-structure* and *weak-structure* conditions. All participants reported amplified spacing in the *object* versus the *baseline* condition ($t(12)=7.76$, $p<1e-5$, $d=2.15$, $p_{rep}=0.99$), confirming that space within an object is expanded compared to ground regions.

Distortion was significantly stronger in the *occlusion* condition than in the *separated* condition ($t(12)=3.66$, $p<.005$, $d=1.01$, $p_{rep}=0.98$), despite having both equal spacing and equivalent intervening contours in both conditions.

The distortion was significantly stronger in the *illusory-object* condition than the *circles* condition ($t(12)=5.36$, $p<.001$, $d=1.49$, $p_{rep}=0.99$) or the *rotated-inducers* condition ($t(12)=5.41$, $p<.001$, $d=1.50$, $p_{rep}=0.99$). The illusion was observed despite the absence of real bounding contours and even though the implied object was square, suggesting that the distortion is not dependent on a rectangular aspect ratio of the conditions above (confirmed in separate pilot studies using real objects).

Finally, the distortion was significantly stronger in the *same-object* condition than in the corresponding *weak-structure* conditions: *congruent-between-objects* ($t(12)=7.23$, $p<.0001$, $d=2.00$, $p_{rep}=0.99$), *different-objects* ($t(12)=5.98$, $p<.0001$, $d=1.66$, $p_{rep}=0.99$), and *incongruent-between-objects* ($t(12)=5.60$, $p<.001$, $d=1.55$, $p_{rep}=0.99$).

Our significance tests involved multiple comparisons, including several comparisons (for conditions C-D) of multiple means (*weak-structure* conditions) to a single mean (the corresponding *strong-structure* condition). To control family-wise error rate, we compared the resulting p-values with a corrected p-value based on an overly conservative Bonferroni correction ($\alpha = .05/7 = .007$). In all cases, the comparisons were still significant.

Although the above analyses collapsed over both stationary dot spacings, we verified that neither was solely responsible for the significant effects. All of the above comparisons were significant for both spacings when tested alone. Table S1 reports a complete breakdown of the distortion effect by separation, as well as all associated t-tests between corresponding strong and weak structure by separation.

Our analyses were tightly focused on contrasting the strong vs. weak structure conditions; nevertheless, numerous distortions were observed in the weak structure conditions compared to the *empty* condition. Table S1 also reports the contrast of the mean effect for each condition vs. the *empty* condition. Only one condition (the *rotated inducers*) failed to show a significant ($p<.05$) distortion of space compared to the *empty* condition. These distortions may scale with the amount of structure generally surrounding the dots.

## Discussion and Conclusion

This study introduces a novel illusory warping of space within objects. In all cases, scenes with stronger implied structure surrounding the dots resulted in greater illusory space distortion than those with weaker degrees of local organization. The outputs of perceptual organization processes (objects and groups) are now wellrecognized as units of perception and attentional selection (Scholl, 2001). We have demonstrated that objects distort a low-level visual property, perceived space.

There are several potential reasons why this may occur. As previously mentioned, object-based attention or cortical rescaling of space within objects are two possibilities. Another possibility is that this is a contrast effect, due to differences in how much of their respective frames the dots occupy. For example, the dots inside the object occupy more of the figure context (the object) than dots outside the object occupy of the ground context (the monitor). This explanation is similar to explanations of size contrast illusions, such as the Ebbinghaus illusion, in which a circle surrounded by larger circles looks smaller than when it is surrounded by smaller circles). This hypothesis would predict that the distortion effect would be greater for shorter rectangles than for longer rectangles. This does not seem to be the case. In an additional experiment (N=9) not reported in detail here, we compared the illusory distortion of two dots inside a short rectangle (25 mm x 50 mm) with that inside a longer rectangle (25 mm x 75 mm), and confirmed that there was no difference in the size of the illusory distortion. For a central region (25 mm separation of reference dots) within both objects, there was a significant expansion of perceived space over a no-object condition (both $p < .005$). Numerically, the larger rectangle actually produced a larger effect, contrary to the prediction of the contrast hypothesis, although the difference was not significant, ($t < 1$).

The object-based warping illusion offers a new twist in a long history of spatial distortions due to perceptual organization. In an examination of the Müller-Lyer illusion, Fellows (1967) described distortions in line length judgments, wherein lines enclosed by a rectangular frame appeared longer than lines outside the enclosure. However, this effect was never linked to high-level influences such as object perception, as it is here. More recently, the configural shape illusion (CSI; reported by Palmer & Schloss, VSS 2009) reported distortions in the aspect ratio of a rectangle when grouped with another, adjacent shape. The CSI varied according to the strength of grouping between the two shapes, consistent with our structural manipulations here.

Our results suggest that objects produced a salient warping of space. This distortion was reduced when rather subtle manipulations eliminated objecthood, while leaving intact local, low-level visual features. Prior research has also suggested that perceptual grouping can distort the perceived distance between elements in a scene, but the distortion was unexplainably inconsistent across studies that reported either contraction (Coren & Girgus, 1980) or expansion of scene elements (Vickery & Jiang 2009). The present work demonstrates that objects produce a more striking and unambiguous distortion effect, a robust spatial expansion within the central regions of objects.

Object-based and group-based effects may be interrelated, with an object acting as a common region cue to grouping of the stationary dots (Palmer, 1992), although further research is needed to explore the relationship. The present data hint that regions within grouped elements do show a smaller, but reliable distortion effect. Table S1 shows that most conditions yielded a reliable expansionary distortion over the *empty* condition. The weakest distortions came from those conditions that might be expected to yield the least grouping – the rotated inducers (due to reduced similarity) and the *incongruent between-objects* (due to reduced proximity). Thus, the object distortion effect may apply to structure more generally – more structured regions of the visual scene result in greater distortion effects, with objects representing the greatest possible amount of local structure in a scene. Our results open the door to a new understanding of spatial perception's dependence on perceived structure, and provide a technique for detailed mapping of these effects.

Object-based warping may be related to attention, which involuntarily spreads across or arbitrarily selects entire surfaces of incidentally selected regions belonging to objects. Alternatively, it may reflect a fundamental property of visual representation. The visual system may devote an exaggerated cortical representation to visual regions perceived as belonging to a figure's surface, due to the primacy of objects in perceptual computations. Future studies will further distinguish these possibilities.

In conclusion, when probed, distance within objects appears greater than distances outside objects. This effect may provide diagnostic measure of perceived structure, and implications for the underlying representation of structured regions of visual space.

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Table S1

| **Condition** | **Type of structure** | **Small separation distortion mean (S.E.M.)** | **Contrast with corresponding strong-structure, small separation** | **Large separation distortion mean (S.E.M.)** | **Contrast with corresponding strong-structure, large separation** | **T-test vs. empty condition** |
|---|---|---|---|---|---|---|
| Rectangle | Strong | 21.05 (2.75) | -- | 13.07 (2.37) | -- | t(12)=7.76 p<1e-5 d=2.15 prep > 0.999 |
| *Empty* | *Weak* | *6.11 (1.78)* | *t(12)=7.40 p<9e-6 d=2.05 prep > 0.999* | *1.52 (1.25)* | *t(12)=6.65 p<3e-5 d=1.85 prep > 0.999* | |
| Occlusion | Strong | 17.49 (2.19) | -- | 11.57 (2.37) | -- | t(12)=7.23 p<1e-4 d=2.01 prep > 0.999 |
| *Separation* | *Weak* | *14.53 (2.46)* | *t(12)=2.76 p<0.02 d=0.7 prep > 0.93* | *7.45 (2.22)* | *t(12)=3.19 p<0.008 d=0.88 prep > 0.96* | *t(12)=5.91 p<1e-4 d=1.64 prep > 0.99* |
| Kanizsa square | Strong | 12.09 (2.26) | | 7.77 (2.03) | | *t(12)=6.80 p<1e-4 d=1.89 prep> 0.999* |
| *Circles* | *Weak* | *8.92 (2.26)* | *t(12)=4.06 p<0.002 d=1.13 prep > 0.98* | *2.51 (1.61)* | *t(12)=5.24 p<0.001 d=1.45 prep > 0.99* | *T(12)=2.60 p<0.05 d=0.72 prep = 0.92* |
| *Rotated inducers* | *Weak* | *7.17 (2.19)* | *t(12)=5.45 p<0.001 d=1.51 prep > 0.99* | *2.30 (1.71)* | *t(12)=4.30 p<0.002 d=1.19 prep > 0.98* | *t(12)=1.00 p=0.34 d=0.28 prep = 0.61* |
| Same-object | Strong | 17.16 (2.24) | | 20.39 (2.30) | | t(12)=9.01 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | $p<1e-5$ $d=2.50$ prep > 0.999 |
| *Congruent between-objects* | *Weak* | *11.57 (1.77)* | $t(12)=8.16$ $p<1e-5$ $d=2.26$ *prep > 0.999* | *7.66 (1.80)* | $t(12)=5.10$ $p<0.001$ $d=1.41$ *prep > 0.99* | $t(12)=5.56$ $p<0.001$ $d=1.54$ *prep > 0.99* |
| *Different-objects* | *Weak* | *13.73 (2.02)* | $t(12)=5.95$ $p<1e-4$ $d=1.65$ *prep > 0.99* | *8.64 (1.85)* | $t(12)=4.89$ $p<0.001$ $d=1.36$ *prep > 0.99* | $t(12)=7.63$ $p<1e-5$ $d=2.12$ *prep > 0.999* |
| *Incongruent between-objects* | *Weak* | *10.78 (2.40)* | $t(12)=6.18$ $p<1e-4$ $d=1.72$ *prep > 0.99* | *7.46 (1.77)* | $t(12)=3.73$; $p<0.005$ $d=1.03$ *prep > 0.98* | $t(12)=6.02$ $p<1e-4$ $d=1.67$ *prep > 0.99* |