Configuration influence on crowding

Tomer Livne
Department of Neurobiology, The Weizmann Institute of Science,
Rehovot, Israel

Dov Sagi
Department of Neurobiology, The Weizmann Institute of Science,
Rehovot, Israel

The influence of configuration on visual crowding was tested. Eight Gabor patches surrounding a central one were arranged in a way that created several global configurations differing by their internal arrangements (smooth contour vs. random), while still preserving pairwise relationships between the target and flankers. Orientation discrimination and contrast detection of the central Gabor were measured. These measurements revealed differences in the magnitude of crowding produced by the different configurations, especially on the discrimination task. The crowding effect was stronger when random configurations were used and was reduced considerably when a smooth one was used. These results showed the typical dependence of crowding on eccentricity and target–flanker separation, which was independent of the configural effect. Controlling flankers' local orientation allowed addressing the nature of the effect. It was found to be sensitive to spatial relations and did not represent a simple averaging of local orientation estimates. Our results show that crowding operates at a level where configuration information has already been extracted. We relate all this to the object-based nature of perception.

Keywords: crowding, configuration, visual periphery, orientation discrimination, contrast detection

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Introduction

The perception of a visual object is critically affected by spatial context, as demonstrated by phenomena such as crowding and masking. Crowding is a situation where the presence of flankers disrupts the observers' ability to identify a visual target. This definition is somewhat general and is often narrowed down by some experimentally obtained characteristics. In particular, crowding refers to a phenomenon that is observed when target and flankers are positioned within some critical distance in the visual field, which is considered to be about 0.5 of the eccentricity being used. This scaling has been demonstrated with letters, digits, and bars (Andriessen & Bouma, 1976; Bouma, 1970; Pelli, Palomares, & Majaj, 2004; Strasburger, Harvey, & Rentschler, 1991). Similar scaling was suggested to hold also for Gabor stimuli (Felisbert, Solomon, & Morgan, 2005; Levi, Hariharan, & Klein, 2002; Wilkinson, Wilson, & Ellemberg, 1997), although only partial tests were carried out. This spatial limit is largely independent of the elements' size (Levi et al., 2002; Pelli et al., 2004; Strasburger et al., 1991), thus allowing for relatively large separations between target and flankers. Crowding is thought to affect mainly identification and fine discrimination (He, Cavanagh, & Intriligator, 1997; Pelli et al., 2004), with detection of targets defined by luminance or luminance-contrast much less affected or not at all (Andriessen & Bouma, 1976). The situation in which flankers affect luminance or luminance-contrast detection is usually referred to as "masking," or more specifically, in the case of masking by flankers, as "lateral masking." Such masking effects typically show a critical range that depends on the elements' size and not on eccentricity (Polat & Sagi, 1993; Shani & Sagi, 2005). An exception was recently reported by Petrov and McKee (2006), where masking does scale with eccentricity rather than with target size, but the range they found was much smaller than that of crowding. Lateral-masking effects can be either positive (reduced contrast detection threshold) or negative (increased contrast detection threshold), depending on the target–flanker distance and the stimulus configuration (Polat & Sagi, 1993).

Crowding and lateral-masking effects were found to depend on target–flanker similarity. The most notable case is orientation selectivity, showing maximal effects when target and flanker assume the same orientation (crowding: Andriessen & Bouma, 1976; masking: Polat & Sagi, 1993; Shani & Sagi, 2005). In the present study, we considered the possible effect of flankers' configuration on crowding. Configuration effects reflect integrative processes within the visual system, being dependent on the relationship between the stimulus elements. Here we consider orientation-defined configurations that require spatial integration of local orientations. In lateral masking, detection thresholds are reduced in the presence of collinear (co-oriented and co-aligned) flankers (Polat & Sagi, 1993, 1994), thus showing both orientation selectivity and configuration dependence. Such interactions are thought to underlie the

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integration of contour segments. Contour integration was shown to be facilitated when the individual segments are aligned (Bonneh & Sagi, 1998, 1999; Field, Hayes, & Hess, 1993) and when the contour is closed (Kovács & Julesz, 1993). These effects are often described as a manifestation of the gestalt rules of good continuation and closure, and thus can be considered as corresponding to grouping processes. Such grouping processes, possibly producing low-level objects, may affect the allocation of attention within the visual field (Duncan, 1984). Thus, the effects of configuration on crowding may be expected either through integrative processes operating on the target and flankers (possibly segmenting the stimulus) or by the way attention is allocated to the stimulus.

The experiments described here tested whether crowding is dependent on the relations between the flankers themselves, that is, whether allowing for perceptual grouping of the flankers affects crowding. In addition, we tested the effect of target–flankers' spatial relations on crowding. The basic experimental design used here is similar to that of Andriessen and Bouma (1976), who studied orientation selectivity of crowding, but with some important differences. Andriessen and Bouma used a line target surrounded by eight iso-oriented lines serving as flankers, measuring orientation thresholds for the detection of the presence of tilt relative to a reference. Although there are many differences in the details of the stimuli and procedures used, the main differences in our view are that the present study (a) used Gabor signals instead of lines, (b) created different configurations of flankers while having the target surrounded by flankers of several different orientations, and (c) used an orientation discrimination task. The present experiments were divided into two parts: in the first part only the configural question was addressed, testing several configurations at a limited number of eccentricities and target–flanker separations. The results showed a clear effect of configuration on crowding. In the second part only two configurations were used, with the intention of testing how changing eccentricity and target–flanker separation would affect the results found in the previous stage, determining whether there was some scaling between these two parameters, and whether they interact with the configural factor.

General method

Apparatus and procedure

Experiments were done using a PC, with an NVIDIA Quadro4 980 XGL graphics adapter using a Diamond Pro 930sb screen (MITSUBISHI INC.); gamma correction was applied to produce displayed luminance with linear behavior. The mean screen luminance was 33 cd/m^2 in an otherwise dark environment.

The viewing distance in all experiments was 1 m. A fixation cross (0.5°) was located at the center of the screen during the whole experiment. In each trial it was presented alone for either 300 ms (part I) or 150 ms (part II), then a stimulus appeared for either 100 ms (part I) or 70 ms (part II), either left or right from fixation (orientation discrimination experiments) or on both sides simultaneously (detection experiments). After the presentation time (100 or 70 ms), only the fixation cross remained on the screen and subjects gave their response using the mouse keys. The experiments were self-paced and the subjects initiated each trial by pressing a key.

Stimuli

Stimuli consisted of 6 cpd Gabor patches (Figure 1), which are defined by wavelength λ, and *SD* of the Gaussian envelope σ, in this case $\lambda = \sigma = 0.16°$ (see Polat & Sagi, 1993). The stimulus was composed of flankers arranged on an imaginary circle centered on the target (Figure 1). To evaluate whether configural information created by the global arrangement of flankers

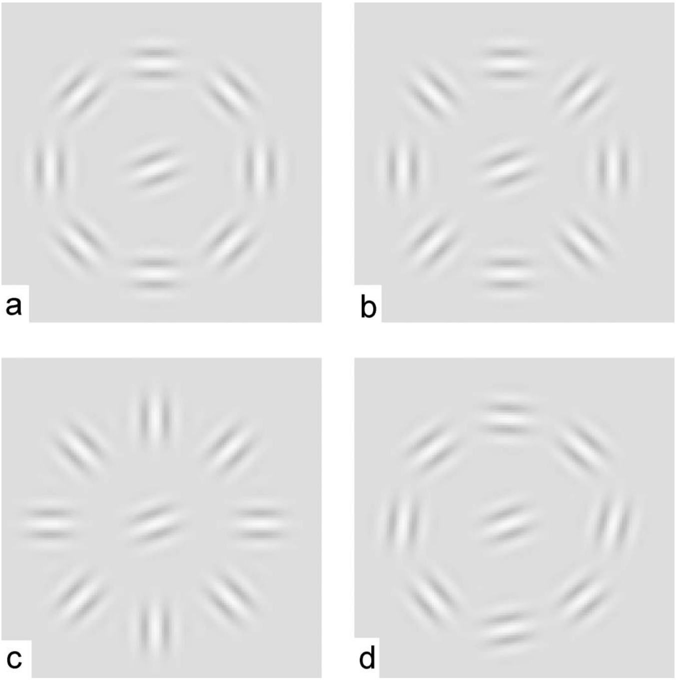

Figure 1. Stimuli used in the experiment; the central Gabor was the target, the eight Gabors surrounding it are referred to as flankers. In panels a, b, and c the flankers' orientations are identical and only their position relative to the target is different. In panel d, each Gabor was independently tilted in each trial by 15°. In the remainder of the paper, we refer to these configurations as follows: (a) smooth contour; (b) interrupted contour; (c) sun; (d) jitter contour. In this example, the target–flanker separation is 4.8σ, far enough to establish that they will excite different receptive fields.

surrounding a target affects the crowding effect, we created four main configurations each of which had eight flankers surrounding a central target. In an additional condition there was only a target with no flankers (considered as the base line measurement). In one configuration the flankers created the impression of a closed circular contour (referred to as "smooth contour" condition). Two additional configurations were symmetric shapes with no collinear continuation between adjacent flankers. In one of these the position of four patches was changed ("interrupted contour" condition); in the other the position of the remaining four patches was also changed, creating a circle defined by perpendicular Gabors ("sun" condition). Thus, the overall local Gabors' orientations were identical but on each configuration they were placed at different locations around the target. The fourth configuration was similar to the first one but each patch was given a random jitter of 15° on each trial ("jitter" condition) (see Figure 1). In all four configurations the target–flankers' separation was identical. In some of the experiments, several manipulations to these configurations were introduced; these will be explained in the appropriate sections.

Tasks

We had subjects perform two tasks in different experiments: orientation discrimination and spatial 2AFC contrast detection. In the orientation discrimination task the subjects were asked to report only the orientation of the central target (left vs. right tilt from the horizontal orientation), appearing randomly to the left or right of the fixation cross. Each configuration was tested separately, with two interleaved staircases, one for each visual field. In the detection task the same flankers' configuration appeared on both sides of the fixation cross simultaneously and the subject had to indicate on which side a horizontal Gabor target appeared.

Data collection

A staircase method was used in which the tested parameter's amplitude increased by 25% after a wrong response and decreased by the same factor after three consecutive right responses. Eight such reversals were allowed, and only the last six were taken into account. This method was shown to converge to 79% correct response (Levitt, 1971), which was treated as threshold. In the discrimination experiment, a 40° orientation deviation from the horizontal was set as an upper bound and crossing it three times resulted in the termination of the block.

Results were averaged across sessions. They are log transformed and are presented as threshold elevation, calculated by subtracting the threshold of the target-only condition (treated as the base threshold) from each condition separately. Error bars in all graphs represent the standard error (*SE*) of the log data.

Subjects

Six subjects participated in the experiments: five of them were paid for their participation and were naïve to the purpose of the experiment. TL is the first author.

Part I—Effects of configuration on crowding

Orientation discrimination with same contrast target and flankers

Stimuli and procedure

The four configurations (see Figure 1), and the base line condition, described above were used; the task was orientation discrimination. Each session was repeated twice, resulting in four independent measurements for each configuration. Targets were displayed at 2.5° eccentricity, with a center-to-center target–flanker separation of 4.8σ (0.76°), subjects RK, TL, and AL. In addition, subject AL performed the task at 2.5° eccentricity with a separation of 3.2σ (0.51°) and at 5° eccentricity with separations of 3.2σ (0.51°) and 6.4σ (1.02°)

The flankers and the target had the same contrast, either 78% (RK, TL, and AL) or 20% (RK and TL) within different sessions.

Results

Results are presented in Figure 2. At 2.5° eccentricity with 0.76° separation, there was either a modest or no threshold elevation at all with the smooth contour configuration, elevation of −0.13, 0.07, and 0.24 log units with 78% contrast stimuli (subjects RK, TL, and AL, respectively), and −0.02 and 0.04 log units with 20% contrast stimuli (RK and TL). With the interrupted contour configuration, a stronger threshold elevation was measured: 0.46, 1.05, and 0.66 with 78% contrast (RK, TL, and AL, respectively) and 0.58 and 0.51 log units with 20% contrast (RK and TL, respectively). This is an average difference of 0.61 log units between the smooth and interrupted configurations (across subjects and contrasts levels). A similar although smaller-in-magnitude pattern of results was found with the sun configuration, an elevation of 0.37, 0.55, and 0.57 log units with 78% contrast (RK, TL, and AL, respectively) and of 0.29 and 0.46 log units with 20% contrast (RK and TL, respectively). Under the jitter contour

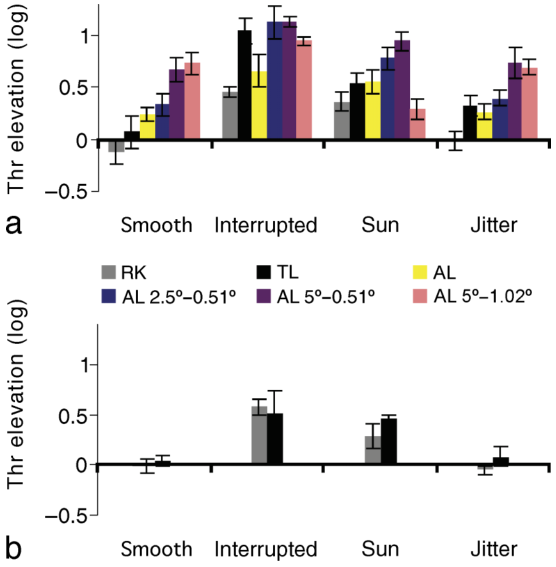

Figure 2. Orientation discrimination task—right/left tilt; 2.5° eccentricity, target–flanker separation of 0.76°; (a) target and flankers' contrast 78%; (b) target and flankers' contrast 20%. In both panels a and b, the same pattern of results was found; with the interrupted contour configuration thresholds increased considerably more than with the smooth contour configuration, with a difference of up to 0.97 log units. Similar differences, although sometimes smaller, were found between the sun and the smooth contour configurations; these were up to 0.48 log units. These results indicate a strong configural effect.

condition, RK had no threshold elevation: −0.02 and −0.05 log units (78% and 20% contrast, respectively), whereas TL had some elevation also under this condition: 0.32 and 0.08 log units (for 78% and 20% contrast). AL also had some threshold elevation with the jitter configuration, 0.27 log units.

Using 0.51° separation, subject AL was tested at both 2.5° and 5° eccentricity to verify that the results are not limited to the previously used parameters (separation and eccentricity values). Indeed, the results were similar in nature, with some increase in the threshold elevations at 5°. Thresholds were elevated by 0.34 and 0.68 log units with the smooth contour configuration (2.5° and 5° eccentricity, respectively), 1.13 log units with the interrupted contour configuration at both eccentricities, 0.78 and 0.94 with the sun configuration, and 0.4 and 0.74 log units with the jitter contour. At 5° with a separation of 1.02° AL's thresholds were elevated with all configurations, 0.73, 0.95, 0.29, and 0.70 (smooth, interrupted, sun, and jitter contour, respectively). The smaller magnitude of the configural difference (between the smooth and the interrupted contour configuration) measured at 5° with the 1.02° separation compared to the one obtained with a 0.51° separation is consistent with the results reported in part 2 (see below), where this issue was addressed systematically.

We performed a repeated measure analysis of variance (ANOVA) on these results and found a significant effect of configuration, $F(3,5) = 20.01$, $p = .003$. To further test the effect, we conducted paired sample t tests, comparing the different conditions, correcting the α level using the Bonferroni correction to prevent type I errors (the p values presented are uncorrected). We found a significant difference between the smooth and interrupted configurations, $D = 0.56$, $t(7) = 6.78$, $p < .001$; between the sun and interrupted configurations, $D = 0.28$, $t(7) = 3.69$, $p = .008$; and between the jitter and interrupted configurations, $D = 0.5$, $t(7) = 8.19$, $p < .001$. The difference between the smooth and sun configuration was not significant, $D = 0.28$, $t = 2.62$, $p = .034$; the difference between the smooth and jitter condition also was not significant, $D = 0.06$, $t(7) = 1.85$, $p = .106$; and the difference between the jitter and sun configurations was also not significant, $D = 0.22$, $t(7) = 2.4$, $p = .048$.

Effects on detection

As indicated in the introduction, crowding is expected to affect discrimination and detection of a target differently, that is, to affect discrimination but not detection. To verify that our stimuli could be considered as representing a crowding situation, we had our subjects perform the contrast detection task, in addition to the orientation discrimination task.

Procedure

We again used the same configurations as before but now had our subjects perform the spatial 2AFC contrast detection task. Targets were displayed at 2.5° eccentricity, with a center-to-center target–flanker separation of 4.8σ (0.76°) for subjects RK, TL, and AL. Subjects TL and AL were tested also at 5° with a separation of 6.4σ (1.02°). In different sessions the flankers assumed either 78% (RK, TL, and AL) or 20% (RK and TL) contrast level.

Results

At 2.5° eccentricity with a target–flanker separation of 0.76°, detection thresholds were hardly affected by the presence of flankers; at 20% contrast the results were 0.02 and 0.03 log units for the smooth contour configuration (RK and TL); 0.08 and 0.07 log units for the interrupted contour; 0.14 and 0.01 log units for the sun configuration; and −0.06 and 0.07 log units for the jitter configuration. At 78% contrast, the results were −0.01, 0.05, and 0.05 log units for the smooth contour configuration (RK, TL, and AL); −0.12, 0.04, and 0.00 log units for the interrupted contour; 0.00, 0.00, and 0.14 log units for the sun configuration; and −0.01, 0.03, and −0.03 log units for the jitter configuration (see Figure 3). At 5° eccen-

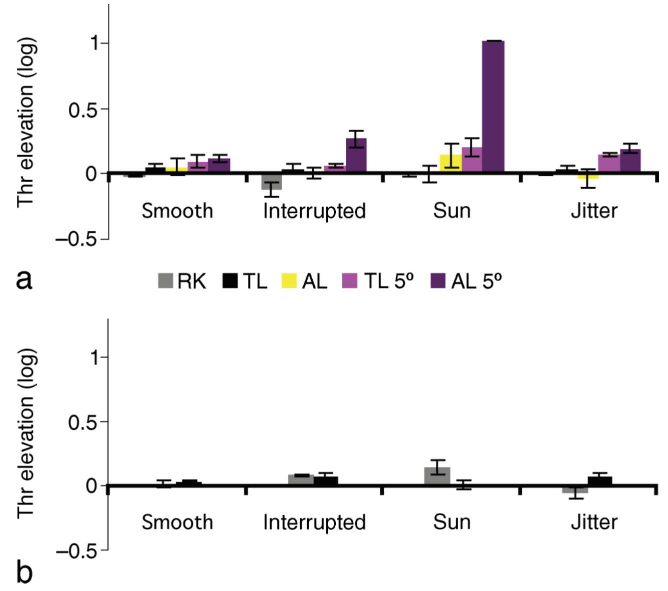

Figure 3. Spatial 2AFC contrast detection task; (a) Flankers' contrast 78%, target at 2.5° with a target–flanker separation of 0.76° (RK, TL, and AL); (b) Target at 2.5° eccentricity, flankers' contrast 20%, target–flanker separation 0.76°.

tricity (with flankers at 78% contrast), thresholds were somewhat more affected, with elevations of 0.01 and 0.12 with the smooth contour; 0.06 and 0.27 with the interrupted contour; 0.2 and 1.02 sun configuration; and 0.15 and 0.19 with the jitter contour (all results are of TL and AL, respectively). We performed a repeated measure analysis of variance (ANOVA) on these results and found no significant effect of configuration, $F(3,4) = 0.86$, $p = .53$.

In the above sections, we measured differences between the different conditions (configurations). To directly evaluate the presence of crowding, a one-sample t test was conducted on each condition. At the discrimination task, the results (threshold elevation, TE) of three configurations were found to be significantly different from zero: interrupted contour, TE = 0.81, $t = 8$, $p < .001$; sun, TE = 0.53, $t = 6.37$, $p < .001$; and jitter contour, TE = 0.3, $t = 2.86$, $p = .024$. The smooth contour was not found to be significantly different from zero, TE = 0.24, $t = 2.17$, $p = .067$. At the detection task, only the smooth contour's results were significantly different from zero, but by a negligible difference, 0.05 log units, TE = 0.05, $t = 3.01$, $p = .02$. All other configurations' results were not significantly different from zero, $p > 0.167$. This difference between detection and discrimination supports our initial assumption that the stimulus sets we created indeed cause crowding, as practically defined in the literature (e.g., Pelli et al., 2004).

In the discrimination task we found a strong effect of flankers' global configuration on the threshold for discrimination of a Gabor target's orientation. The fact that the configurations were composed of the same Gabors, differing only with respect their relative location (except for the jitter contour where random orientation jitter was introduced), and still different magnitudes of the crowding effect were measured (e.g., an average difference of 0.57 log units between the smooth and interrupted contour across all measurements), indicates that features are not free floating when crowded (Pelli et al., 2004) and that crowding is not simply produced by pooling all the orientation estimates in the array (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001).

Orientation discrimination with target and flankers having different contrasts

Stimuli

We repeated the orientation discrimination experiment with two subjects (RK and TL), this time the target and flankers having different contrast levels. We had either the flankers at 78% contrast and the target at 20% contrast, or vice versa, the flankers at 20% contrast and the target at 78% contrast. The two contrast combinations were tested at separate sessions. The configurations and task were identical to those used in the previous experiment. The target was placed at an eccentricity of 2.5°, with a target–flanker separation of 4.8σ (0.76°).

Results

When the target was at a low contrast (20%) and the flankers were at a high contrast (78%), the same pattern as in the previous experiment was observed: there was a large elevation of threshold with the interrupted contour configuration 0.46 and 0.59 log units (RK and TL), which was also found with the sun configuration 0.34 and 0.47 log units (same subjects). There was no elevation of threshold in the smooth contour condition −0.04 and −0.02 log units, and in the jitter contour condition 0.06 and 0.07 log units (RK and TL, respectively) (see Figure 4a).

In contrast, when the target was at a high contrast and the flankers were at a low contrast, no threshold elevation occurred (except under one condition with TL), with the following results: smooth contour −0.32 and −0.02, interrupted contour −0.25 and 0.02, sun −0.12 and 0.16, and jitter contour −0.26 and 0.0 (all results are from RK and TL, respectively, and are presented in log units; see Figure 4b).

We ran a paired sample t test comparing the results of these two conditions, comparing each subject's result with each configuration on both contrast combinations. We found them to be significantly different, $D = 0.34$, $t(7) = 2.36$, $p = .005$, with a stronger threshold elevation in the high contrast flankers condition than in the low contrast flankers condition. Our results are consistent with those of Kooi, Toet, Tripathy, and Levi (1994), who

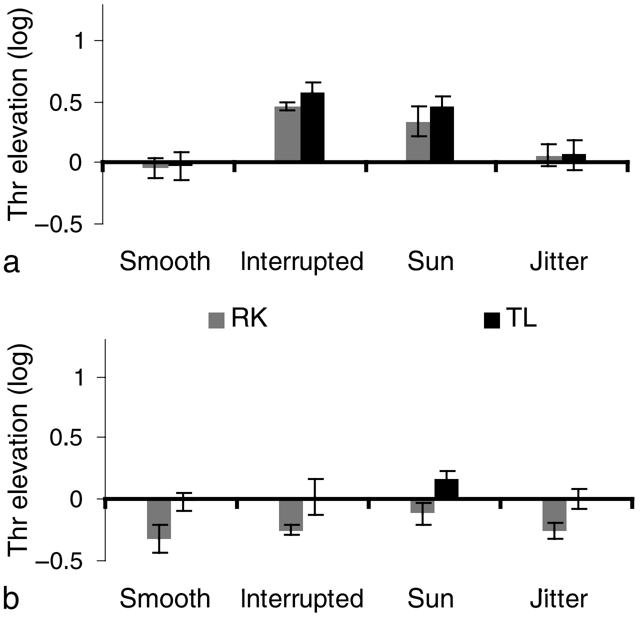

Figure 4. Orientation discrimination task, with target and flankers of different contrasts. (a) Target at 20%, flankers at 78%; (b) target at 78%, flankers at 20%. In panel a the pattern of results was similar to the one found in the same-contrast experiment, with strong crowding with the interrupted and sun configurations, and no crowding with the smooth and jitter configurations. In panel b, where the target's contrast is about four times the flankers' contrast, a different pattern of results was found. Most noticeably there was almost no threshold elevation, that is, no crowding, under most conditions. Also differences between the interrupted contour and the smooth contour configurations were less than 0.1 log units, and the lowest performance was observed with the sun configuration. This points to asymmetric relations between the target's and flankers' contrasts.

reported a similar target–flanker contrast ratio asymmetry in crowding. This can be seen as further evidence that the situation we created should be considered as crowding.

Test for an additive effect in configural crowding

Stimuli

This experiment was designed to test an additive explanation for the difference found between three of the above configurations (smooth contour, interrupted contour, and sun). As mentioned above, all three were composed of the same Gabors, only at different positions. Moreover, in each pair, four patches were at the same locations and the other four were displaced. Because on most conditions a stronger crowding effect was found in two out of the three configurations (interrupted and sun), it is possible that the effect was due to the pattern created by the four patches arrangements, which was not present in the smooth contour configuration. Thus, four new configurations were tested to see whether they would create crowding. Each configuration was created by removing every other patch from one of the three configurations (smooth contour, interrupted contour, and sun). The task was orientation discrimination. Two subjects participated, TL and RK.

Results

Threshold elevations of varying magnitudes were observed with three of the configurations for TL: 0.45, 0.23, and 0.22 log units, with the forth configuration producing only a slight threshold increase of 0.08 log units. RK had threshold elevation with only two configurations: 0.15 and 0.33 log units, and none with the other two: 0.00 and 0.02 log units. The configuration that produced the strongest threshold elevation was the one present only in the sun configuration (the results and configurations are presented in Figure 5).

Although crowding was found, the pattern of the results can rule out additivity as an explanation for the results reported in the previous sections. In both subjects, the sum of the threshold elevations measured for the configurations composing both the smooth contour (configuration 1 and 3 in Figure 5) and the interrupted contour (configurations 1 and 4 in Figure 5) yielded the same results. An additive explanation for the difference observed between the two configurations would require a difference in the threshold elevation caused by the two right configurations in Figure 5 (configuration 3 taken from the smooth contour, and configuration 4 taken from the interrupted contour). Whereas the two original configurations differ in these two subjects by 0.58 and 0.97 log units (RK and TL, respectively), there are no differences

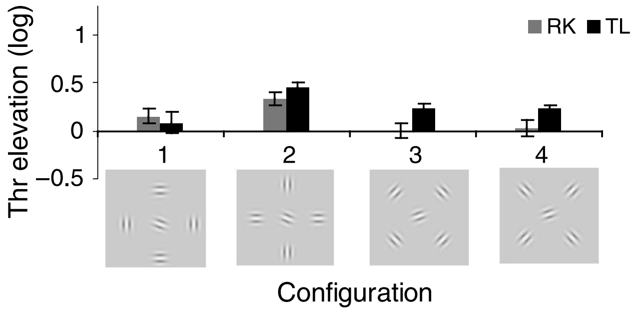

Figure 5. Test for additivity. Discrimination task; here we tested the crowding produced by the partial configurations that three of the original configurations share or differ by. Configurations 1 + 3 create the smooth contour configuration; 1 + 4 the interrupted contour; and 2 + 4 creates the sun configuration. If the difference in the effects observed for the three configurations was due to these differences, then we would expect the rightmost configuration to produce the strongest effect, which is clearly not the case. In fact it was found to produce the same effect as its substitute in the smooth contour configuration (second from the right).

in the effects caused by the partial configurations by which they differed.

Continuation and closure as explanations for the reduced crowding effect under the smooth contour condition

Because the additive explanation was ruled out, we decided to try to explore alternative explanations for the configural differences that were found. We examined continuation and closure as the source for the reduced crowding under the smooth contour condition. To do so, we introduced several modifications to this configuration (see Figure 6) and tested how they would affect the discrimination thresholds. First, each of the Gabors was removed separately, creating a gap anywhere in the contour (an example for this is the leftmost data point in Figure 6). Next, pairs of opposite patches were removed; this was done to break the physical continuity of the Gabor signals (next four configurations). In the third manipulation, instead of removing the pairs, they were replaced with orthogonal Gabors, thus maintaining physical continuity while breaking only the contour's collinearity (next four configurations). Two configurations were added where every adjacent pair of patches was taken from one of the original configurations (the two rightmost configurations of Figure 6). This can also be seen as combining two configurations from the previous manipulation and it was done to again address the question of additivity, but this time when physical continuity was preserved. The task was again orientation discrimination. Subject RK only.

Results

No threshold elevation was observed when a single Gabor was removed from the smooth contour configuration (0.01 log units). The effect of removing a pair of opposite patches depended on which pair was removed, elevating thresholds by 0.17, 0.03, −0.1, and 0.32 log units. A stronger threshold elevation was observed when collinearity was interrupted, and as with the continuity break there was variability in the magnitude: 0.07, 0.98, 0.34, and 0.52 log units. The results of the last manipulation also varied considerably and the elevations were 0.17 and 0.68 with the different configurations. The pattern with all three manipulations was similar and the lowest performance was observed when the horizontal pair was the one changed (see Figure 6).

From the results of these manipulations, a stronger support for the rejection of a simple signal pooling explanation for crowding is obtained, especially because both physical continuity and collinearity seem to affect the extent of the effect. Closure does not seem to be essential for the reduction of crowding to occur, at least when only one patch is removed and collinearity of the remaining ones is preserved.

Part II—The extent of configural selectivity in crowding

In this experiment, separation and eccentricity scaling were tested. We used two eccentricities and various separations; we measured the effects that these manipulations had on the same subjects to define the spectrum and ratio of this scaling. We were also interested to see whether the configurational differences are independent of this scaling.

Subjects and procedure

Three subjects participated (OE, AG, and OG), only two configurations were used: smooth contour and interrupted contour. Subjects were tested separately on different occasions on each eccentricity; each measurement was repeated three times. Each block consisted of two interleaved staircases, one for each visual field (discrimination experiment); on each block a different configu-

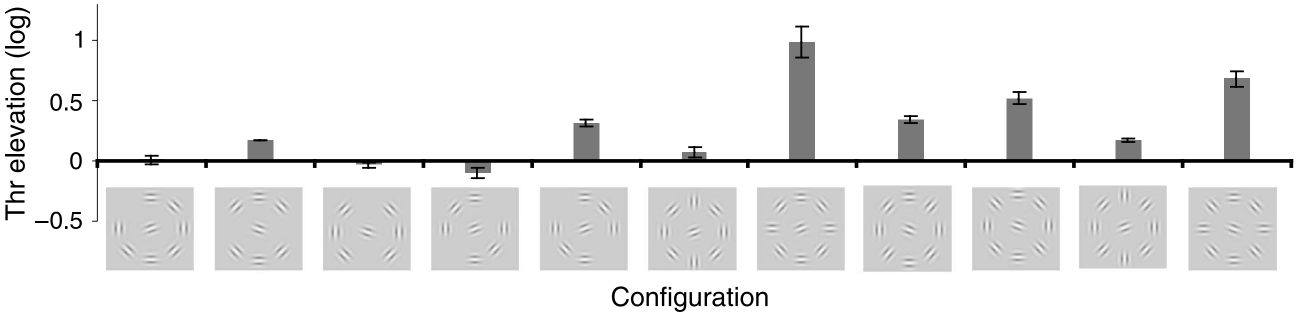

Figure 6. Closure and continuation effect, RK only (configurations and the threshold elevation they produced: refer to the text for explanations).

ration and/or different target–flanker separation were used. Two tasks were measured separately: orientation discrimination and spatial 2AFC contrast detection.

Results

Because we expected crowding to affect our subjects' performance in the discrimination task but not in the detection task, we treated the results separately and conducted statistical analysis independently for each task.

Threshold elevation was measured at two eccentricities (2.5° and 5°) and with eight different target–flanker separations (only five at 2.5°). As shown in Figure 7 (left column), in the discrimination task there are differences in the threshold elevations caused by the two configurations, at least with the smaller separations. Lower thresholds for the smooth contour configurations were measured at 2.5° up to 1.02°, 1.53°, and 0.76° separation, at 5° it held up to 2.04°, 0.76°, and 1.53° in different subjects (OE, AG, and OG, respectively). A two-way ANOVA was conducted on the discrimination results (shared separations of 0.51°–2.04°), with configuration (two levels—smooth and interrupted) and eccentricity (two levels—2.5° and 5°) as the independent variables and threshold elevation as the dependent variable; a main effect was found for configuration, $F(2,1) = 557.78$, $p = .002$. No main effect of eccentricity was found, $F(2,1) = 7.64$, $p = .11$; also no interaction was found, $F(2,1) = 0.17$, $p = .72$. To also test for interactions with target–flanker separation, we ran the test again only over the first three separations (0.51°–1.02°), this time with separation as an additional independent variable (3 levels). The main effect of configuration remained, $F(2,1) = 260.17$, $p = .004$, and

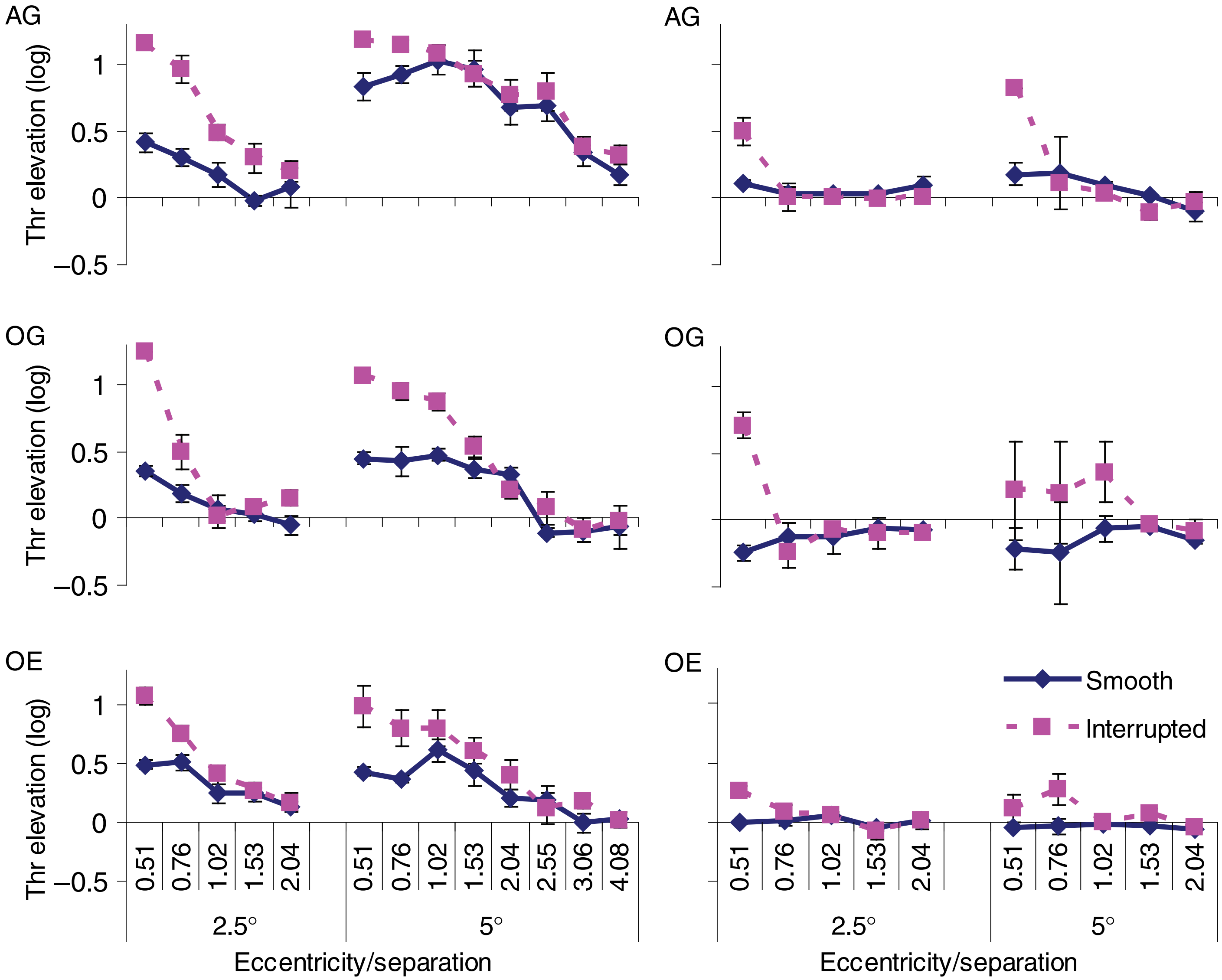

Figure 7. The extent of the configural effect as a factor of target–flanker separation and eccentricity in discrimination (left column) and detection (right column).

an eccentricity–separation interaction also emerged, $F(2,1) = 198.46$, $p = .05$. No other effects were found.

In the detection task (Figure 7, right column), differences were found only with 0.51° separation at 2.5° eccentricity (all subjects) and at 5° differences were found up to 0.76°, 0.51°, and 1.02° (OE, AG, and OG, respectively). A two-way ANOVA conducted on the detection results (shared separations of 0.51°–2.04°), with configuration (two levels—smooth and interrupted) and eccentricity (two levels—2.5° and 5°) as the independent variables and threshold elevation as the dependent variable found no effects: configuration, $F(2,1) = 6.95$, $p = .12$; eccentricity, $F(2,1) = 1.45$, $p = .35$; configuration-eccentricity interaction, $F(2,1) = 15.11$, $p = .06$.

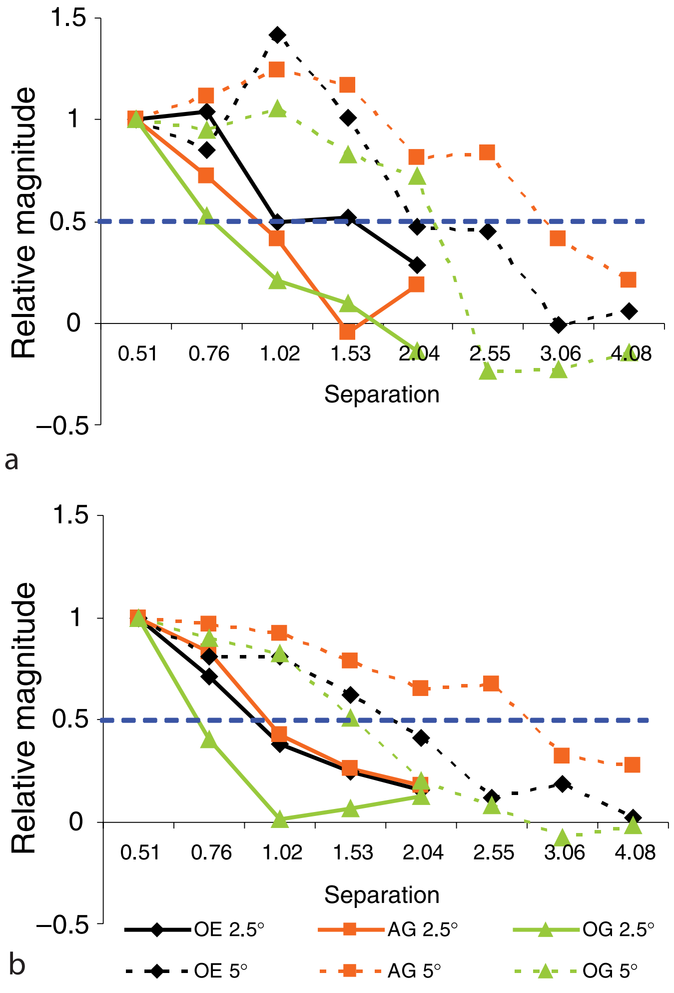

Figure 8. Threshold elevation results normalized according to the smallest separation value (0.51°) of the same eccentricity. (a) Smooth contour; (b) interrupted contour. The horizontal dashed line represents half the magnitude of crowding compared to the 0.51° separation reference. Using a Gaussian fit we found the average distance at which half the magnitude of the effect was reached: for the smooth contour, M = 1.03°, SE = 0.23 and M = 2.37°, SE = 0.39 (2.5° and 5° eccentricity, respectively); and for the interrupted contour, M = 0.92°, SE = 0.11, and M = 1.98°, SE = 0.47 (2.5° and 5° eccentricity, respectively). This indicates that the range of crowding increases with increasing eccentricity.

We re-present in Figure 8 the results shown in Figure 7, normalized to the results obtained with the smallest separation (0.51°) in each eccentricity. This provides a better graphical presentation of the dependence of separation on eccentricity. The results are plotted separately for each configuration in Figure 8 (a, smooth contour; b, interrupted contour). The horizontal dashed line represents half the magnitude of the 0.51° results and is drawn on the graph to provide an easy comparison reference. We fitted each of the data sets using a Gaussian fit and averaged the results. The results of the fits showed that at 2.5° eccentricity, half the magnitude of the effect was reached at 0.43 and 0.46 of the separation needed for the same result at 5° (results are for smooth and interrupted contours, respectively). This shows that the critical range for crowding increases with increasing eccentricity. Our results indicate that scaling and the configural effect operate independently in crowding.

The direct evidence presented here for Gabor signals, showing scaling of this critical distance with eccentricity, points to the limitation of a receptive-field-based account for crowding. In the present study, the scale of the low-level receptive fields that are sensitive to the stimuli did not vary significantly with eccentricity because Gabor signals of an equal, band-limited scale were used. Previous results concerning scaling using letters or bars that activate receptive field of different sizes could be explained, at least in part, by the shift of processing to larger receptive fields with increasing eccentricity. Such a shift in processing is expected from the dependency of the processing scale on eccentricity found in the retina and cortex.

General Discussion

The results described here show a strong crowding effect on the discrimination of orientation when using Gabor stimuli as target and flankers. A configural effect on crowding was found; different spatial arrangements of identical flankers produced a different amount of interference with the discrimination of a target, as evaluated by the elevation of thresholds. Collinear arrangement of the flankers in a continuous, closed, or incomplete circular configuration resulted in small or no crowding effects; arranging the same flankers along the same circle but without collinear continuity resulted in considerably more interference. This pattern was observed across eccentricities (2.5° and 5°) and target–flanker separations. It was also found across contrast levels (20% and 78%). The only exception was when the target was at a high contrast and the flankers were at a low contrast in which case no crowding was observed with any configuration. Several possible explanations for the configural effect were tested and rejected: additive effects of local target–flanker spatial relations and physical continuity. Collinear continuity was found to be the most determining factor contributing to the effect. Eccentricity separation scaling was observed and was found to be independent from the configural effect.

Our results were obtained with relatively simple stimuli, Gabor patches, and task orientation discriminations. Nevertheless, they were found to be similar to those obtained with more complex stimuli (e.g., letters, digits, and bars) and with different tasks. Although we were not the first to use Gabors in crowding experiments (Felisberti et al., 2005; Levi et al., 2002; Parkes et al., 2001; Wilkinson et al., 1997), some critical comparisons were missing, especially eccentricity separation scaling. The similar behavior of different types of stimuli in crowding (e.g., critical spacing, scaling, and contrast asymmetry) seems to indicate either a similar processing level or similar rules governing different processing levels. In the following sections, we will consider several explanations or models suggested for crowding and discuss them in light of our new results.

Previous explanations for crowding

Spatial averaging

Parkes et al. (2001) suggested that crowding is related to texture perception. According to their "compulsory averaging" model, in crowded arrays, target and flankers are processed independently and their individual orientations are computed but only their spatial average is available for reporting. One of the properties of our flankers' arrangements was that the mean orientation was the same in all trials and in all configurations. In such a situation, the orientation averaging model predicts a crowding effect that depends on the number of flankers, but not on their orientation or configuration. The results clearly show that thresholds differed between configurations, despite their equal number of flankers, thus ruling out models that are based on spatial averaging of local orientation. Such a conclusion is consistent with earlier results showing orientation selectivity of the crowding effect (Andriessen & Bouma, 1976; Solomon, Felisberti, & Morgan, 2004).

Spatial resolution

According to one explanation for crowding, crowded percepts are the product of an inappropriate feature integration process (Pelli et al., 2004). According to this explanation, crowding occurs when subjects have to identify a complex feature in the stimuli. To do so, they have to integrate the outcome of several basic feature detectors. This integration is suggested to be carried out within an integration field, which operates over increasingly larger areas as one moves further into visual periphery. As a result from this integration fields' size limitation, in crowded displays, even when centered on the target, the integration process incorporates information also from flankers' signals. Thus, according to this explanation, the extent of crowding is determined exclusively by target–flanker separation and its ratio with eccentricity. A consideration of our configural effect strongly suggests that such an explanation may at least be incomplete. If crowding was the consequence of only such hard-wired spatial mechanisms, then no differences would be expected from the different configurations used here because all were tested using the same target–flanker separation (center-to-center).

According to another explanation, crowding represents an attentional resolution limitation (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001). According to this explanation, crowding is assumed to result from poor attentional acuity that prevents subjects from attending to or selecting only the target, despite the fact that they can detect its presence due to their more refined visual acuity. Although the limitation here is a critical spacing that scales with eccentricity, as in the previous account, the interference is also modulated by late selection processes. Interference according to this model is assumed to occur only from flankers that are compatible with the target along its defining dimension (e.g., spatial frequency or color). Grouping may reduce the individual flankers' representation and hence reduce crowding (see details below).

Positional uncertainty

Crowding can also be the result of positional uncertainty (Huckauf & Heller, 2002; Strasburger, 2005). According to this type of explanation, spatial localization is limited and thus crowding is the result of reporting on a flanker instead of the target. Unlike in the feature integration account where features are "free floating," here complete objects are not localized or are assigned wrong locations. At the extreme form of this account, each stimulus part (target and flankers) is being processed uninterrupted and independently. However, unlike the attentional resolution account where the target is always selected, alone or together with flankers, here only one object is eventually selected, either the target or a flanker. This account is supported by results showing that in letter crowding experiments, subjects incorrectly report on a flanker letter more often than on a letter not present in the display (e.g., Huckauf & Heller, 2002; Strasburger, 2005). In contrast to this, in the same experiments, an additional considerable number of mistakes were reports of a letter different from both the target and flankers. In its basic form, the positional uncertainty explanation could not account for the configural effect. However, configural effects can be incorporated into this account if positional or categorical tags are assigned to objects such as contours. The categorical and semantic content of the flankers has been previously found to affect crowding (Huckauf, 2006; Huckauf, Heller, & Nazir, 1999).

The configural effect

A saliency account

Felisberti et al. (2005) tested the role of target saliency in crowding and concluded, based on their results, that the target's saliency can attenuate the effect (see also Andriessen & Bouma, 1976). They manipulated saliency by several means (contrast, orientation, and depth information). We also tested the effect that relative target contrast has and found similar results, with an abolishment of crowding when the target's contrast exceeds by approximately four times that of the flankers. However, in the present experiment a different kind of saliency may also be considered, one that is created by orientation contrast. In a pairwise consideration, adjacent flankers in the different configurations differ by the contrast they produce. As Rubenstein and Sagi (1990) demonstrated, in the context of texture segmentation, orientation differences between background elements compete with orientation differences that mark target–background boundaries, thus reducing the efficiency of target detection (and localization). In the present research, this can correspond to the different orientation contrasts produced by adjacent pairs of Gabors in each configuration. In the smooth contour there is a gradual change in the flankers' orientation, which produces little competition with the target–flanker contrasts. This results in defining the target as the only salient region, thus enabling good performance under the smooth condition (less crowding). In the random contours there is a strong contrast between the pairs that create several additional salient regions that are expected to compete with the target and to reduce performance.

A grouping account

When considering the global arrangement of the flankers in the present experiment, one might expect better grouping to be produced by the smooth contour. Grouping according to local orientation similarity is assumed to occur at early visual processing stages (Bonneh & Sagi, 1998, 1999; Field et al., 1993; Gilbert, 1998; Polat & Sagi, 1993, 1994). Such an explanation puts crowding at a processing stage that deals with low-level visual objects, such as contours, rather than with elementary features such as orientation. In a way, this explanation is similar to that offered by the "saliency" account because both refer to the decrease of orientation continuity with the random contours, but grouping assumes, in addition, the creation of behaviorally relevant objects (to some extent, this view is compatible with the attentional resolution account; He et al., 1996; Intriligator & Cavanagh, 2001). Further research is required to decide which of these two accounts (local saliency or grouping) fairs better, or to integrate them in a single theoretical framework.

Conclusions

Based on the present results, we conclude that crowding cannot be predicted and hence cannot be accounted for only by target–flanker separation or its ratio with eccentricity. When crowding occurs, spatial relations are taken into account. From this it follows that crowding does not operate prior to the linking of local orientations. Like other visual processes, crowding is sensitive to the presence of object information—here a collinear contour created by the flankers. Such information, when present, can neutralize it completely.

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Corresponding author: Dov Sagi.
Email: Dov.Sagi@weizmann.ac.il.
Address: Department of Neurobiology, The Weizmann Institute of Science, Rehovot 76100, Israel.

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