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Multiple Level Crowding: Crowding at the Object Parts Level and at the Object Configural level

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Abstract
In crowding, identification of a peripheral target in the presence of nearby flankers is worse than when the target appears alone. Prevailing theories hold that crowding occurs because of integration or "pooling" of low-level features at a single, relatively early stage of visual processing. Recent studies suggest that crowding can occur also between high-level object representations. The most relevant findings come from studies with faces and may be specific to faces. We examined whether crowding can occur at the object configural level in addition to part-level crowding, using nonface objects. Target (a disconnected square or diamond made of four elements) identification was measured at varying eccentricities. The flankers were similar either to the target parts or to the target configuration. The results showed crowding in both cases: Flankers interfered with target identification such that identification accuracy decreased with an increase in eccentricity, and no interference was observed at the fovea. Crowding by object parts, however, was weaker and had smaller spatial extent than crowding by object configurations; we related this finding to the relationship between crowding and perceptual organization. These results provide strong evidence that crowding occurs not only between object parts but also between configural representations of objects.

Keywords
Crowding, perceptual organization, grouping, gestalt, object configuration, object parts, visual attention

Introduction

Crowding is the impairment in the identification of a peripheral target object in the presence of nearby flankers, despite the fact that the same target object can be readily identified in

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isolation (Bouma, 1970). Crowding has been studied extensively and is known to have a number of characteristics (for recent reviews see, Levi, 2008; Pelli & Tillman, 2008; Whitney & Levi, 2011).

Crowding impairs target identification but not detection (e.g., Livne & Sagi, 2007; Pelli, Palomares, & Majaj, 2004). It depends on target eccentricity and the distance between the target and flankers. At a given eccentricity, target identification improves as the distance between the target and flankers increases. The minimum distance between target and flankers at which crowding is relieved is known as the critical spacing. The critical spacing typically scales with target eccentricity (e) and across a great number of studies it is reported to be around 0.5e (e.g., Bouma, 1970; Kooi, Toet, Tripathy, & Levi, 1994; Levi & Carney, 2009; Pelli et al., 2004; but see, e.g., Manassi, Sayim, & Herzog, 2012; Vickery, Shim, Chakravarthi, Jiang, & Luedeman, 2009). Also, crowding depends on the similarity between the target and flankers, such that flankers more similar to the target in contrast polarity, color, shape, depth, spatial frequency, and complexity produce stronger crowding (e.g., Bernard & Chung, 2011; Chung, Levi, & Legge, 2001; Kooi et al., 1994; Zhang, Zhang, Xue, Liu, & Yu, 2009). Crowding has been demonstrated with relatively simple visual stimuli such as Gabor stimuli, letters, and digits (e.g., Felisberti, Solomon, & Morgan, 2005; Pelli et al., 2004; Strasburger, Harvey, & Rentschler, 1991) and with more complex stimuli such as objects and faces (e.g., Louie, Bressler, & Whitney, 2007; Wallace & Tjan, 2011).

Although the specific explanation for crowding varies between theories (e.g., mandatory averaging, excessive feature integration, attention resolution), most of the prevailing theories of crowding hold that crowding occurs because of integration or "pooling" of low-level features at a single, relatively early stage of visual processing (e.g., He, Cavanagh, & Intriligator, 1996; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004).

Recent research, however, has suggested that crowding can occur at different levels of visual processing: not only between lower level features but also between high-level representations of objects. The most relevant findings come from studies with face stimuli. Louie et al. (2007) demonstrated that when an upright target face was surrounded by upright faces, recognition was significantly worse than when the target face was surrounded by inverted faces or when presented alone. This selective crowding by upright face flankers also occurs between Mooney (two-tone) faces (Farzin, Rivera, & Whitney, 2009), it adheres to all of the diagnostic criteria for crowding (Farzin et al., 2009; Louie et al., 2007), and it is distinguished from within-face, facial feature crowding (Martelli, Majaj, & Pelli, 2005). It has been further demonstrated that a crowded face, the expression of which could not be explicitly recognized, can contribute with high precision to an estimate of the overall group expression (Fischer & Whitney, 2011), suggesting that object-level information survives crowding (see also, Chaney, Fischer, & Whitney, 2014).

Note that crowding between objects (e.g., Wallace & Tjan, 2011) does not necessarily indicate crowding between higher level object representations because the crowding can be between lower levels features or parts of the objects. The selective crowding by upright face flankers, on the other hand, is indeed suggestive of crowding at the object configural level. However, this finding may be specific to faces. Several researchers consider faces to be processed differently than other objects, with faces processed in a more holistic fashion than objects and preferentially activating the cortical region fusiform face area (e.g., Kanwisher, McDermott, & Chun, 1997; McKone, Kanwisher, & Duchaine, 2007; Tanaka & Farah, 2003).

In this study, we examined systematically whether crowding can occur at different levels, specifically, between high-level configural representations of objects and between object parts, with simple, nonface objects. To this end we used a disconnected configuration made up of four elements grouped (by closure and collinearity) into a global configuration (a square-like or a diamond-like shape) as the target object. The target was presented in isolation or surrounded by flankers at varying eccentricities, and target identification was measured. The flankers were similar either to the target object parts or to the target object whole or configuration, thus allowing us to examine crowding between object parts and crowding between higher level, configural representations of objects.

Experiments 1a and 1b

The target object in these experiments was a square or a diamond configuration made of four L elements. The target object was presented at varying eccentricities, alone or surrounded by six flankers. The flankers were either L elements similar to the target object parts (Experiment 1a) or tilted squares similar to the target object whole (Experiment 1b). The task was to identify the target by pressing one of two response keys.

Method

Participants. Participants in all experiments were students at the University of Haifa and were paid for participation. All participants provided informed consent to a protocol approved by the Ethics Committee of the Psychology Department at University of Haifa. All had normal or corrected-to-normal vision. Twelve individuals (20–27 years old, all females) participated in Experiment 1a, and 12 (20–33 years old, 3 males) participated in Experiment 1b.

Stimuli and apparatus. The target was a disconnected configuration—a square-like or a diamond-like—made of four black L elements. Each arm of the L element subtended $0.55^\circ \times 0.08^\circ$. Each side of the global configuration subtended 1.37°. The target object was presented in isolation (no-flankers condition) or was surrounded by six different flankers (flankers condition) randomly sampled on each trial from a set of possible flankers. In Experiment 1a (Figure 1(a)), the set of possible flankers included eight L elements, four of which were identical to the L elements of the square target and four were identical to the L elements of the diamond target. The size of the L flankers was identical to the size of the elements of the target. In Experiment 1b (Figure 1(c)), the set of possible flankers included 12 tilted outlined squares, 6 tilted to the right (6.43°, 12.86°, 19.29°, 25.72°, 32.15°, and 38.58°) and 6 tilted to the left (-6.43°, -12.86°, -19.29°, -25.72°, -32.15°, and -38.58°). Thus, the flankers in Experiment 1a were similar to the target object parts, and the flankers in Experiment 1b were similar to the target object whole. The flankers were centered on an imaginary circle. The center-to-center distance between target and flanker was fixed at 2.19°. Stimuli were presented against a gray background ($54\,cd/m^2$).

All the experiments were conducted on a PC with a 19-in. CRT color monitor set at a resolution of $1,024 \times 768$ pixels and a refresh rate of 100 Hz, using E-Prime. Viewing distance was fixed at 57 cm with a chinrest.

Procedure. Each trial started with a fixation mark ($0.5^\circ \times 0.5^\circ$ black cross) presented at the center of the screen. After 750 ms, the target with or without six flankers appeared for 120 ms

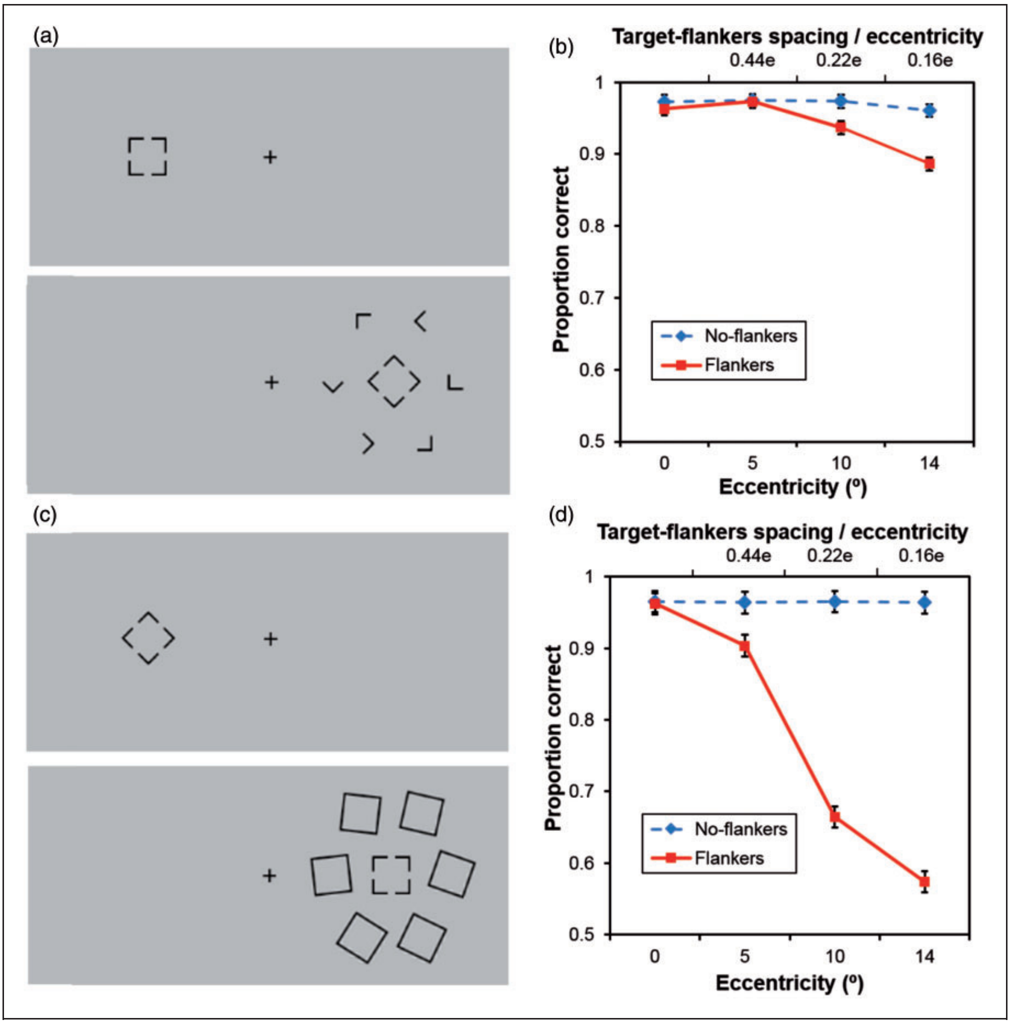

Figure 1. Examples of target and flankers used in Experiment 1a (a) and Experiment 1b (c). The target was presented in isolation or surrounded by six flankers, right or left of fixation. Results from Experiment 1a (b) and Experiment 1b (d): mean accuracy as a function of eccentricity and flankers. Error bars represent within subjects $\pm$ *SEM*.

at the fovea (0°) or at 5°, 10°, or 14° to the left or right of fixation. For the foveal presentation, the fixation mark disappeared after 750 ms; for the peripheral presentations, the fixation mark remained on the screen for the entire duration of the trial, and the participants were asked to fixate on it throughout the trial. Using a two-alternative forced-choice task, participants were asked to identify the target by pressing one of two response keys. Following the target presentation, the gray screen remained until a response was received for a maximum of 3,000 ms. Intertrial interval was 1,000 ms. Across the experimental trials, all the combinations of eccentricity, field (right, left), flankers (flankers, no flankers), and target (square, diamond) were presented with equal frequency in a random fashion. There were 480 experimental trials preceded by 24 practice trials.

Results and Discussion

Mean accuracy (proportion correct) of target identification as a function of flankers (flankers, no-flankers) and eccentricity is presented in Figure 1(b) and (d), for Experiments 1a and 1b, respectively. The accuracy data were submitted to a 4 (eccentricity) $\times$ 2 (flankers) 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 (two tailed).

Experiment 1a. The ANOVA showed a significant effect of eccentricity, $F(3, 33) = 11.79$, $p < .0001$, $\eta_p^2 = .52$, a significant effect of flankers, $F(1, 11) = 23.10$, $p = .0005$, $\eta_p^2 = .68$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 5.66$, $p = .0030$, $\eta_p^2 = .34$. As shown in Figure 1(b), when the target appeared in isolation, identification was highly accurate and did not vary with eccentricity, $F < 1$. When flankers were present, accuracy varied significantly with eccentricity, $F(3, 33) = 11.04$, $p < .0001$, $\eta_p^2 = .50$. A small but significant effect of the flankers was observed at 10° eccentricity, reducing accuracy from 97.3% to 93.7%, $t(11) = 2.48$, $p = .03$, and at 14° eccentricity, reducing accuracy from 96.0% to 88.6%, $t(11) = 4.18$, $p = .0015$. No significant effect of flankers was observed at the fovea, $t(11) = 1.17$, $p = .2633$, and at 5° eccentricity, $t(11) = 0.14$, $p = .8862$.

Experiment 1b. The ANOVA revealed significant effects of eccentricity, $F(3, 33) = 65.48$, $p < .0001$, $\eta_p^2 = .86$, and flankers, $F(1, 11) = 96.64$, $p < .0001$, $\eta_p^2 = .89$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 77.00$, $p < .0001$, $\eta_p^2 = .87$. As shown in Figure 1(d), identification in the no-flankers condition was highly accurate and did not vary with eccentricity $F < 1$. When flankers were present, accuracy decreased significantly with eccentricity, $F(3, 33) = 80.33$, $p < .0001$, $\eta_p^2 = .88$. A significant effect of flankers was observed in all peripheral presentations. Flankers reduced accuracy from 96.3% to 90.3% at 5° eccentricity, $t(11) = 2.69$, $p = .0207$, from 96.5% to 66.4% at 10° eccentricity, $t(11) = 10.19$, $p < .0001$, and from 96.3% to 57.3% at 14° eccentricity, $t(11) = 10.57$, $p < .0001$. In the latter, performance in the flankers condition was not significantly different from chance, $t(11) = 2.04$, $p = .0661$. No effect of flankers was observed at the fovea, $t(11) = 0.26$, $p = .7879$.

The results of Experiments 1a and 1b showed that flankers interfered with target identification at larger eccentricities, and no effect of flankers was observed at the fovea. These findings are consistent with other findings of crowding (e.g., Levi, 2008; Pelli et al., 2004). However, the present results showed a difference between the two experiments: Crowding was observed at smaller eccentricity and it was stronger when the target object was surrounded by similar object wholes (Experiment 1b) than when the target object was surrounded by similar object parts (Experiment 1a). To directly compare the crowding effect between the two experiments, we calculated a crowding score by subtracting accuracy in the flankers condition from accuracy in the no-flankers condition at each eccentricity (for each subject in each experiment). The crowding score indicates how much the presence of flankers hindered target identification compared with when the target was presented in isolation. A two-way mixed design ANOVA (eccentricity as within-subjects factor and experiment as a between-subjects factor) was conducted on the crowding scores. The analysis revealed a significant effect of eccentricity, $F(3, 66) = 73.67$, $p < .0001$, $\eta_p^2 = .77$, and a significant effect of experiment, $F(1, 22) = 61.06$, $p < .0001$, $\eta_p^2 = .74$. Most importantly, the interaction between eccentricity and experiment was significant, $F(3, 66) = 38.29$, $p < .0001$, $\eta_p^2 = .64$. There was no difference between the two experiments in foveal presentation, $t(22) = 0.57$, $p = .5723$. The flankers had no effect at the fovea, both when they were similar to the target object parts (Experiment 1a) and when they were similar to the target object whole (Experiment 1b), indicating no crowding at the fovea regardless of flankers type. On the other hand, at 5° eccentricity, there was a significant difference between the two experiments, $t(22) = 2.35$, $p = .0284$. Target identification was hindered when the target object was surrounded by similar object wholes (Experiment 1b) but not when it was surrounded by similar object parts (Experiment 1a). A significant difference between the two experiments was observed also at 10° eccentricity and 14° eccentricity, $t(22) = 8.03$, $p < .0001$, $t(22) = 7.71$, $p < .0001$, respectively, indicating that object wholes flankers had a greater detrimental effect on target identification than object parts flankers.

These results confirmed that crowding was evident at smaller eccentricity and that it was stronger when the target object was flanked by similar object wholes than by similar object parts. It is possible, however, that the results obtained in Experiment 1a were simply due to the L flankers, which for some reason may be ineffective flankers, or at least less effective flankers than tilted squares, and not to the fact that the L flankers were similar to the target object parts, whereas the tilted square flankers were similar to the target object whole. The next experiments address this issue.

Experiments 2a and 2b

These experiments were designed to examine whether similar results as those obtained in Experiments 1a and 1b will be obtained with stimuli that differ from the ones used in Experiments 1a and 1b mainly in the parts of the target object.

The target in Experiments 2a and 2b was a disconnected configuration (a square or a diamond) made of four black lines (Figure 2(a) and (c)). In the flankers condition, the target object was surrounded by lines similar to the target object parts (Experiment 2a) or by tilted squares similar to the target object whole (Experiment 2b). If the difference in crowding between Experiments 1a and 1b is due to the similarity relation between the target and the flankers—whether the flankers are similar to the target object parts or to the target object whole, then Experiments 2a and 2b are expected to yield similar results to those of Experiments 1a and 1b, with crowding being stronger and occurring at smaller eccentricity in Experiment 2b (object wholes flankers) than in Experiment 2a (object parts flankers). To foreshadow, the results of Experiments 2a and 2b replicated the results of Experiments 1a and 1b.

Method

Participants. Twelve individuals (19–27 years old, 3 males) participated in Experiment 2a, and 12 (19–27 years old, 4 males) participated in Experiment 2b.

Stimuli and procedure. The target was a disconnected configuration (a square or a diamond) made of four black lines. Each line subtended $0.78° \times 0.08°$. Each side of the (completed) configuration (square and diamond) subtended 1.37°. In Experiment 2a, there was a set of eight possible flankers, which included two lines of the square (vertical and horizontal), two lines of the diamond (right and left diagonal), and four tilted lines (22.5°, 67.5°, −22.5°, and −67.5°; Figure 2(a)). The size of the lines was identical to the size of the line elements of the target. In Experiment 2b, the set of possible flankers included the same 12 tilted squares as in Experiment 1b (Figure 2(c)). Thus, the flankers in Experiment 2a were similar to the target object parts, whereas the flankers in Experiment 2b were similar to the target object whole.

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

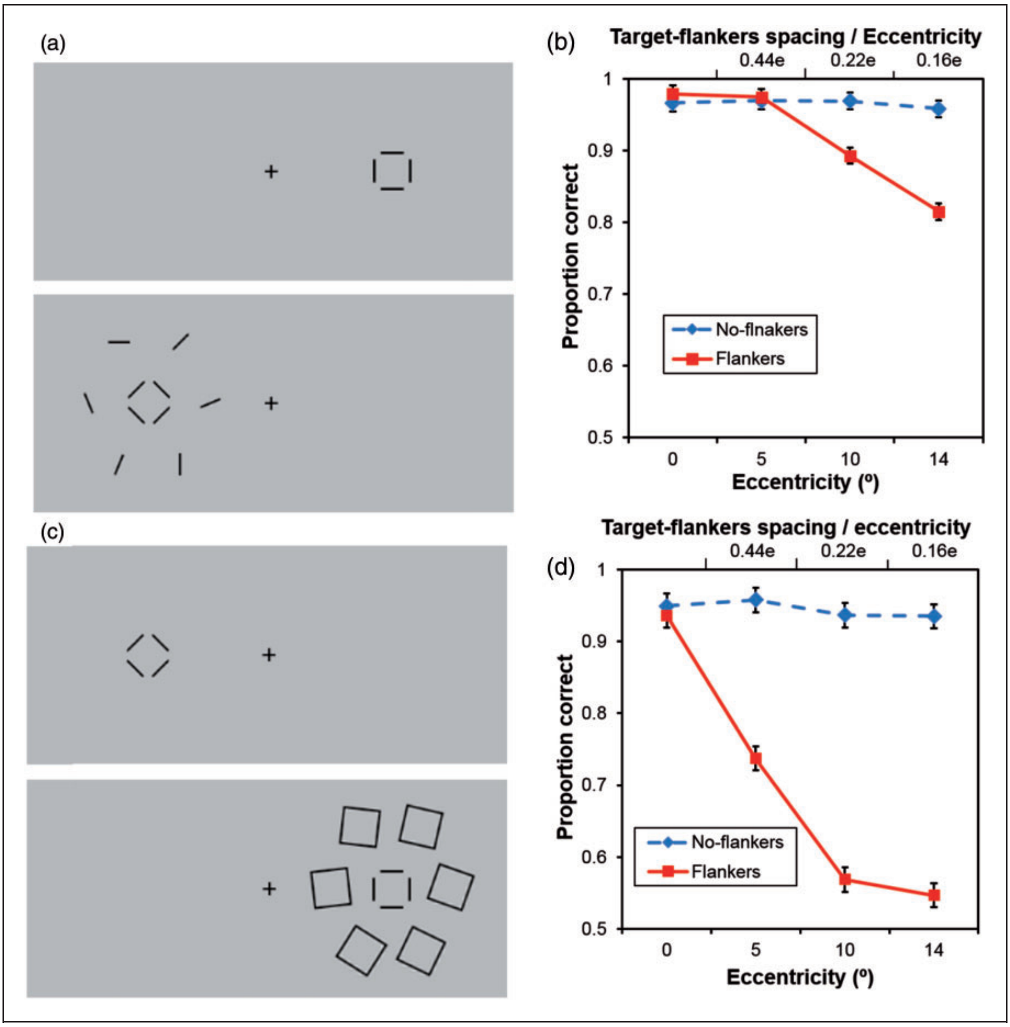

Figure 2. Examples of the target and flankers used in Experiment 2a (a) and Experiment 2b (c). The target was presented in isolation or surrounded by six flankers, right or left of fixation. Results from Experiment 2a (b) and Experiment 2b (d): mean accuracy as a function of eccentricity and flankers. Error bars represent within subjects ± *SEM*.

Results and Discussion

Mean accuracy of target identification as a function of flankers and eccentricity is presented in Figure 2(b) and (d), for Experiments 2a and 2b, respectively. Data analyses were the same as in Experiments 1a and 1b.

Experiment 2a. The ANOVA showed significant main effects of eccentricity, $F(3, 33) = 24.94$, $p < .0001$, $\eta^2_p = .69$, and flankers, $F(1, 11) = 12.03$, $p = .0052$, $\eta^2_p = .52$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 20.24$, $p < .0001$, $\eta^2_p = .65$. Accuracy of target identification varied with eccentricity when flankers were present, $F(3, 33) = 25.95$, $p < .0001$, $\eta^2_p = .70$, but not when the target was presented in isolation, $F < 1$. Flankers reduced accuracy from 96.9% to 89.3%, $t(11) = 2.52$, $p = .0286$, at 10° eccentricity, and from 95.8% to 81.5%, $t(11) = 6.14$, $p < .0001$, at 14° eccentricity. No significant effect of flankers was observed at the fovea, $t(11) = 2.52$, $p = .2313$, and at 5° eccentricity, $t(11) = 0.57$, $p = .5796$.

Experiment 2b. The ANOVA revealed significant effects of eccentricity, $F(3, 33) = 57.07$, $p < .0001$, $\eta_p^2 = .83$, and flankers, $F(1, 11) = 250.78$, $p < .0001$, $\eta_p^2 = .96$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 54.12$, $p < .0001$, $\eta_p^2 = .83$. Identification was highly accurate and did not vary with eccentricity when the target was presented in isolation, $F(3, 33) = 1.26$, $p = .3026$, but accuracy decreased significantly with eccentricity when flankers were present, $F(3, 33) = 60.96$, $p < .0001$, $\eta_p^2 = .85$. Flankers reduced accuracy in all peripheral presentations: from 94.7% to 72.6% at 5° eccentricity, $t(11) = 5.85$, $p = .0002$, from 93.4% to 53.8% at 10° eccentricity, $t(11) = 15.48$, $p < .0001$, and from 92.9% to 51.0% at 14° eccentricity, $t(11) = 16.14$, $p < .0001$. Performance at 10° eccentricity, $t(11) = 2.05$, $p = .0655$, and at 14° eccentricity, $t(11) = 0.54$, $p = .5970$, was not significantly different from chance. No significant effect of flankers was observed at the fovea, $t(11) = 1.41$, $p = .1850$.

To directly compare the crowding effect between Experiments 2a and 2b, we again calculated crowding scores [accuracy(no-flankers)−accuracy(flankers)] at each eccentricity (for each subject in each experiment) and submitted them to a two-way mixed design ANOVA. The effects of eccentricity, $F(3, 66) = 70.22$, $p < .0001$, $\eta_p^2 = .76$, and experiment, $F(1, 22) = 92.98$, $p < .0001$, $\eta_p^2 = .81$, were significant, as was the interaction between eccentricity and experiment, $F(3, 66) = 17.99$, $p < .0001$, $\eta_p^2 = .45$. There was no significant difference between the two experiments in foveal presentations, $t(22) = 1.90$, $p = .07$: In both experiments, there was no effect of flankers at the fovea. On the other hand, at 5° eccentricity, object whole flankers affected target identification, but object parts flankers did not, $t(22) = 5.56$, $p < .0001$. A significant difference between the two experiments was also observed at 10° eccentricity and at 14° eccentricity, $t(22) = 8.07$, $p < .0001$, $t(22) = 7.89$, $p < .0001$, respectively, indicating a larger influence of the object whole flankers than the object parts flankers on target identification.

Thus, the results of Experiments 2a and 2b replicated the results of Experiments 1a and 1b. Taken together, the results of Experiments 1 and 2 showed that crowding is evident at smaller eccentricity and that there is more crowding when a target object is flanked by other similar objects than by similar object parts. Crowding by object wholes flankers was observed at 5° eccentricity and farther. For the fixed target-flanker spacing used in our experiments, target-flanker spacing at 5° eccentricity is 44% of target eccentricity (0.44e), which is within the range of 0.4e to 0.5e reported for critical spacing using other kinds of stimuli including letters and faces (e.g., Bouma, 1970; Louie et al., 2007; Pelli et al., 2004). Crowding of object parts was observed only at 10° eccentricity (0.22e) and farther, suggesting that the critical spacing for object parts flankers is smaller than that for object whole flankers. In addition, at 10° eccentricity (0.22e) and 14° eccentricity (0.16e), crowding by object flankers was stronger than crowding by object parts flankers.

The following experiments were designed to support this conclusion and to rule out alternative accounts.

Experiment 3

The results of Experiments 1 and 2 suggest that object wholes flankers are more potent than object parts flankers. Yet, the object whole flankers were larger than the object parts flankers, and at a given target-flanker center-to-center distance, the contours of the target and flankers were closer to each other with the object whole flankers (0.23°, Experiment 1b) than with the object parts flankers (0.82°, Experiment 1a; see Figures 1(a)/2(a) and 1(c)/2(c)). One may argue that it is the difference in the target-flanker contour distance that accounts for the difference in crowding between the object parts flankers and object whole flankers. Previous research, demonstrating that crowding is independent of flanker size (Levi & Carney, 2009; Pelli et al., 2004), and that crowding is dependent on the center-to-center distance between the target and flankers and not on the proximity of their contours (Levi & Carney, 2009), suggests that this is not a very plausible account. Nonetheless, given the novelty of the present stimuli in testing crowding and the effects of object parts flankers versus object wholes flankers, we addressed this alternative account.

To this end, we used the same stimuli as the ones in Experiment 1a (Figure 1(a)), except that the L flankers were now closer to the target, such that the target-flanker contour distance was the same as the one with the object whole flankers (0.23°, Experiment 1b). If the weaker crowding of the L flankers (Experiment 1a) versus the strong crowding of the tilted square flankers (Experiment 1b) is due to the smaller target-flanker contour distance in the latter, then a strong crowding is expected in the present experiment. If, however, the difference in crowding is due to the similarity relation between the target and the flankers—whether the flankers are similar to the target object parts or to the target object whole, then a weak crowding is expected in this experiment.

Methods

Participants. Twelve individuals (18–26 years old, 4 males) participated in Experiment 3.

Stimulus and procedure. The target and flankers were identical to the ones in Experiment 1a (see Figure 1(a)), except that the minimal target-flanker contour distance was 0.23° (the same as the target-flanker contour distance with the object wholes flankers in Experiments 1b and 2b). All other aspects of the stimuli and procedure were identical to those of Experiment 1.

Results and Discussion

Mean accuracy of target identification as a function of flankers and eccentricity is presented in Figure 3. The ANOVA showed significant main effects of eccentricity, $F(3, 33) = 17.60$, $p < .0001$, $\eta_p^2 = .62$, and flankers, $F(1, 11) = 11.84$, $p = .0055$, $\eta_p^2 = .50$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 8.27$, $p = .0003$, $\eta_p^2 = .43$. Significant effect of the flankers was observed at 10° eccentricity, reducing accuracy from 94.4% to 88.0%, $t(11) = 2.42$, $p = .0336$, and at 14° eccentricity, reducing accuracy from 91.7% to 78.8%, $t(11) = 4.37$, $p = .0011$. No significant effect of flankers was observed at the fovea, $t(11) = 1.01$, $p = .3296$, and at 5° eccentricity, $t(11) = 1.42$, $p = .1816$.

The crowding effect observed in this experiment is similar to the one found in Experiment 1a (see Figure 1(b)). An ANOVA conducting on the crowding scores of Experiments 3 and 1a showed no difference between the experiments. The only significant effect was the effect of eccentricity, $F(3, 66) = 13.26$, $p < .0001$, $\eta_p^2 = .38$. There was no significant effect of experiment, $F(1, 22) = 1.93$, $p = .1785$, and no significant interaction between eccentricity and experiment, $F(3, 66) = 1.63$, $p = .1898$. Thus, the crowding effect of the object parts remained weak even when the target-flanker contour distance was as small as the target-flanker contour distance with the object whole flankers.

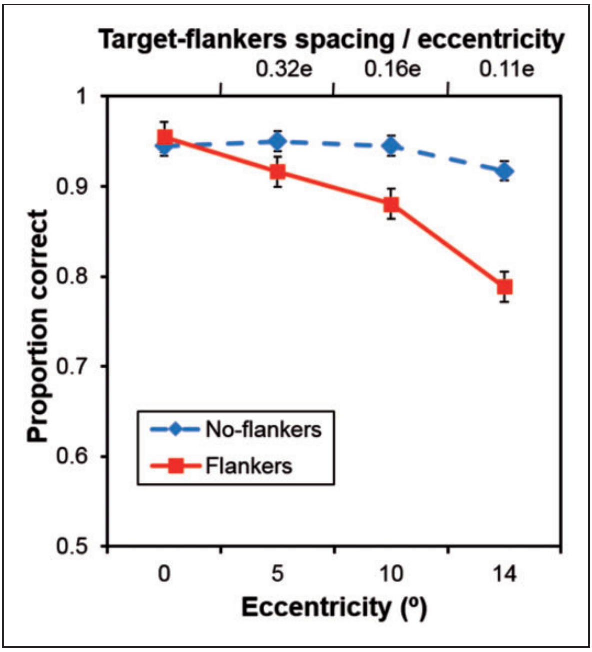

Figure 3. Results from Experiment 3: mean accuracy as a function of eccentricity and flankers. Error bars represent within subjects ± *SEM*.

Experiments 4a–4c

Could the difference between crowding by object wholes and crowding by object parts be due just to degree of similarity between target and flanker? The object whole flankers are similar to the target in parts (and parts number) and in global configuration, whereas the object-part flankers are similar only to the target parts (and only one part); perhaps the higher degree of similarity for the former than for the latter accounts for the difference in the crowding effects. To address this issue, we used flankers that were similar to the target object in one aspect (global configuration or parts) and dissimilar in the other aspect (parts or global configuration, respectively), and equated the number of parts. Thus, the flankers in Experiment 4a (configuration similarity) were similar to the target in global configuration but dissimilar in parts, and the flankers in Experiment 4b (part similarity) were similar to the target in parts but dissimilar in global configuration. Experiment 4c (dissimilarity) served as a control experiment—the flankers were dissimilar to the target both in parts and global configuration, providing baseline crowding. If it is just the degree of similarity that matters, a similar crowding effect is expected in Experiments 4a and 4b, because in both experiments there is similarity in one aspect and dissimilarity in another aspect. This crowding effect should be larger than the crowding effect in Experiment 4c (dissimilarity in both aspects) and smaller than the crowding effect observed with object whole flankers (i.e., in Experiments 1b or 2b; similarity in both aspects). On the other hand, if it is the level at which similarity arises (i.e., similarity in object parts vs. similarity in global configuration) that matters, such that similarity in global configuration induces stronger crowding than similarity in parts (as suggested by the results of Experiments 1 and 2), then a stronger crowding is expected to be observed in Experiment 4a than in Experiment 4b, and the former is expected to be similar to the crowding effect observed with object whole flankers.

Method

Participants. Twelve individuals (20–27 years old, 5 males) participated in Experiment 4a, 12 (23–30 years old, 3 males) participated in the Experiment 4b, and 12 (23–33 years old, 3 males) participated in Experiment 4c.

Stimuli and procedure. The target was identical to the target in Experiments 1a and 1b: A disconnected square-like or diamond-like configuration made of four black L elements. The set of possible flankers in Experiment 4a (Figure 4(a)) included 12 tilted disconnected square configurations, each made of four lines ($0.86^\circ \times 0.08^\circ$ each) and subtended $1.33^\circ \times 1.33^\circ$. In Experiment 4b (Figure 4(c)), the set of possible flankers included 12 tilted "cross" configurations, each made of four L elements ($0.55^\circ \times 0.08^\circ$ each), and subtended $1.37^\circ \times 1.37^\circ$. In Experiment 4c, the set of possible flankers included 12 tilted fan-like configurations, each of which made of four curved lines ($0.55^\circ \times 0.08^\circ$) and subtended $1.33^\circ \times 1.33^\circ$ (Figure 4(e)).

All other aspects of the stimuli, apparatus, and procedure were identical to those of Experiments 1 and 2.

Results and Discussion

Mean accuracy of target identification as a function of flankers and eccentricity is presented in Figure 4(b), (d), and (f), for Experiments 4a, 4b, and 4c, respectively. Data analyses were the same as in Experiment 1.

Experiment 4a. There were significant main effects of eccentricity, $F(3, 33) = 105.67$, $p < .0001$, $\eta^2_p = .90$, and flankers, $F(1, 11) = 186.81$, $p < .0001$, $\eta^2_p = .94$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 82.19$, $p < .0001$, $\eta^2_p = .88$. Accuracy of target identification decreased significantly with eccentricity, $F(3, 33) = 116.33$, $p < .0001$, $\eta^2_p = .91$, when surrounded by flankers, but not when appeared in isolation, $F(3, 33) = 1.64$, $p = .1998$. Flankers reduced accuracy from 95.7% to 73.7% at 5° eccentricity, $t(11) = 7.36$, $p < .0001$, from 93.7% to 56.8% at 10° eccentricity, $t(11) = 14.93$, $p < .0001$, and from 93.5% to 54.6% at 14° eccentricity, $t(11) = 14.33$, $p < .0001$. No significant effect of flankers was observed at the fovea, $t(11) = 1.05$, $p = .3133$. Granted that the target and flankers were dissimilar in parts, these results show crowding between the representations of the global configuration of target and flankers.

Experiment 4b. The effect of eccentricity, $F(3,33) = 49.47$, $p < .0001$, $\eta^2_p = .82$, flankers, $F(1, 11) = 62.01$, $p < .0001$, $\eta^2_p = .85$, and the eccentricity X flankers interaction, $F(3, 33) = 37.38$, $p < .0001$, $\eta^2_p = .77$, were significant. Flankers reduced accuracy from 98.4% to 92.6% at 5° eccentricity, $t(11) = 2.59$, $p = .0251$, from 96.1% to 73.1% at 10° eccentricity, $t(11) = 5.83$, $p < .0001$, and from 95.6% to 65.7% at 14° eccentricity, $t(11) = 10.36$, $p < .0001$. No significant effect of flankers was observed at the fovea, $t(11) = 0$. Since the flankers were similar to target in parts but dissimilar in configuration, these results show crowding at the object-part level.

Experiment 4c. The ANOVA showed significant main effects of eccentricity, $F(3, 33) = 23.40$, $p < .0001$, $\eta^2_p = .65$, and flankers, $F(1, 11) = 42.73$, $p < .0001$, $\eta^2_p = .80$, and a significant interaction between eccentricity and flankers, $F(3, 33) = 26.23$, $p < .0001$, $\eta^2_p = .70$. Flankers reduced accuracy from 98.4% to 92.1% at 10° eccentricity, $t(11) = 3.65$, $p = .0038$, and from

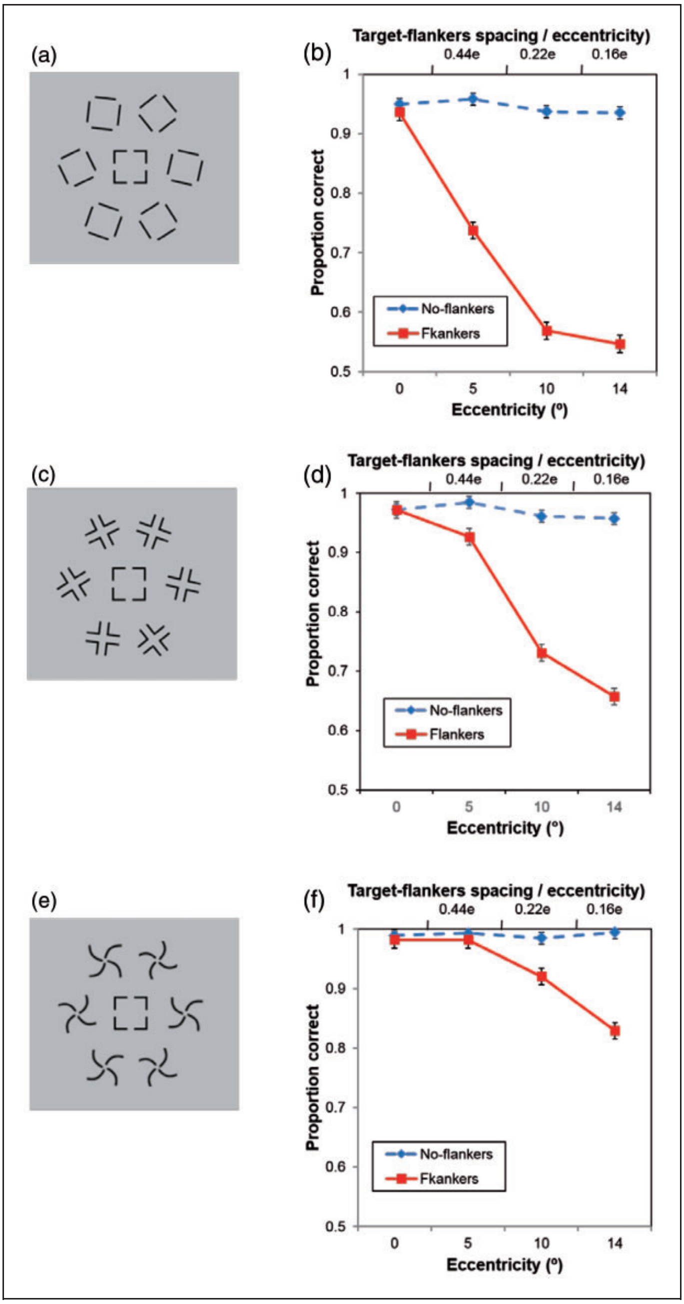

Figure 4. Examples of target and flankers used in Experiment 4a (a), 4b (c), and 4c (e). Results from Experiment 4a (b), 4b (d), and 4c (f): mean accuracy as a function of eccentricity and flankers. Error bars represent within subjects $\pm$ *SEM*.

99.4% to 82.9% at 14° eccentricity, $t(11) = 6.87$, $p < .0001$. No significant effect of flankers was observed at the fovea, $t(11) = 1.60$, $p = .1372$, and at 5° eccentricity, $t(11) = 1.30$, $p = .2199$. These results show that there is some crowding even when the flankers are dissimilar to the target in both parts and global configuration.

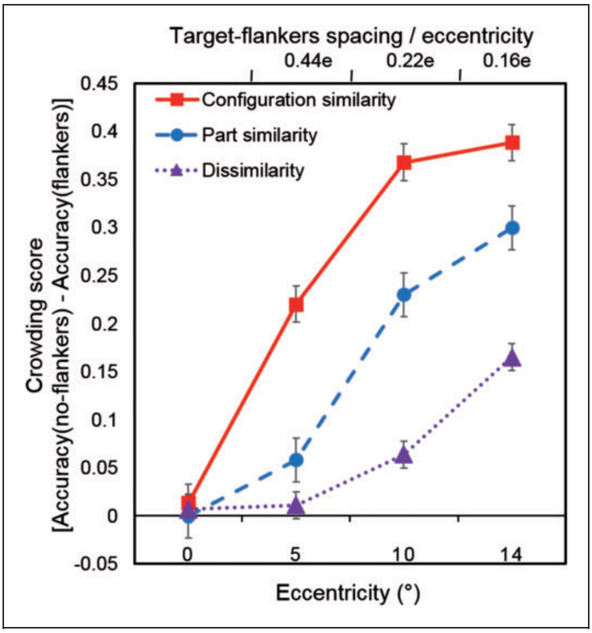

Figure 5. Crowding scores [accuracy(no-flankers)−accuracy(flankers)] as a function of eccentricity for Experiment 4a (configuration similarity), Experiment 4b (part similarity), and Experiment 4c (dissimilarity). Error bars represent ± *SEM*.

The results of Experiments 4a–4c showed that the three experiments differed in strength and in spatial extent of crowding. Crowding scores for each experiment as a function of eccentricity are presented in Figure 5. Analysis of the crowding scores revealed a significant effect of eccentricity, $F(3, 99) = 126.14$, $p < .0001$, $\eta_p^2 = .79$, a significant effect of experiment, $F(2, 33) = 33.84$, $p < .0001$, $\eta_p^2 = .67$, and a significant interaction between eccentricity and experiment, $F(6, 99) = 12.04$, $p = .0001$, $\eta_p^2 = .42$. There was no difference between the three experiments in foveal presentation, $F < 1$: The flankers had no effect at the fovea, regardless of the similarity relation between target and flankers. As shown in Figure 5, in all peripheral presentations, the crowding score was highest when the flankers were similar to the target in global configuration (Experiment 4a), intermediate when they were similar to the target in parts (Experiment 4b), and lowest when they were dissimilar to the target in both global configuration and parts (Experiment 4c), $F(2, 33) = 24.52$, $p < .0001$, $\eta_p^2 = .60$, $F(2, 33) = 28.02$, $p < .0001$, $\eta_p^2 = .63$, $F(2, 33) = 17.63$, $p < .0001$, $\eta_p^2 = .52$, for 5°, 10°, and 14° eccentricity, respectively. Tukey HSD comparisons ($\alpha = .05$) confirmed that the crowding scores for similarity in global configuration were significantly higher than for similarity in parts, which in turn were significantly higher than for dissimilarity, at all peripheral presentations, with one exception of a nonsignificant difference between part similarity and dissimilarity at 5° eccentricity.

Thus, both configural similarity and part similarity between target and flankers produced significantly larger crowding effect than dissimilarity in both configuration and parts, clearly indicating crowding at the object part level and crowding at the object configural level. Similarity in global configuration, however, induced more crowding than similarity in parts. Also, the crowding by flankers similar in global configuration (but dissimilar in parts) was observed at the same eccentricities and was of similar magnitude as crowding with object wholes flankers in Experiments 1b and 2b, confirming that the crowding observed with the latter involved crowding between the representations of the global configuration of the target and flankers.

The present findings suggest that degree of similarity per se cannot account for the differential crowding effect by object-whole and object-part flankers. Target-flanker similarity in one aspect and dissimilarity in the other aspect produced crowding that differed in strength, depending on whether the similarity was in global configuration or in parts. Target-flanker similarity in global configuration produced strong crowding even when dissimilarity in parts was introduced, and this crowding was significantly stronger than the crowding produced by target-flanker similarity in parts, even when target and flankers were equated for number of parts.

Note that the crowding by target-flanker similarity in object parts observed in Experiment 4b was stronger than the crowding by the object parts observed in Experiments 1a, 2a, and 3. For example, comparison of crowding scores between Experiment 4b and Experiment 1a revealed a significant interaction between experiment and eccentricity, $F(3, 66) = 17.32$, $p < .0001$, $\eta_p^2 = .53$, with a significantly stronger crowding in the former at all peripheral presentations and no difference in foveal presentation. Presumably, increasing the similarity between the target and flankers by equating the number of parts in target and flankers or increasing the amount of "energy" of the flankers in Experiment 4b versus Experiment 1a, increased the crowding effect. Nonetheless, as noted earlier, this crowding effect was significantly weaker than the crowding effect induced by target-flankers configural similarity, indicating that the observed difference between crowding by configural similarity and crowding by part similarity was above and beyond differences in degree of similarity or in amount of flankers "energy."

General Discussion

The present study examined whether crowding can occur at different levels, specifically, at the object configural level in addition to feature- or part-level crowding, using simple, nonface, objects. Target (a disconnected square-like or diamond-like configuration) identification was measured at varying target eccentricities. The flankers that surrounded the target were similar either to the target object parts or to the target object whole or configuration. Crowding was observed in both cases. Across all the experiments, flankers interfered with target identification, such that the accuracy of target identification decreased with an increase in eccentricity, and no interference was observed at the fovea. Crowding was weaker and had smaller spatial extent when the flankers were similar to the target object parts than when the flankers were similar to the target object configuration, including when degree of feature similarity was controlled for. These results demonstrate crowding at the object parts level and crowding at the object configural level. The latter is similar to the findings of crowding with faces (Farzin et al., 2009; Louie et al., 2007), thus indicating that crowding between object configural representations is by no means specific to faces.

It should be noted that some previous studies reported findings that can be seen as suggestive of object-level crowding (e.g., Kooi et al., 1994; Manassi, Sayim, & Herzog, 2013; Nazir, 1992), but unlike the present study, these studies did not control for the degree of feature similarity between target and flankers. For example, Nazir (1992) presented observers with a "Landolt square" target, and the task was to indicate the location of the gap in the target stimulus—right, up, left, or down. The target was flanked with squares, Snellen-Es, or bars. The results showed more crowding with the square flankers than with the E flankers or the bar flankers, which may suggest crowding at the object whole level. However, these results can be accounted for by degree of feature similarity because the square was more similar to the "Landolt square" in terms of its features (two vertical and two horizontal bars, four corners) than was the E or the bar. Similarly, degree of feature similarity can also account for the finding of Manassi et al. (2013) that a target square was crowded by flanking squares but lesser when the flanking squares were rotated because the flanking square was more similar to the target square in terms of its features (e.g., vertical and horizontal lines), than was the rotated flanking square (oblique lines vs. vertical and horizontal lines).

Thus, our results, along with the recent results with faces (Farzin et al., 2009; Fischer & Whitney, 2011; Louie et al., 2007), show unequivocally that crowding can occur at multiple levels—not only between low-level features or parts but also between object configural representations. Any comprehensive model of crowding must account for these findings (Chaney et al., 2014).

How can the weaker crowding by target-flanker part similarity than by target-flanker configuration similarity be explained? We examined and ruled out two possible explanations: target-flanker contour proximity and degree of similarity. Decreasing the distance between the contours of the target object and the contours of the object parts flankers, such that it was the same as with the object whole flankers, did not increase the crowding effect (Experiment 3). Using flankers that were similar to the target in one aspect and dissimilar in the other aspect produced differential crowding effects, depending on the level at which similarity between target and flankers arises—whether between object parts or between object configurations. Flankers similar to the target object in configuration but dissimilar in parts (Experiment 4a) produced stronger crowding than flankers similar to the target in parts but dissimilar in configuration (Experiment 4b). Thus, neither target-flanker contour proximity nor degree of similarity per se appeared to be a good predictor of strength of crowding.

Herzog and coworkers (Herzog & Manassi, 2015; Manassi et al., 2012; Saarela, Sayim, Westheimer, & Herzog, 2009; Saarela, Westheimer, & Herzog, 2010; see also, Livne & Sagi, 2007, 2010) suggested that one of the best predictors of crowding is grouping: Crowding is weak whenever the target segregates from the flankers and crowding is strong when the target groups with the flankers. For example, Livne and Sagi (2007) showed that crowding of a Gabor target by similar Gabor flankers decreased when the flankers were grouped by collinearity into a circular configuration. Manassi et al. (2012) showed that Vernier offset discrimination deteriorated when flanked by two single lines, but crowding diminished when the lines became part of a rectangle. Also, performance was strongly worsened when one shorter line to the left and one to the right flanked the Vernier, but it improved when further lines were added, demonstrating that adding flankers can actually weaken crowding probably because the shorter lines grouped with each other and did not group with the Vernier.

Presumably, in our experiments, the target parts are strongly grouped (by proximity, collinearity, and closure) into an "object" (a square or a diamond configuration). Therefore, the target parts, although similar to the flankers, are not grouped with the flankers; consequently the target stands out from the flankers when it is surrounded by similar object parts (Figures 1(a), 2(a), and 4(c)), resulting in weaker crowding.

It is also possible, that crowding was further weakened, at least when the target object was surrounded by single object parts (Experiments 1a, 2a, 3), because the target object captured attention. This explanation is suggested by the research on the relationship between perceptual organization and attention on the one hand, and the research on the relationship between crowding and attention, on the other hand. Kimchi and coworkers (Kimchi, Yeshurun, & Cohen-Savransky, 2007; Yeshurun, Kimchi, Sha'shoua, &

Carmel, 2009) demonstrated that the mere organization of some elements in the visual field into an "object" (i.e., a coherent unit that conforms to Gestalt factors such as closure and collinearity) captures attention in a stimulus-driven manner. In several experiments, observers were presented with an array of multiple L elements, a subset of which formed a coherent perceptual unit (object) on some trials (object trials) and no perceptual unit on the other trials (no-object trials). The task was to report the color of a target, which was defined by its location relative to a cue. The object was task irrelevant and was not associated with abrupt onset or any other unique transient. Nonetheless, response times to the target on the object trials were faster when the cue appeared within the object and slower when the cue occurred outside the object, indicating that the object captured attention automatically. Several studies demonstrated that crowding can be modulated by attention (e.g., Felisberti et al., 2005; Scolari, Kohnen, Barton, & Awh, 2007; Strasburger, 2005; Yeshurun & Rashal, 2010). For example, Yeshurun and Rashal (2010) measured orientation identification of a rotated T target with and without flankers and manipulated attention by peripheral precues. They showed that precuing target location significantly improved identification accuracy and reduced the critical distance. Thus, when surrounded by object parts flankers, the target object—a strongly organized unit—captured attention, which reduced crowding. Obviously, the target object does not capture attention when it is surrounded by similar object wholes or configurations. Consequently, crowding by object parts flankers was weaker and had a smaller spatial extent than crowding by object whole flankers.

Our proposed interpretation for the weaker crowding by object parts (with or without the additional possible effect of capture of attention) implies that crowding is preceded by grouping processes, as has been previously suggested by Livne and Sagi (2010) and by Manassi et al. (2012).

Furthermore, it also implies that the strength of crowding by object-part flankers or by object-configuration flankers is dependent on the strength of the grouping of the target object's parts—the stronger the grouping the weaker the crowding by object-part flankers and the stronger the crowding by object-configuration flankers. In other words, the stronger is the target's "objecthood," the less likely it is to be crowded by flankers similar to its parts relative to flankers similar to its configuration. Preliminary results appear to support this conjecture, showing that decreasing the proximity between the target parts, thereby decreasing the grouping between them (i.e., decreasing the strength of the target's "objecthood"), increases crowding by flankers similar to the target parts. Further research is required to systematically address these issues. Such research may have the potential of providing a diagnostic test for "objecthood."

Finally, the evidence presented here that crowding is not limited to low-level features or parts interactions, but can occur between high-level configural representations of objects, along with the evidence that grouping and overall configuration of flankers have a significant influence on crowding (e.g., Livne & Sagi, 2007, 2010; Manassi et al., 2012, 2013; Saarela et al., 2009, 2010), challenge not only the specific models of crowding, but rather the general view of hierarchical feedforward processing stages, which underlies these models (see Herzog & Manassi, 2015, for thorough review and discussion), and calls for assigning an important role for perceptual organization (Pomerantz & Portillo, 2011; Wagemans, Elder, et al., 2012; Wagemans, Feldman, et al., 2012) in models of vision.

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