

# Crowding and perceptual organization: Target's objecthood influences the relative strength of part-level and configural-level crowding

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**In visual crowding, identification of a peripheral object is impaired by nearby objects. Recent studies have demonstrated that crowding is not limited only to interaction between low-level features or parts, as presumed by most models of crowding, but can also occur between high-level, configural representations of objects. In this study we show that the relative strength of crowding at the part level versus the configural level is dependent on the strength of the target's perceptual organization. The target's strength of organization was manipulated by presence or absence of closure and good continuation or by proximity between the target's parts. The flankers were similar either to the target parts or to the target configuration. The stronger the target's organization was, the weaker the crowding was by part flankers (Experiments 1 and 2). Most importantly, the target's strength of organization interacted with target-flanker similarity, such that crowding by target-flanker similarity in configuration was greater than that by target-flanker similarity in parts for strongly organized targets, but lesser for weakly organized targets (Experiments 3 and 4). These results provide strong evidence that perceptual-organization processes play an important role in crowding.**

## Introduction

Crowding is a perceptual phenomenon in which the recognition of an object presented in the periphery of the visual field is impaired by the presence of nearby objects (Bouma, 1970), yet the detection of the object is not disrupted.

Crowding depends on the target object's eccentricity and the center-to-center distance between the target object and the flankers (i.e., *target-flanker spacing*). The critical spacing—the minimum target-flanker

spacing at which crowding is relieved—is proportional to eccentricity ( $e$ ), and has been widely reported to be  $\sim 0.5e$  (for reviews, see Levi, 2008; Pelli & Tillman, 2008; Whitney & Levi, 2011; but see Herzog & Manassi, 2015). Crowding also depends on the similarity between the target and flankers: Crowding is stronger the more similar the flankers are to the target in color, contrast polarity, shape, spatial frequency, depth, complexity, and identity (e.g., Chung, Levi, & Legge, 2001; Dakin, Cass, Greenwood, & Bex, 2010; Freeman, Chakravarthi, & Pelli, 2012; Kooi, Toet, Tripathy, & Levi, 1994; Nazir, 1992; Zhang, Zhang, Xue, Liu, & Yu, 2009).

Over the years, several explanations have been offered for crowding. The most prevailing and influential models attribute crowding to faulty feature integration or pooling over local regions (e.g., Levi, 2008; Parkes, Lund, Angelucci, Solomon & Morgan, 2001; Pelli & Tillman, 2008). In different models, pooling refers to excessive feature combination that occurs when target and flankers fall within the same “integration field” (Pelli, Palomares, & Majaj, 2004), or when target and flankers are combined into a textural representation based on averaging target and flanker signals (Parkes et al., 2001) or more complex summary statistics (Balas, Nakano, & Rosenholtz, 2009). Other explanations include feature substitution (e.g., Strasburger, 2005; Strasburger, Harvey, & Rentschler, 1991) and limits of attentional resolution (e.g., He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001). Notwithstanding the differences, all models presume that crowding occurs because of obligatory combination of low-level features at a single, relatively early stage of visual processing.

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Recently, different aspects of these models have been challenged (e.g., Whitney & Levi, 2011). Of particular relevance to the present article are recent findings which have suggested that crowding can occur not only between low-level features but also between high-level, configural representations of objects (Chaney, Fischer, & Whitney, 2014; Farzin, Rivera, & Whitney, 2009; Fischer & Whitney, 2011; Kimchi & Pirkner, 2015; Louie, Bressler, & Whitney, 2007). Most of these findings come from studies with face stimuli. For example, greater impairment in upright face identification has been observed when the face was flanked by upright faces than by inverted faces (that preserve featural information but disrupt configural information), and the asymmetry vanished when the target was an inverted face (Louie et al., 2007). This selective crowding by upright face flankers has also been found with Mooney faces, which clearly limit featural information (Farzin et al., 2009). Also, object-level information, such as facial expression, appears to survive crowding (e.g., Faivre, Berthet, & Kouider, 2012; Fischer & Whitney, 2011).

We have demonstrated (Kimchi & Pirkner, 2015) that crowding at the object configural level is not specific to faces and can occur also for nonface objects. In a critical experiment in that study, participants were presented with a target made of four L elements organized into a diamond-like or a square-like configuration. The target was surrounded by flankers similar to the target in global configuration but dissimilar in elements (parts) or similar in parts but dissimilar in global configuration, so that the level at which similarity between the target and flankers arose varied, while the degree of similarity was controlled for.<sup>1</sup> Crowding occurred at the object part level and the object configural level, with even more crowding at the configural level than at the part level. These results demonstrate multiple-level crowding and indicate that crowding is influenced not by the degree of similarity per se between the target and flankers, but rather by the level at which the similarity between target and flankers arises.

We suggested that the finding of weaker crowding by similarity in object parts than by similarity in object configuration was due to the strong perceptual organization of the target—namely, the strong grouping (by proximity, good continuation, and closure) of the target's elements into an object (a square or a diamond configuration). We reasoned that because of this internal grouping, the target parts—although similar to part flankers—were not grouped with the flankers; consequently, the target stood out from the flankers, resulting in weaker crowding. In line with this suggestion, we hypothesized that the strength of crowding at the object-part or the object-configuration level is dependent on the strength of the target's

perceptual organization, such that crowding at the configuration level is greater than at the part level when the target's organization is strong, but lesser when the target's organization is weak.

The present study aimed to examine this hypothesis. We manipulated the strength of the target's perceptual organization (or the target's degree of objecthood) by Gestalt grouping factors. The grouping factors of closure, good continuation, and proximity, proposed originally by Wertheimer (1923), have been documented in the literature as playing a crucial role in perceptual organization (e.g., Feldman, 2003, 2007; Field, Hayes, & Hess, 1993; Geisler, Perry, Super, & Gallogly, 2001; Kubovy, Holcombe, & Wagemans, 1998; Mathes & Fahle, 2007). Proximity has been considered a particularly powerful factor (e.g., Elder & Goldberg, 2002; Kubovy et al., 1998), whereas the role of symmetry in perceptual organization has been less clear (e.g., Machilsen, Pauwels, & Wagemans, 2009; Pomerantz & Portillo, 2011). Studying the formation of visual objects, Feldman (2007) demonstrated that the degree of objecthood of a simple line configuration increases with its degree of internal regularity, which depends on the co-occurrence of Gestalt grouping cues; the configuration with the strongest objecthood exhibits its regular spatial relations of good continuation, parallelism, and symmetry. The crucial role of closure in perceptual organization and, in particular, the formation of shape was noted by the Gestalt psychologists (e.g., Koffka, 1935) and has been demonstrated in several psychophysical studies (e.g., Elder & Zucker, 1993, 1994; Hadad & Kimchi, 2008; Kimchi, 2000; Kovács & Julesz, 1993). Elder and Zucker (1994) have further suggested that the degree of closure is a function of the size of the gap (i.e., the proximity) between the closure-induced contour segments, and Hadad and Kimchi (2008) have demonstrated that it also depends on the distribution of the gaps along the contours. (For reviews on perceptual grouping, see Peterson & Kimchi, 2013; Wagemans et al., 2012.)

Thus, in different experiments, we manipulated the strength of the target's organization, or degree of objecthood, by the presence or absence of closure and good continuation (Experiments 1 and 3) or by the proximity between the target's parts (Experiments 2 and 4). The target was presented in isolation or surrounded by flankers, at varying eccentricities and fixed target-flanker spacing or at fixed eccentricity and varying target-flanker spacing, and target identification was measured. Participants were requested to make a two-alternative forced-choice response to the two relevant targets. In the task's instructions, no reference was made to global configuration or to parts: Participants were presented with pictures of the relevant stimuli and requested to press a designated key for each. This was done in order to avoid a bias toward

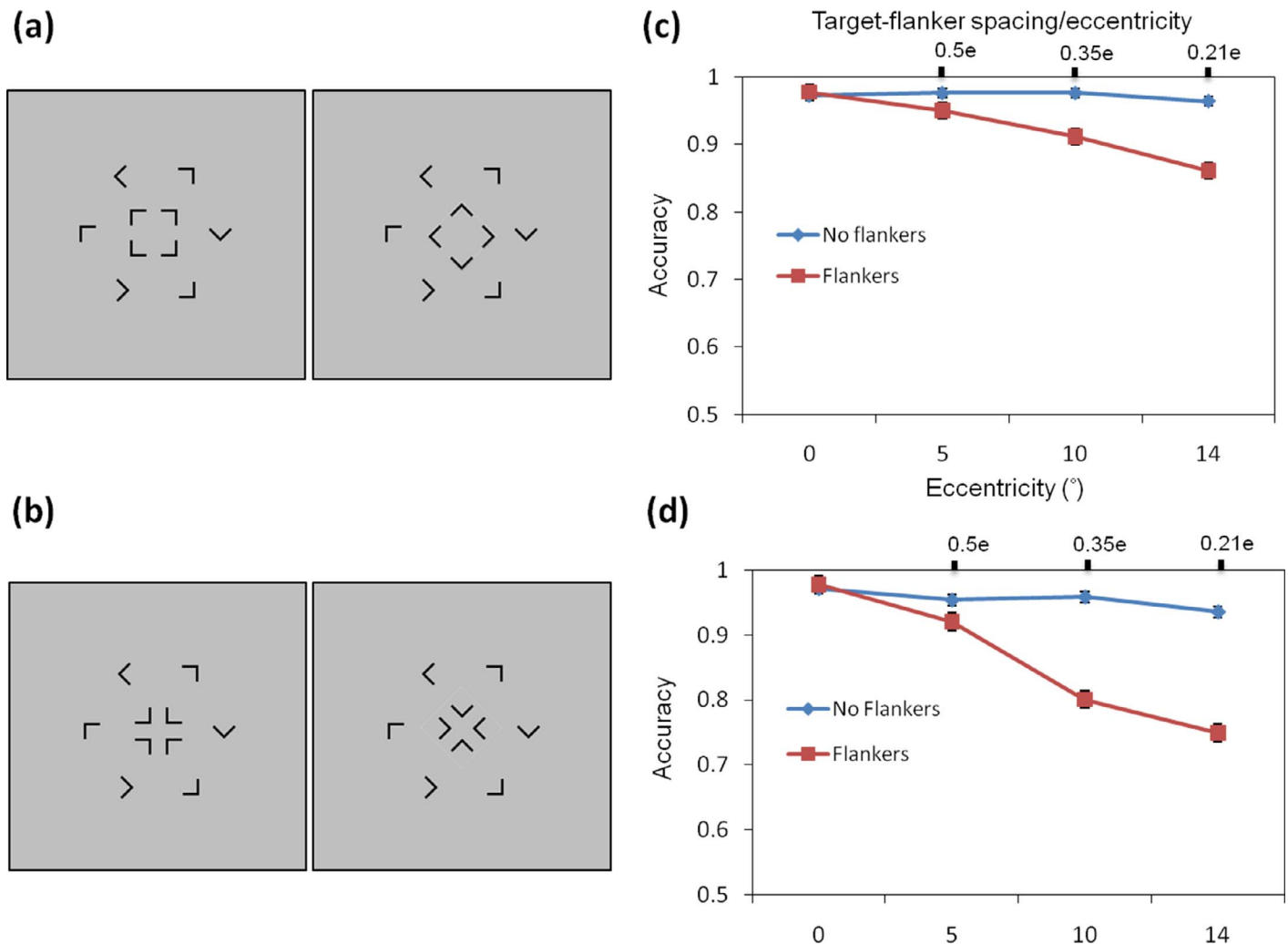


Figure 1. Examples of target and flankers used in (a) Experiment 1a and (b) Experiment 1b. Results from (c) Experiment 1a and (d) Experiment 1b: mean accuracy as a function of eccentricity and flankers conditions. Error bars represent within-subject standard error of the mean.

the global configuration or the parts (in principle, the task could be performed based on global shape or on the orientation of a single element). The flankers were similar to the target in parts or in configuration, thus allowing us to examine how the strength of the target's organization influences the relative strength of crowding by target-flanker similarity in parts versus configuration.

## Experiments 1a and 1b

Experiments 1a and 1b examined the influence of the strength of the target object's organization on crowding by object-part flankers. In Experiment 1a, the target object consisted of four L elements, which were grouped by the Gestalt grouping factors of closure, good continuation, parallelism, and symmetry into a

square-like or a diamond-like configuration (Figure 1a). In Experiment 1b, the target object was a cross-like or an X-like configuration made of four L elements, with no closure or good continuation, but parallelism and symmetry present in the target (Figure 1b). Proximity between the target's parts was held constant in both experiments. Accordingly, the target's organization was relatively stronger in Experiment 1a than in Experiment 1b. The flankers in both experiments were L elements similar to the target's parts. The target object was presented at varying eccentricities, alone or surrounded by six flankers. The task was to identify the target by pressing one of two response keys.

Target-flanker similarity was the same in both experiments, predicting similar crowding. If, however, crowding by object-part flankers is influenced by the strength of the target's organization, such that the stronger the organization the weaker the crowding,

more crowding was expected in Experiment 1b than in Experiment 1a.

## Method

### Participants

Participants in all the experiments reported in this article were students at the University of Haifa and were paid or granted course credit for participation. All had normal or corrected-to-normal vision, and none participated in more than one experiment. All participants provided informed consent to a protocol approved by the Ethics Committee of the Psychology Department at the University of Haifa. Fourteen individuals (19–33 years old; 11 women, three men) participated in Experiment 1a, and 14 (19–32 years old; 11 women, three men) participated in Experiment 1b.

### Stimuli and apparatus

The target was a disconnected configuration—square-like or a diamond-like in Experiment 1a, and cross-like or X-like in Experiment 1b—made of four black L elements (see Figure 1a and 1b). Each arm of the L element subtended  $0.55^\circ \times 0.08^\circ$ . Each side of the global configuration subtended  $1.6^\circ$ . The target was presented in isolation (no-flankers condition) or surrounded by six different flankers (flankers condition) randomly sampled on each trial from a set of eight L elements. Three of the presented flankers were identical to the L elements of the square-like and cross-like targets, and three were identical to the L elements of the diamond-like and X-like targets. The size of the L flankers was identical to the size of the elements of the target. The flankers were centered on an imaginary circle. The center-to-center distance between target and flankers was fixed at  $2.24^\circ$ . In all experiments the stimuli were presented against a gray background ( $54 \text{ cd/m}^2$ ).

All the experiments were conducted on a PC with a 24-in. LCD color monitor (BenQ XL2420Z) set at a resolution of  $1,920 \times 1,080$  pixels and a refresh rate of 100 Hz, using E-Prime. Viewing distance was fixed at 57 cm with a chin rest.

### Procedure

At the beginning of each trial, a black fixation mark ( $0.5^\circ \times 0.5^\circ$  cross) appeared for 750 ms at the center of the screen, followed by the target, which appeared for 120 ms at the fovea ( $0^\circ$ ) or at  $5^\circ$ ,  $10^\circ$ , or  $14^\circ$  eccentricity to the left or right of fixation, with or without six flankers. The fixation mark remained on screen until target offset (except in foveal presentation, in which the fixation mark disappeared with target onset), followed

by a gray screen which remained until a response was received (for a maximum of 3,000 ms). Using a two-alternative forced-choice task, participants were asked to identify the target by pressing one of two response keys. The intertrial interval was 1000 ms. All the combinations of eccentricity, field (right, left), flankers (flankers, no flankers), and target (square or diamond in Experiment 1a; cross or X in Experiment 1b) were presented with equal frequency in a random fashion across the experimental trials. There were 480 experimental trials preceded by 32 practice trials in each of the experiments.

## Results and discussion

Mean accuracy (proportion correct) of target identification as a function of flanker condition (flankers, no-flankers) and eccentricity is presented in Figure 1c (Experiment 1a) and 1d (Experiment 1b).

The accuracy data for each experiment were submitted to a  $4$  (eccentricity)  $\times$   $2$  (flanker condition) repeated-measures analysis of variance (ANOVA). The effect of the flankers on target identification was assessed by the difference between identification accuracy in the no-flankers and flankers conditions at each eccentricity, using paired  $t$  tests with a Bonferroni-corrected significance level of 0.0125.

As can be seen in Figure 1, crowding effects were evident in both experiments. The ANOVAs showed a significant effect of eccentricity:  $F(3, 39) = 19.35$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.6$  (Experiment 1a), and  $F(3, 39) = 53.59$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.85$  (Experiment 1b); a significant effect of flankers:  $F(1, 13) = 17.66$ ,  $p = 0.0010$ ,  $\eta_p^2 = 0.58$  (Experiment 1a), and  $F(1, 13) = 48.83$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.79$  (Experiment 1b); and a significant interaction between eccentricity and flankers:  $F(3, 39) = 13.32$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.51$  (Experiment 1a), and  $F(3, 39) = 47.21$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.78$  (Experiment 1b). In both experiments, when the target appeared in isolation, identification was highly accurate (average 97.2% and 95.5%, for Experiments 1a and 1b, respectively), and a small but significant effect of eccentricity was observed for Experiment 1b,  $F(3, 39) = 3.5$ ,  $p = 0.0243$ ,  $\eta_p^2 = 0.21$ . When flankers were present, accuracy varied significantly with eccentricity,  $F(3, 39) = 21.41$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.62$  (Experiment 1a), and  $F(3, 39) = 69.54$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.84$  (Experiment 1b). A significant effect of flankers was observed at  $10^\circ$  eccentricity, reducing accuracy from 97.6% to 91.1% in Experiment 1a,  $t(13) = 5.08$ ,  $p = 0.0002$ , and from 95.8% to 80% in Experiment 1b,  $t(13) = 9.0$ ,  $p < 0.0001$ ; and at  $14^\circ$  eccentricity, reducing accuracy from 96.4% to 86.1% in Experiment 1a,  $t(13) = 3.91$ ,  $p = 0.0018$ , and from 93.6% to 74.9% in Experiment 1b,  $t(13) = 8.04$ ,  $p < 0.0001$ . No effect of flankers was observed at the fovea

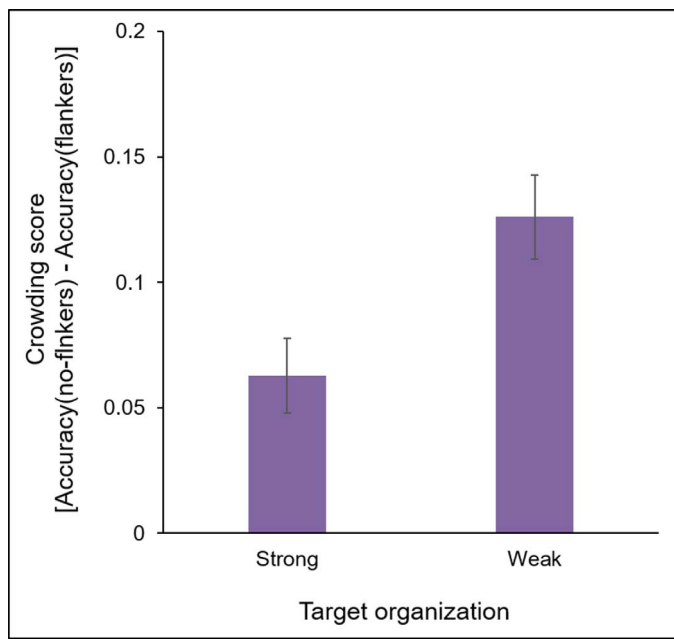


Figure 2. Crowding scores (no-flankers accuracy – flankers accuracy) as a function of target organization (strong organization: Experiment 1a; weak organization: Experiment 1b). Error bars represent standard error of the mean.

or at 5° eccentricity. These results indicate that crowding occurred in both experiments.

To compare the strength of crowding between the strongly organized target (Experiment 1a) and the weakly organized target (Experiment 1b), we calculated a crowding score by subtracting accuracy in the flanker condition from accuracy in the no-flankers condition across all eccentricities, excluding the fovea (in which no crowding is expected and none was observed), for each subject in each experiment. This score indicates how much the flankers impaired target identification. Mean crowding scores as a function of target organization are presented in Figure 2. A comparison between the crowding scores revealed a significantly stronger crowding for the weakly organized target than for the strongly organized target,  $t(26) = 2.74$ ,  $p = 0.0111$ , Cohen's  $d = 1.034$ .<sup>2</sup>

The flankers in the two experiments were identical and equally similar to the target's parts. In addition, as mentioned earlier, in both experiments (as in all experiments reported in this article) there was no reference in the task's instructions to global configuration or to parts. Therefore, the difference in the strength of crowding between the two experiments is likely to be accounted for by the difference in the strength of the target's organization: Crowding by part flankers was significantly stronger when the target's organization was relatively weak, with no closure and good continuation present in the target (Experiment

1b), than when the target was strongly grouped by closure and good continuation (Experiment 1a).

There is, however, a caveat. The stronger crowding observed for the weakly organized target may be a result of a confound between the manipulation of target organization and grouping between target and flankers. In the strongly organized targets (Experiment 1a) the L elements were all turned inward, whereas in the weakly organized targets (Experiment 1b) they were all turned outward. Consequently, the elements in the weakly organized targets were more likely to group with the flankers (e.g., by good continuation) than the elements in the strongly organized target. In light of previous findings demonstrating that target–flanker grouping affects crowding (e.g., Chakravarthi & Pelli, 2011; Manassi, Sayim, & Herzog, 2012), the more crowding for the weakly organized than for the strongly organized targets may be accounted for by target–flanker grouping. In the following experiment, in which all the target's elements were turned inward and the strength of the target organization was manipulated by proximity, this confound was eliminated.

## Experiment 2

In this experiment we manipulated the strength of target organization by the proximity between the target's parts, and examined, as in Experiment 1, the influence of the strength of target organization on crowding by part flankers. The target object was a square-like or a diamond-like configuration made of four L elements, and the proximity between the elements varied in three conditions. In the high-proximity condition, the target's parts were close to each other, yielding strong organization; in the medium-proximity condition, the target's parts were farther apart from each other, yielding weaker organization; and in the low-proximity condition, the target's parts were the farthest apart from each other, yielding the weakest organization. In this experiment the target's eccentricity was fixed and we varied the spacing between target and flankers. As in the previous experiment, the flankers were L elements similar to the target's parts, and the task was to identify the target by pressing one of two response keys.

## Method

### Participants

Twelve individuals (18–30 years old; 11 women, one man) participated in this experiment.

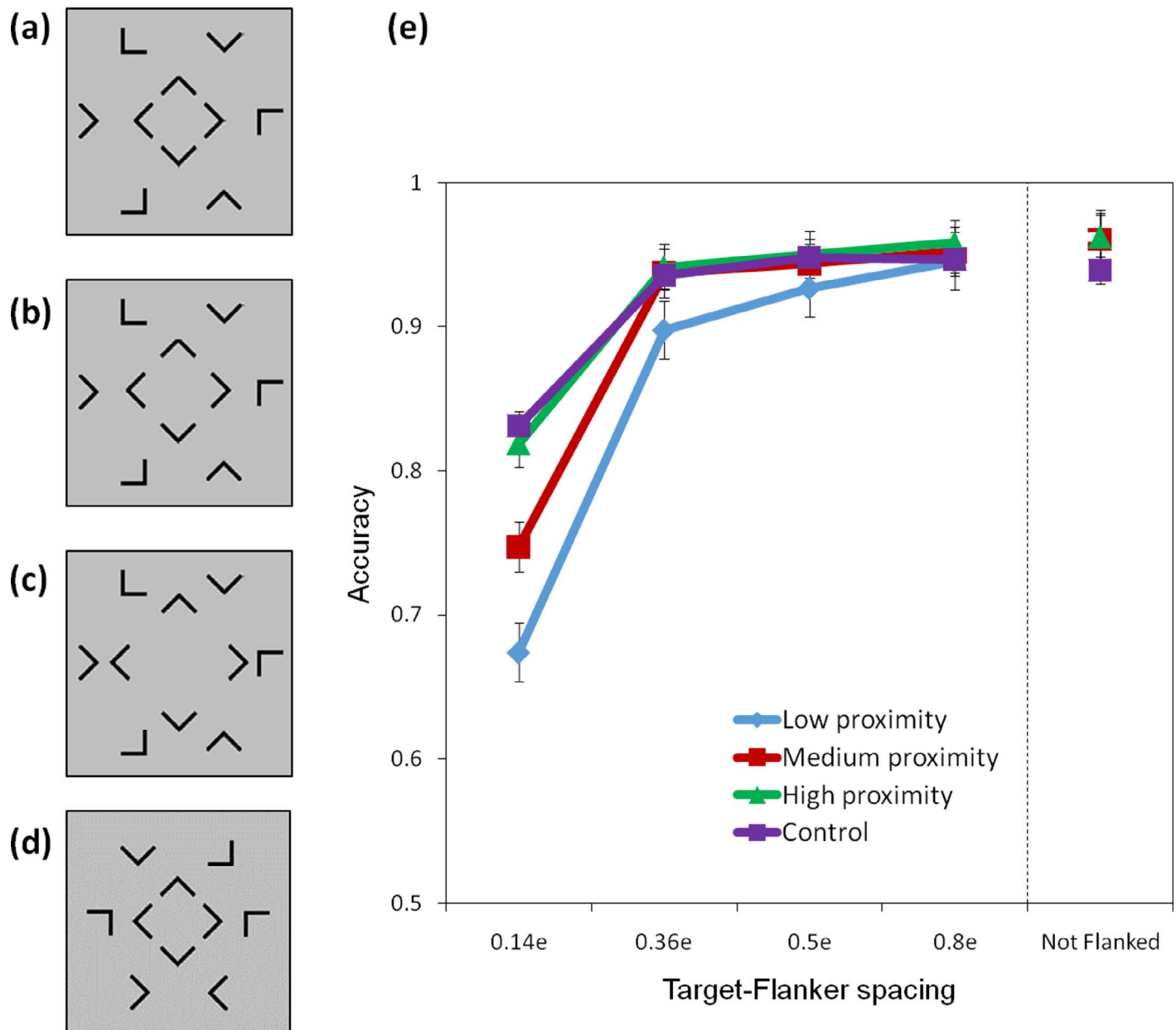


Figure 3. Examples of targets and flankers used in Experiment 2 in (a) high-proximity condition, (b) medium-proximity condition, (c) low-proximity condition, and (d) control condition. The examples depict a diamond-like target. (e) Results: mean accuracy as a function of target-flanker spacing and proximity condition. Error bars represent within-subject standard error of the mean.

### Stimuli and apparatus

The target was a square-like or a diamond-like disconnected configuration made of four black L elements. Each arm of the L element subtended  $0.55^\circ \times 0.08^\circ$ . In the high-proximity condition (Figure 3a), each side of the global configuration subtended  $1.38^\circ$  and the distances between the elements subtended  $0.28^\circ$  each. In the medium-proximity condition (Figure 3b), each side subtended  $1.6^\circ$  and the distances between the elements subtended  $0.5^\circ$  each. In the low-proximity condition (Figure 3c), each side subtended  $2.18^\circ$  and the distances between the elements subtended  $1^\circ$ .

All other aspects of the stimuli and apparatus were identical to those of Experiment 1a.

### Procedure

At the beginning of each trial, a fixation mark (a black cross subtending  $0.5^\circ \times 0.5^\circ$ ) appeared for 750 ms at the center of the screen. Then the target appeared for 120 ms at  $13.8^\circ$  eccentricity to the left or right of fixation. The target appeared alone or was surrounded by six flankers positioned at a target-flanker spacing (i.e., center-to-center distance between target and

flanker) of  $1.93^\circ$  ( $0.14e$ ),  $4.97^\circ$  ( $0.36e$ ),  $6.9^\circ$  ( $0.5e$ ), or  $11.4^\circ$  ( $0.8e$ ). Proximity conditions (high, medium, and low) were blocked and their order was counterbalanced across participants. Within each block, all the combinations of spacing ( $1.93^\circ$ ,  $4.97^\circ$ ,  $6.9^\circ$ ,  $11.4^\circ$ , not flanked), field (right, left), and target (square-like or diamond-like configuration) were presented with equal frequency in a random fashion. In each block there were 200 experimental trials preceded by 20 practice trials.

All other aspects of the procedure were identical to those of Experiments 1a and 1b.

## Results and discussion

Mean accuracy of target identification as a function of proximity (high, medium, and low) and spacing ( $0.14e$ ,  $0.36e$ ,  $0.5e$ ,  $0.8e$ , and not flanked) is presented in Figure 3e. The accuracy data were submitted to a 5 (spacing)  $\times$  3 (proximity) repeated-measures ANOVA. The effect of the flankers on target identification at each spacing was assessed by comparing identification accuracy at that spacing with accuracy in the no-flanker condition, for each proximity condition, using Bonferroni-corrected paired  $t$  tests ( $p = 0.0125$ ).

The ANOVA showed a significant effect of spacing,  $F(4, 44) = 52.01$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.83$ ; a significant effect of proximity,  $F(2, 22) = 3.69$ ,  $p = 0.0415$ ,  $\eta_p^2 = 0.25$ ; and a significant interaction between spacing and proximity,  $F(8, 88) = 3.45$ ,  $p = 0.0017$ ,  $\eta_p^2 = 0.24$ . As can be seen in Figure 3e, when the target was not flanked, identification was highly accurate and did not vary between proximity conditions,  $F < 1$ . When flankers were present, accuracy varied significantly with spacing:  $F(4, 44) = 14.23$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.56$  (high proximity);  $F(4, 44) = 28.21$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.72$  (medium proximity);  $F(4, 44) = 34.0$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.76$  (low proximity). The flankers hindered target identification at the smallest spacing ( $0.14e$ ), and the strength of crowding varied between the proximity conditions,  $F(2, 22) = 6.11$ ,  $p = 0.0078$ ,  $\eta_p^2 = 0.36$ . Crowding was the strongest for the low-proximity condition, reducing accuracy from 96% (not-flanked target) to 67.4%,  $t(11) = 7.21$ ,  $p < 0.0001$ ; weaker for the medium-proximity condition, reducing accuracy from 96% to 74.7%,  $t(11) = 6.36$ ,  $p = 0.0002$ ; and weakest for the high-proximity condition, reducing accuracy from 96.3% to 81.9%,  $t(11) = 4.47$ ,  $p = 0.0038$ . For the low-proximity condition, significant crowding was also found at the larger spacing of  $0.36e$ , reducing accuracy from 96% to 89.8%,  $t(11) = 3.88$ ,  $p = 0.0102$ . No significant effect of flankers was observed at any other spacing in any of the proximity conditions.

These results suggest that the stronger the target's organization (based on grouping the target's parts by

proximity), the weaker the crowding by flankers similar to its parts. Crowding was relatively weak and was observed only at the smallest target–flanker spacing when the target was relatively strongly organized (i.e., high- and medium-proximity conditions). Crowding was stronger and was observed at a larger spatial extent when the organization of the target was weaker (i.e., low-proximity condition).

Note, however, that decreasing the proximity (i.e., increasing the distance) between the target's parts resulted in an increase in the overall size of the target. Consequently, at any given target–flanker spacing (based on target–flanker center-to-center distance), the contour-to-contour distance between the target and flankers varied as a function of proximity. Thus, the minimal contour-to-contour distance was the smallest in the low-proximity condition ( $0.07^\circ$ ,  $3.07^\circ$ ,  $5^\circ$ , and  $9.14^\circ$ , at spacings of  $0.14e$ ,  $0.36e$ ,  $0.5e$ , and  $0.8e$ , respectively), larger in the medium-proximity condition ( $0.41^\circ$ ,  $3.46^\circ$ ,  $5.36^\circ$ , and  $9.5^\circ$ ), and largest in the high-proximity condition ( $0.58^\circ$ ,  $3.59^\circ$ ,  $5.52^\circ$ , and  $9.67^\circ$ ). One could argue that the finding of stronger crowding and a larger spatial extent of crowding for the low-proximity condition than for the other two proximity conditions is accounted for by the smaller target–flanker contour-to-contour distance rather than by the weak organization of the target.

To rule out this alternative account we conducted a control experiment, in which 12 additional individuals (20–35 years old; seven women, five men) identified targets that were identical to those in the high-proximity condition, with identical flankers, but with smaller target–flanker contour-to-contour distance (see Figure 3d). In order to specifically address the finding of the larger spatial extent of crowding observed in the low-proximity condition (i.e., crowding in this condition was observed also at a spacing of  $0.36e$ , in which the target–flanker contour-to-contour distance was  $3.07^\circ$ ), we presented the target at  $12.36^\circ$  eccentricity, so that target–flanker contour-to-contour distances were  $0.35^\circ$ ,  $3.07^\circ$ ,  $4.8^\circ$ , and  $8.51^\circ$  (for spacings of  $0.14e$ ,  $0.36e$ ,  $0.5e$ , and  $0.8e$ , respectively). As can be seen in Figure 3e, the results of the control condition were similar to those for the high-proximity condition. This was confirmed by a mixed-design ANOVA, which yielded a significant effect of spacing,  $F(4, 88) = 34.64$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.61$ , but no effect of condition,  $F < 1$ , nor an interaction between condition and spacing,  $F < 1$ . A significant effect of flankers in the control condition was observed only at the smallest spacing ( $0.14e$ ), reducing accuracy from 93.9% to 83.1%,  $t(11) = 5.79$ ,  $p = 0.0004$ , much like in the high-proximity condition.

These results show that decreasing the target–flanker contour-to-contour distance, while keeping the high proximity between the target's parts, had no influence on the strength of crowding nor on its spatial extent,

indicating that the observed differences in crowding between the proximity conditions—and specifically the larger spatial extent of crowding in the low-proximity condition—are the result of the strength of the target’s organization rather than the target–flanker contour-to-contour distance. Note that the present finding that crowding is not dependent on the target–flanker contour-to-contour distance is consistent with previous findings (Kimchi & Pirkner, 2015; Levi & Carney, 2009; but see Rosen, Chakravarthi, & Pelli, 2014).

The results of Experiment 2 converge with the results of Experiments 1a and 1b, demonstrating that identical flankers, equally similar to the target’s parts, nevertheless produced less or more crowding depending on the strength of the target’s organization: The stronger the target was organized, the weaker the crowding was by part flankers. Presumably, a good separation between the target’s parts and the flankers, which occurs when the target is strongly organized, deteriorates when the target’s organization weakens, resulting in stronger interference by the flankers.

Experiments 1a, 1b, and 2 had the advantage of using identical flankers and an equal degree of target–flanker similarity, while manipulating the strength of the target’s organization. Our hypothesis, however, concerns not just the relation between the target’s organization and crowding by part flankers, but more generally the relationship between the strength of the target’s organization and the relative strength of crowding at the part level versus at the configuration level. Specifically, we hypothesized more crowding at the configuration level than at the part level when the target is strongly organized, and vice versa when the target is weakly organized. The following experiments address this hypothesis.

## Experiments 3a, 3b, 3c, and 3d

In these experiments we manipulated the strength of the target’s organization by the presence or absence of closure and good continuation (as in Experiments 1a and 1b). The flankers were similar to the target in one aspect but dissimilar in the other aspect, controlling for the degree of target–flanker similarity. The strength of target organization and the level of target–flanker similarity were manipulated between experiments (see Figure 4a–4d).

If the strength of crowding by configuration similarity versus part similarity is dependent on the strength of the target’s organization (i.e., target’s objecthood), then an interaction between target organization strength and target–flanker similarity is expected, such that crowding by flankers similar in configuration should be greater than by flankers similar

in parts when the target is strongly organized (Experiments 3a and 3b) but lesser when the target is weakly organized (Experiments 3c and 3d).

## Method

### Participants

Twelve individuals (19–28 years old; 11 women, one man) participated in Experiment 3a, 12 (20–34 years old; 10 women, two men) participated in Experiment 3b, 12 (20–26 years old; 10 women, two men) participated in Experiment 3c, and 12 (20–32 years old; 10 women, two men) participated in Experiment 3d.

### Stimuli and procedure

The targets in Experiments 3a and 3b were square-like and diamond-like configurations identical to the targets in Experiment 1a (Figure 4a and 4b), and those in Experiments 3c and 3d were cross-like and X-like configurations identical to the targets in Experiment 1b (Figure 4c and 4d). The target object appeared with or without six flankers at the fovea ( $0^\circ$ ) or at  $7^\circ$ ,  $10^\circ$ , or  $17^\circ$  eccentricity to the left or right of fixation. The flankers could be similar to the target in configuration but dissimilar in parts (Experiments 3a and 3c) or similar in parts but dissimilar in configuration (Experiments 3b and 3d). The flankers in Experiment 3a were square-like configurations made of four lines, each of which subtended  $1.1^\circ \times 0.08^\circ$  (Figure 4a); those in Experiment 3b were cross-like configurations made of four L elements identical to the elements in the target (Figure 4b); those in Experiment 3c were cross-like configurations made of four lines, each of which subtended  $0.58^\circ \times 0.08^\circ$  (Figure 4c); and those in Experiment 3d were square-like configurations made of four L elements identical to the target’s elements (Figure 4d). The overall size of each flanker was identical to that of the target. The flankers were centered on an imaginary circle and were randomly sampled on each trial from a set of 12 tilted figures: six tilted to the right ( $6.43^\circ$ ,  $12.86^\circ$ ,  $19.29^\circ$ ,  $25.72^\circ$ ,  $32.15^\circ$ , and  $38.58^\circ$ ) and six tilted to the left ( $-6.43^\circ$ ,  $-12.86^\circ$ ,  $-19.29^\circ$ ,  $-25.72^\circ$ ,  $-32.15^\circ$ , and  $-38.58^\circ$ ). The center-to-center spacing between target and flanker was fixed at  $3.54^\circ$ . In each experiment there were 480 experimental trials preceded by 32 practice trials.

All other aspects of the stimuli and procedure were identical to those of Experiments 1a and 1b.

## Results and discussion

Mean accuracy of target identification as a function of flankers and eccentricity is presented in Figure 4e–4h for Experiments 3a–3d, respectively.



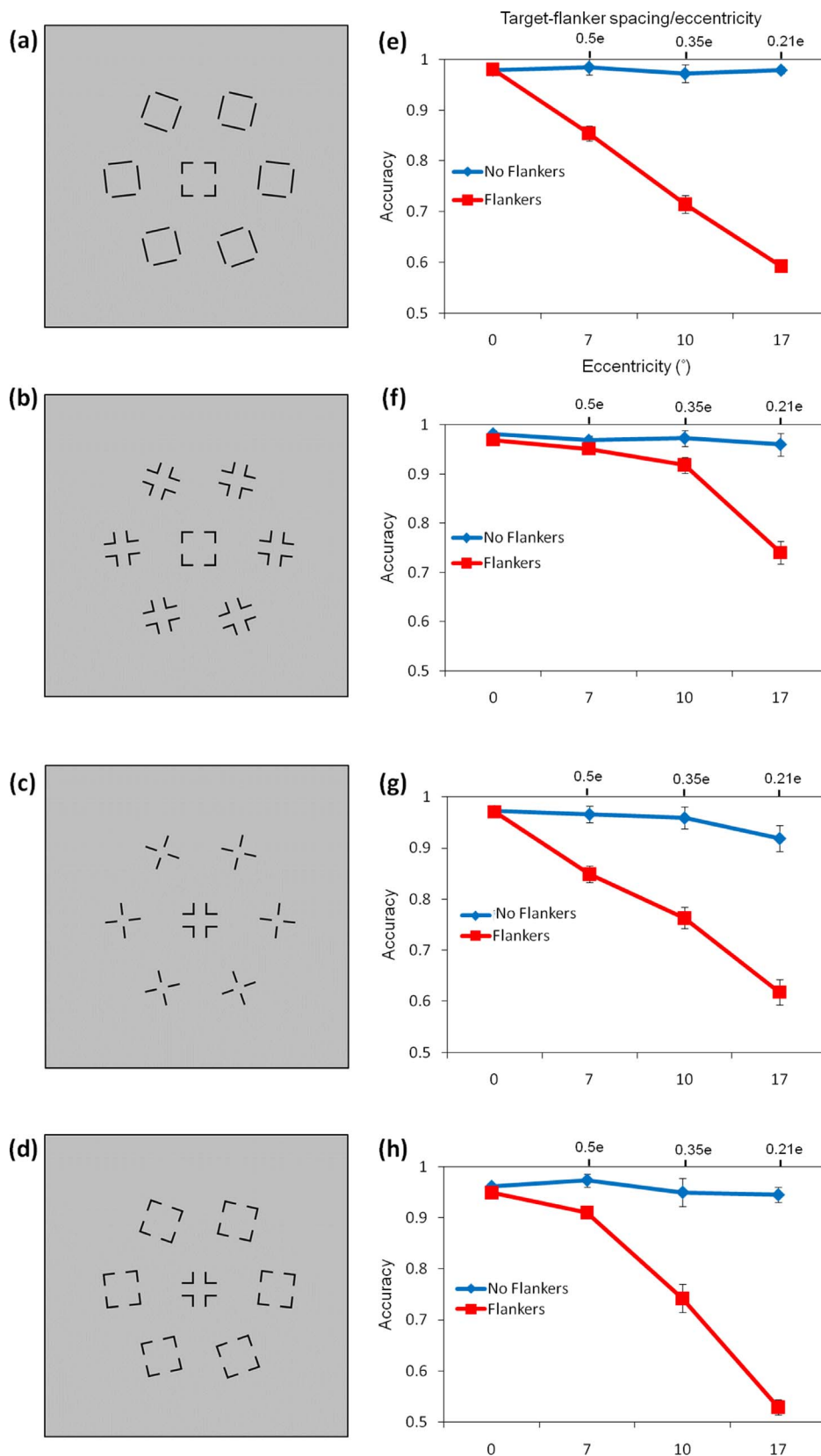


Figure 4. Examples of targets and flankers used in (a) Experiment 3a (strong organization, configuration similarity), (b) Experiment 3b (strong organization, element similarity), (c) Experiment 3c (weak organization, configuration similarity), and (d) Experiment 3d (weak organization, element similarity). The examples depict a square-like target for Experiments 3a and 3b and a cross-like target for Experiments 3c and 3d. Results from (e) Experiment 3a, (f) Experiment 3b, (g) Experiment 3c, and (h) Experiment 3d: mean accuracy as a function of eccentricity and flanker condition. Error bars represent within-subject standard error of the mean.

We first examined crowding for each experiment. The accuracy data of each experiment were submitted to a 4 (eccentricity)  $\times$  2 (flanker condition) repeated-measures ANOVA. The analyses showed (for Experiments 3a–3d, respectively) a significant effect of eccentricity:  $F(3, 33) = 107.86, p < 0.0001, \eta_p^2 = 0.91$ ;  $F(3, 33) = 34.43, p < 0.0001, \eta_p^2 = 0.76$ ;  $F(3, 33) = 45.4, p < 0.0001, \eta_p^2 = 0.8$ ;  $F(3, 33) = 72.74, p < 0.0001, \eta_p^2 = 0.87$ ; a significant effect of flankers:  $F(1, 11) = 256.98, p < 0.0001, \eta_p^2 = 0.96$ ;  $F(1, 11) = 28.42, p = 0.0002, \eta_p^2 = 0.72$ ;  $F(1, 11) = 106.66, p < 0.0001, \eta_p^2 = 0.91$ ;  $F(1, 11) = 200.44, p < 0.0001, \eta_p^2 = 0.95$ ; and a significant interaction between eccentricity and flankers:  $F(3, 33) = 122.53, p < 0.0001, \eta_p^2 = 0.92$ ;  $F(3, 33) = 29.06, p < 0.0001, \eta_p^2 = 0.72$ ;  $F(3, 33) = 25.63, p < 0.0001, \eta_p^2 = 0.70$ ;  $F(3, 33) = 54.53, p < 0.0001, \eta_p^2 = 0.83$ .

As can be seen in Figure 4e–4h, when the target appeared in isolation, identification was highly accurate (average 97.9%, 97.1%, 95.4%, and 95.7%, in Experiments 3a–3d, respectively) and did not vary with eccentricity—except in Experiment 3d, where a small but significant effect of eccentricity was observed,  $F(3, 33) = 3.4, p = 0.0290, \eta_p^2 = 0.24$ . When flankers were present, accuracy decreased significantly with eccentricity:  $F(3, 33) = 127.94, p < 0.0001, \eta_p^2 = 0.92$ ;  $F(3, 33) = 41.71, p < 0.0001, \eta_p^2 = 0.79$ ;  $F(3, 33) = 57.52, p < 0.0001, \eta_p^2 = 0.84$ ;  $F(3, 33) = 68.71, p < 0.0001, \eta_p^2 = 0.86$  (for Experiments 3a–3d, respectively). Bonferroni-corrected paired  $t$  tests ( $p = 0.0125$ ) showed a significant interfering effect of flankers for Experiments 3a, 3c, and 3d at 7°, reducing accuracy to (respectively) 85.4%,  $t(11) = 5.98, p < 0.0001$ ; 84.9%,  $t(11) = 5.16, p = 0.0003$ ; and 91.1%,  $t(11) = 3.42, p = 0.0057$ ; and at 10° eccentricity, reducing accuracy to 71.4%,  $t(11) = 10.52, p < 0.0001$ ; 76.3%,  $t(11) = 6.64, p < 0.0001$ ; 74.2%,  $t(11) = 5.34, p = 0.0002$ . For all experiments, there was a significant interfering effect of flankers at 17° eccentricity, reducing accuracy to (respectively) 59.3%,  $t(11) = 38.97, p < 0.0001$ ; 74%,  $t(11) = 6.86, p < 0.0001$ ; 61.8%,  $t(11) = 8.45, p < 0.0001$ ; and 52.9%,  $t(11) = 19.61, p < 0.0001$ . No significant effects of flankers were observed at the fovea.

These results indicate that crowding occurred in all four experiments, and the spatial extent of the crowding was similar except that it was smaller in Experiment 3b, in which the target was strongly organized and the flankers were similar to the target in parts (and dissimilar in configuration).

Having demonstrated crowding in each experiment, we turn now to compare the relative strength of crowding at the configuration and element levels for the strongly organized target (Experiments 3a and 3b) and the weakly organized target (Experiments 3c and 3d).

As noted earlier, our hypothesis predicts an interaction between target organization and target–flanker

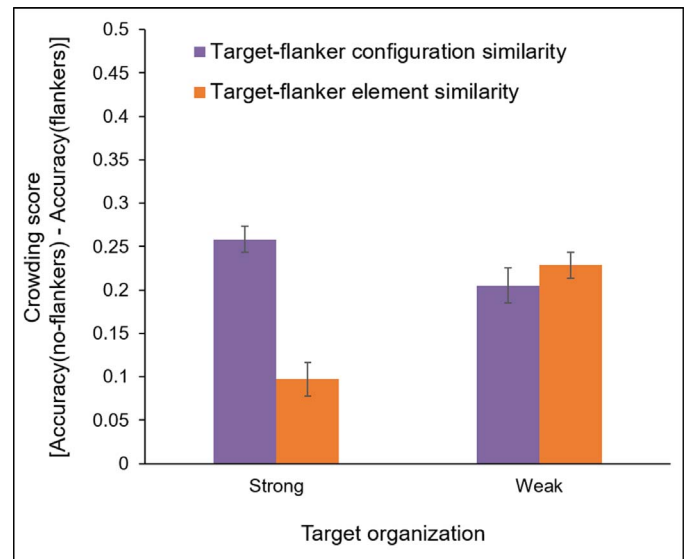


Figure 5. Crowding scores (no-flankers accuracy – flanker accuracy) as a function of target–flanker similarity and strength of target organization. Error bars represent standard error of the mean.

similarity, such that crowding by similarity in configuration is likely to be stronger than crowding by similarity in element when target organization is strong, but weaker when target organization is weak. To test this prediction, crowding scores were calculated across all eccentricities but the fovea, for each subject in each experiment. The mean crowding scores for target–flanker similarity (configuration similarity and element similarity) for strongly organized and weakly organized targets are presented in Figure 5.

The crowding scores were submitted to a 2 (target organization: strong vs. weak)  $\times$  2 (target–flanker similarity: part vs. configuration) between-subjects ANOVA. The analysis revealed a significant main effect of target organization,  $F(1, 44) = 4.70, p = 0.0356, \eta_p^2 = 0.096$ , and a significant effect of target–flanker similarity,  $F(1, 44) = 15.27, p = 0.0003, \eta_p^2 = 0.25$ . Critically, the interaction between target organization and target–flanker similarity was significant,  $F(1, 44) = 26.97, p < 0.0001, \eta_p^2 = 0.38$ . As can be seen in Figure 5, crowding by similarity in configuration was stronger than crowding by similarity in element when the target was strongly organized,  $t(22) = 6.52, p < 0.0001$ , Cohen’s  $d = 2.78$ —replicating our previous findings (Kimchi & Pirkner, 2015)—but it tended to be weaker than crowding by similarity in element when the target was weakly organized, though this tendency was not statistically significant.

The finding of the interaction between strength of target organization and target–flanker similarity (configuration vs. element) supports our hypothesis. We note that the difference between crowding by target–flanker similarity in parts and in configuration for the

weakly organized target, though it appeared to be in the opposite direction, was not as large as the difference observed for the strongly organized target (see Figure 5). This may be due to the fact that apparently our attempt to control for the degree of target–flanker similarity in the two similarity conditions for the weakly organized target was not completely successful: The flankers similar to the target in parts were dissimilar in configuration (Experiment 3d), but the flankers similar to the target in configuration—which were assumed to be dissimilar in parts—were somewhat similar to the target parts (Experiment 3c), because the lines in the flankers were parts of the L elements in the target. Consequently, the overall degree of similarity in the latter may have been higher than in the former. Thus, crowding due to the *level* at which similarity arises was expected to be stronger for target–flanker similarity in parts (Experiment 3d) than in configuration (Experiment 3c), but presumably the higher degree of target–flanker similarity in the latter increased crowding for this condition, and as a result, the difference between the two target–flanker similarity conditions decreased.

## Experiments 4a, 4b, 4c, and 4d

In these experiments we manipulated the strength of the target’s organization based on the Gestalt factor of proximity, and as in the previous experiments, flankers were either similar to the target in configuration but dissimilar in parts or vice versa.

## Method

### Participants

Twelve individuals (19–26 years old; 11 women, one man) participated in Experiment 4a, 12 (22–26 years old; 10 women, two men) participated in Experiment 4b, 12 (19–32 years old; eight women, four men) participated in Experiment 4c, and 12 (19–30 years old; eight women, four men) participated in the Experiment 4d.

### Stimuli and procedure

The targets were a square-like or a diamond-like configuration made of four lines, each of which subtended  $0.83^\circ \times 0.08^\circ$ . In the high-proximity experiments (Experiments 4a and 4b), each side of the targets subtended  $1.38^\circ$  and the distances between the lines subtended  $0.55^\circ$  each (Figure 6a and 6b). In the low-proximity experiments (Experiments 4c and 4d), each side of the targets subtended  $2.49^\circ$  and the gaps

between the lines subtended  $1.66^\circ$  each (Figure 6c and 6d). Thus, target grouping by proximity was stronger in Experiments 4a and 4b than in Experiments 4c and 4d. The flankers in Experiments 4a and 4c were square-like configurations made of four black L elements (Figure 6a and 6c), similar to the target in configuration but dissimilar in parts. Each arm of each L element subtended  $0.55^\circ \times 0.08^\circ$  and the gaps between the elements were identical to those in the target. The flankers in Experiments 4b and 4d were cross-like configurations, subtending  $2.21^\circ$  and  $3.31^\circ$ , respectively (Figure 6b and 6d), similar to the target in parts but dissimilar in configuration. The center-to-center spacing between target and flanker was fixed at  $4.09^\circ$ .

All other aspects of the stimuli and procedure were identical to those of Experiments 3a–3d.

## Results and discussion

Mean accuracy of target identification as a function of flankers and eccentricity is presented in Figure 6e–6h for Experiments 4a–4d, respectively. The 4 (eccentricity)  $\times$  2 (flanker condition) repeated-measures ANOVAs (for each experiment) showed (for Experiments 4a–4d, respectively) a significant effect of eccentricity:  $F(3, 33) = 69.0, p < 0.0001, \eta_p^2 = 0.86$ ;  $F(3, 33) = 120.44, p < 0.0001, \eta_p^2 = 0.92$ ;  $F(3, 33) = 40.41, p < 0.0001, \eta_p^2 = 0.79$ ;  $F(3, 33) = 59.21, p < 0.0001, \eta_p^2 = 0.84$ ; a significant effect of flankers:  $F(1, 11) = 146.76, p < 0.0001, \eta_p^2 = 0.93$ ;  $F(1, 11) = 140.67, p < 0.0001, \eta_p^2 = 0.93$ ;  $F(1, 11) = 77.69, p < 0.0001, \eta_p^2 = 0.88$ ;  $F(1, 11) = 205.79, p < 0.0001, \eta_p^2 = 0.95$ ; and a significant interaction between eccentricity and flankers:  $F(3, 33) = 47.07, p < 0.0001, \eta_p^2 = 0.81$ ;  $F(3, 33) = 80.42, p < 0.0001, \eta_p^2 = 0.88$ ;  $F(3, 33) = 32.96, p < 0.0001, \eta_p^2 = 0.75$ ;  $F(3, 33) = 54.89, p < 0.0001, \eta_p^2 = 0.83$ .

As can be seen in Figure 6e–6h, when the target appeared in isolation, identification was highly accurate (average 98.3%, 95.9%, 96.3%, and 96.8%, in Experiments 4a–4d, respectively), and a small but significant effect of eccentricity was observed (except in Experiment 4a):  $F < 1$ ;  $F(3, 33) = 3.1, p = 0.0401, \eta_p^2 = 0.22$ ;  $F(3, 33) = 5.87, p = 0.0025, \eta_p^2 = 0.35$ ;  $F(3, 33) = 5.15, p = 0.0050, \eta_p^2 = 0.32$ . When flankers were present, accuracy decreased significantly with eccentricity:  $F(3, 33) = 69.69, p < 0.0001, \eta_p^2 = 0.86$ ;  $F(3, 33) = 122.55, p < 0.0001, \eta_p^2 = 0.92$ ;  $F(3, 33) = 41.09, p < 0.0001, \eta_p^2 = 0.79$ ;  $F(3, 33) = 62.06, p < 0.0001, \eta_p^2 = 0.85$ .

Bonferroni-corrected paired *t* tests ( $p = 0.0125$ ) showed a significant interference effect of flankers at  $7^\circ$  eccentricity for Experiments 4a, 4c, and 4d (respectively), reducing accuracy to 90.8%,  $t(11) = 3.96, p = 0.0022$ ; 67.2%,  $t(11) = 6.87, p < 0.0001$ ; and 70.5%,  $t(11) = 7.46, p < 0.0001$ ; and for all experiments at  $10^\circ$  eccentricity, reducing accuracy to 80.5%,  $t(11) = 6.67, p < 0.0001$ ; 86.5%,  $t(11)$

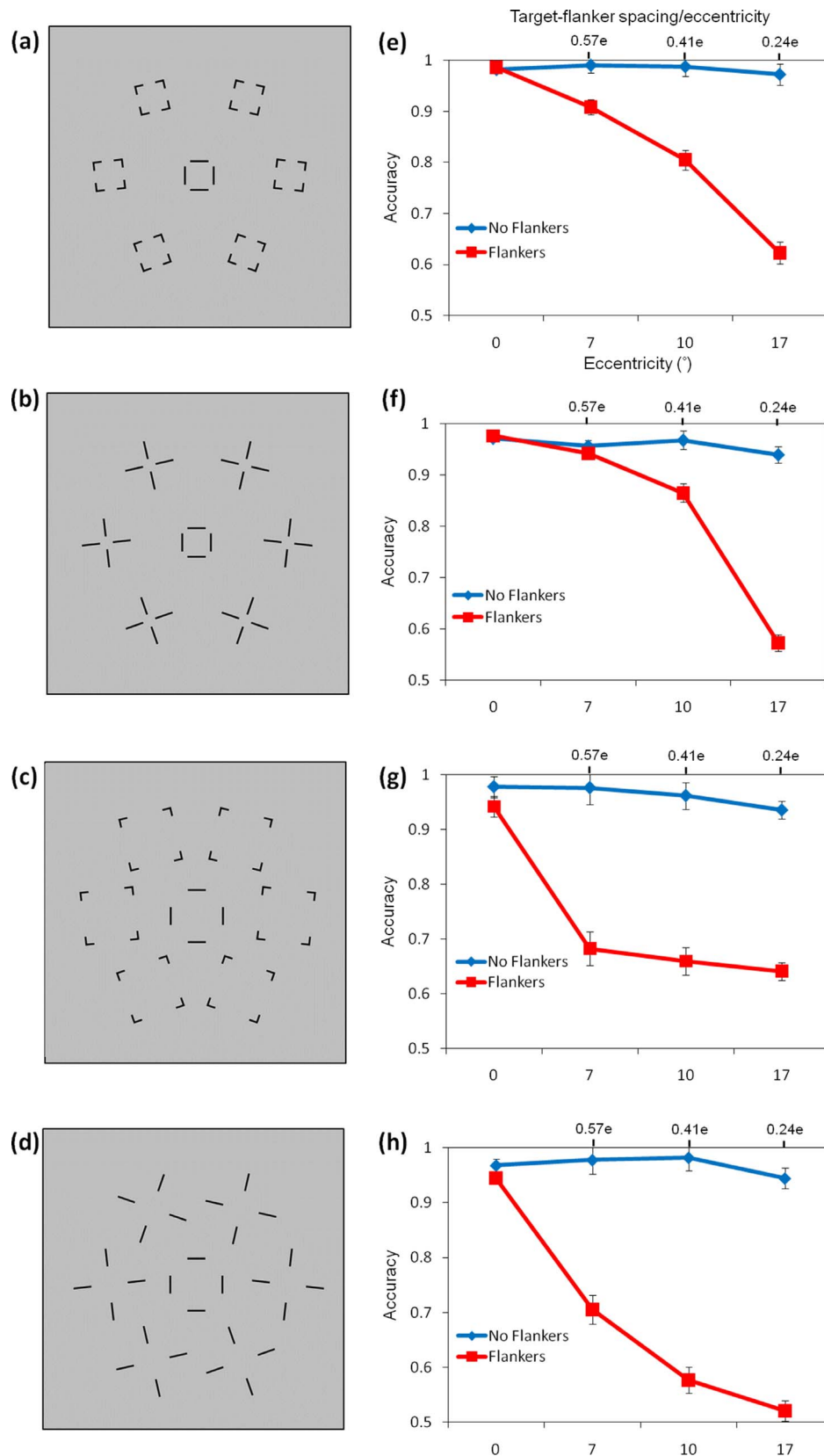


Figure 6. Examples of targets and flankers used in (a) Experiment 4a (strong organization, configuration similarity), (b) Experiment 4b (strong organization, element similarity), (c) Experiment 4c (weak organization, configuration similarity), and (d) Experiment 4d (weak organization, element similarity). The examples depict a square-like target. Results from (e) Experiment 4a, (f) Experiment 4b, (g) Experiment 4c, and (h) Experiment 4d: mean accuracy as a function of eccentricity and flanker condition. Error bars represent within-subject standard error of the mean.

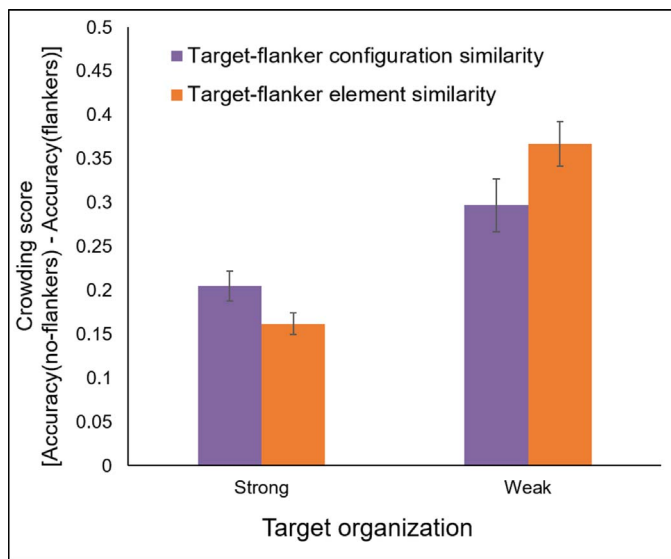


Figure 7. Crowding scores (no-flankers accuracy – flanker accuracy) as a function of target–flanker similarity and strength of target organization. Error bars represent standard error of the mean.

= 3.96,  $p = 0.0022$ ; 64.9%,  $t(11) = 8.72$ ,  $p < 0.0001$ ; and 57.7%,  $t(11) = 12.24$ ,  $p < 0.0001$ ; and at 17° eccentricity, reducing accuracy to 62.3%,  $t(11) = 11.64$ ,  $p < 0.0001$ ; 57.2%,  $t(11) = 16.29$ ,  $p < 0.0001$ ; 63.2%,  $t(11) = 12.7$ ,  $p < 0.0001$ ; and 52.1%,  $t(11) = 15.72$ ,  $p < 0.0001$ . No significant effects of flankers were observed at the fovea.

These results indicate that crowding occurred in all four experiments, and the spatial extent of the crowding was similar—except that it was smaller in Experiment 4b, in which the target was strongly organized and the flankers were similar to the target in parts (and dissimilar in configuration).

In order to examine the relative strength of crowding at the configuration and part levels for the strongly and weakly organized targets, crowding scores were calculated across all eccentricities but the fovea, for each subject in each experiment. The mean crowding scores for target–flanker similarity (configuration similarity and element similarity) for strongly and weakly organized targets are presented in Figure 7.

The 2 (target organization: strong vs. weak)  $\times$  2 (target–flanker similarity: part vs. configuration) ANOVA conducted on the crowding scores revealed a significant effect of target organization,  $F(1, 44) = 44.57$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.50$ , showing more crowding for the weakly organized target than for the strongly organized one. There was no significant main effect of target–flanker similarity,  $F < 1$ . Most importantly, the interaction between target organization and target–flanker similarity was significant,  $F(1, 44) = 6.20$ ,  $p = 0.0166$ ,  $\eta_p^2 = 0.12$ , indicating that the relative strength of crowding at the configuration and part levels is dependent on the strength of the target’s organization.

As can be seen in Figure 7, there was significantly more crowding by target–flanker similarity in configuration than in elements when the target was strongly organized,  $t(22) = 1.99$ ,  $p = 0.0293$ , Cohen’s  $d = 0.85$ , but significantly more crowding by similarity in elements than in configuration when the target was weakly organized,  $t(22) = 1.76$ ,  $p = 0.0461$ , Cohen’s  $d = 0.75$ .

The present results also showed overall more crowding for the weakly organized targets than for the strongly organized targets (see Figure 7). Perhaps the simplest explanation for this finding is that weakening the target’s organization weakens the target—much as does, for example, lowering the target’s contrast (e.g., Kooi et al., 1994)—thereby impairing its identification. However, according to this account, a similar effect would also be expected for the no-flankers condition; but as can be seen in Figure 6, there is no difference in the no-flankers condition between the strongly and weakly organized targets ( $F < 1$ ), which poses a problem for this account. An alternative explanation concerns a possible difference in target–flanker spacing between the strongly and weakly organized targets. Presumably, the strong grouping of the target’s parts in the strongly organized target could preempt the parts, and target identification is likely to be based on the global shape. In contrast, when the target’s parts are farther apart from one another (i.e., weakly grouped), they are likely to be individuated and may be used to identify the target. If target identification was based on the global shape when the target was strongly organized and on individual parts when it was weakly organized, the relevant spacing for the former was between the centers of the target and the flanker, whereas for the latter it was between the centers of the parts and the flanker. Since the part–flanker spacing was smaller than the target–flanker spacing, it could result in more overall crowding for weakly grouped targets. The notion that the relevant spacing is not necessarily always the target–flanker center-to-center distance has been demonstrated by Rosen et al. (2014), although in that study it depended on the flanker (whether its jagged side was closer or farther from the target) rather than on the target organization. Note that these explanations are speculative, and testing them awaits further research.

## General discussion

This study examined the influence of the strength of the target’s perceptual organization on the relative strength of crowding at the part level and at the configural level. We manipulated the strength of target organization by the presence or absence of Gestalt

grouping factors of closure, good continuation, and degree of proximity, and measured crowding by flankers similar to the target in parts or in configuration. Our results show that the strength of crowding by target–flanker similarity in parts versus configuration is dependent on the strength of the target’s perceptual organization. The stronger the target’s organization, the weaker the crowding was by part flankers (Experiments 1a, 1b, and 2). Most importantly, the strength of target organization interacted with target–flanker similarity, such that crowding by flankers similar to the target in configuration was greater than by flankers similar in parts when the target was strongly organized but lesser when the target was weakly organized (Experiments 3a–3d and 4a–4d).

The present results converge with previous findings (Chaney et al., 2014; Farzin et al., 2009; Fischer & Whitney, 2011; Kimchi & Pirkner, 2015; Louie et al., 2007) demonstrating that crowding can occur at multiple levels, not only between basic features and object parts but also between high-level configural representations of objects. The present findings, however, go beyond the previous ones in delineating conditions under which crowding at the part or configural level is more likely to occur. Our results show that these conditions are related to the strength of the target’s organization, or degree of objecthood: The stronger the target’s objecthood, the more likely it is that crowding at the configural level will be greater than crowding at the part level, and the weaker the target’s objecthood, the more likely it is that crowding at the part level will be greater than crowding at the configural level.

It has been recently suggested that target–flanker grouping plays an important role in crowding, such that crowding is stronger when target and flankers are well grouped together and is much weaker when target and flankers ungroup (e.g., Chakravarthi & Pelli, 2011; Herzog & Manassi, 2015; Herzog, Sayim, Chicherov, & Manassi, 2015; Manassi et al., 2012; Pachai, Doerig, & Herzog, 2016; Saarela, Sayim, Westheimer, & Herzog, 2009). Most of the findings that support this view come from studies that manipulated the organization of the flankers, which presumably caused the target to stand out from them (e.g., Livne & Sagi, 2007, 2010; Manassi et al., 2012; but see Chakravarthi & Pelli, 2011). For example, Livne and Sagi (2007) presented a Gabor target surrounded by Gabor flankers and showed that when the flankers were grouped into a coherent circular contour, crowding was reduced compared to when they did not form a smooth contour. Similarly, Manassi et al. (2012) showed that crowding a vernier target by two line flankers was reduced when the flankers were parts of rectangles, presumably because the rectangles ungroup from the vernier. Livne and Sagi (2011) further demonstrated that crowding of the orientation

of a Gabor target is influenced by interference at both the local level of flanker’s orientation and the global level, namely, the global arrangement of the flankers. Grouping of flankers can also account for the finding that increasing the number of flankers can reduce rather than increase crowding (e.g., Malania, Herzog, & Westheimer, 2007; Manassi et al., 2012; Pöder, 2006; Saarela et al., 2009). For example, Pöder (2006) asked participants to identify the orientation of a blue horizontal bar presented among red horizontal and vertical bars, and observed normal crowding with a few distractors, which was remarkably reduced when the number of distractors increased; and Manassi et al. (2012) showed that two single-line flankers greatly impaired vernier offset discrimination, but adding more line flankers weakened crowding.

In these previous studies, target organization (i.e., the grouping between the target’s elements or parts) and its possible influence on crowding were of no concern, probably because in most of the studies the target was a single-element object (a single Gabor element, a single line, or at the most a vernier). In the current study we used multielement configurations as targets, and showed that the target’s organization can also influence crowding. Presumably, the strength of the target’s organization affects the level at which similarity between target and flankers arises, and thereby the relative strength of crowding by flankers similar to the target in parts versus in configuration. The suggestion that the strength of the target’s organization can influence the level at which target–flanker similarity arises is supported by findings demonstrating that when elements are strongly grouped into a coherent object, the global configuration dominates the elements or parts in information-processing tasks. Notable examples are the dominance of configural properties in discrimination and classification (e.g., Kimchi, 1994; Kimchi & Bloch, 1998) and visual search (e.g., Rensink & Enns, 1995), the global advantage effect (e.g., Kimchi, 1998; Kimchi & Palmer, 1982; Navon, 1977, 2003), and the configural superiority effect (e.g., Pomerantz & Portillo, 2011; Pomerantz, Sager, & Stoeber, 1977). When the grouping between the elements is weaker, the elements may dominate the global configuration. For example, local advantage, rather than global advantage, is observed when the elements in hierarchical stimuli are sparse (e.g., Martin, 1979).

Our results also showed overall more crowding in weakly organized targets, at least under certain circumstances in which target organization was hampered by low proximity between the target’s parts (see Experiments 4a–4d). We speculated that smaller spacing between target parts and flankers in the weakly organized target versus larger target–flanker spacing in the strongly organized target, may account for this finding (see Results and discussion for those experiments).

It should be further noted that although there is ample evidence that grouping between target and flankers is one of the best predictors of crowding (whether it depends on the organization of the flankers, organization of the target, or both), target–flanker grouping does not necessarily induce crowding, as suggested by the configural superiority effect (Pomerantz et al., 1977): When grouping target and flankers produces an emergent feature that can be useful for the task at hand, it can overcome crowding (Kimchi & Pirkner, in preparation; Pomerantz & Cragin, 2012).

The present results, along with previous ones discussed in this article, cannot be easily explained by models of crowding that attribute crowding to pooling or integration of relatively low-level features at a single, relatively earlier stage of visual processing. These results clearly demonstrate that crowding can occur at multiple levels, not only between low-level features or parts but also between high-level configural representations of objects (e.g., Kimchi & Pirkner, 2015; Whitney & Levi, 2011), and strongly suggest that perceptual organization processes, operating on the entire stimulus and at different levels of processing, play an important role in crowding (see also Herzog et al., 2015; Pachai et al., 2016; Pomerantz & Cragin, 2012). Notwithstanding that certain findings of object-level crowding may be accounted for by low-level explanations (Dakin et al., 2010), further research is required to construct a crowding model that takes the configural and perceptual organization effects into account.

*Keywords:* crowding, perceptual organization, grouping, Gestalt, object configuration, object parts, objecthood

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## Footnotes

<sup>1</sup> Previous studies that have reported findings that could be interpreted as demonstrating object-level crowding in nonface stimuli (e.g., Nazir, 1992) did not

control the degree of feature similarity between target and flankers, which could account for their results (for a discussion, see Kimchi & Pirkner, 2015).

<sup>2</sup> Note that comparing crowding strength between the two types of targets, as measured by crowding scores, should be taken with some caution, because performance in the no-flankers condition appears to be at or close to ceiling and thus may impede a true estimate of the crowding magnitude. This issue is avoided in Experiments 3 and 4, because the critical comparison between the strength of crowding at the part and configural levels involves crowding scores calculated for the same target.

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