Emergent features in the crowding zone: When target–flanker grouping surmounts crowding

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Crowding is the impairment of target identification when the target is surrounded by nearby flankers. Two hallmarks of crowding are that it is stronger when the flankers are close to the target and when the target strongly groups with the flankers. Here we show the opposite of both. A chevron target (pointing up or down) was presented at 8° eccentricity in the right visual field. It was surrounded by four flankers. Three of the flankers varied (pointing left or right). The fourth, the *critical flanker* (CF), was fixed in one orientation (left, right, up, down), yielding different configurations with the target. The CF's distance to the target was varied. Target identification depended strongly on the distance and the orientation of the CF. Remarkably, when the target and the CF grouped into a good configuration and elicited an emergent feature, performance was high if the CF was close to the target. This effect was particularly strong when participants were informed about the different CF-target configurations before the experiment. Reducing crowding and grouping by asynchronous presentation of the CF and the other items abolished the effect. When participants reported the entire configuration of the CF and the target, performance rapidly decreased with increasing spacing when the CF and the target were different but not when they were the same, indicating different spatial extents of the corresponding grouping processes. Our results show that the features emerging from the configurations of the target and a flanker strongly modulate crowding. Strong target–flanker grouping can benefit performance.

Introduction

Identification of a target surrounded by flankers is impaired by crowding (Bouma, 1970, 1973; He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001; Latham & Whitaker, 1996; Levi, Klein, & Aitsebaomo, 1985; Pelli, Palomares, & Majaj, 2004; Toet & Levi, 1992; Strasburger, Harvey, & Rentschler, 1991). For example, a target letter that can be identified when presented alone is difficult to identify when flanked by other letters (see Figure 1a). Crowding is a fundamental limit to visual perception (e.g., Whitney & Levi, 2011) which is particularly strong in peripheral vision (Latham & Whitaker, 1996; Levi, Hariharan, & Klein, 2002; Levi, Klein, & Hariharan, 2002; Toet & Levi, 1992). While the mechanisms underlying crowding are not yet known, several properties have been identified that give a detailed characterization of it.

One of the key characteristics of crowding is its dependence on the spacing between the target and the flankers (Bouma, 1973; Kooi, Toet, Tripathy, & Levi, 1994; Toet & Levi, 1992). Flankers usually interfere with target perception only when presented within a certain region around the target—the crowding zone (e.g., Toet & Levi, 1992). The shape of the crowding zone is anisotropic. Flankers located radially have an effect over a larger distance compared to flankers located tangentially (Petrov & Meleshkevich, 2011; Petrov, Popple, & McKee, 2007; Toet & Levi, 1992). Crowding depends strongly on the similarity of the target and the flankers on several dimensions, with
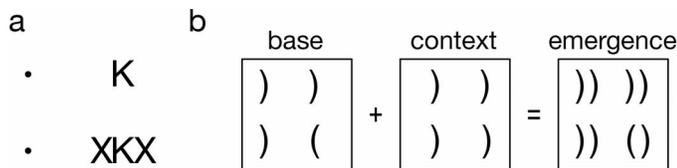
Figure 1. (a) A demonstration of crowding. When an observer fixates on the dot, identification of the letter presented alone (top row) is easier compared to identification of the letter surrounded by flankers (bottom row). (b) Parenthesis stimuli adapted from Pomerantz and Garner (1973). Discrimination of parentheses in an odd-quadrant task was slower when presented alone (base) compared to the presentation within a fixed context (context) because of emergent features (emergence).

stronger crowding when the target is similar to the flankers, for example, with respect to shape, depth, color, and contrast polarity (Bernard & Chung, 2011; Kooi et al., 1994; Manassi, Sayim, & Herzog, 2012, 2013; Põder, 2007; Sayim, Westheimer, & Herzog, 2008, 2010; Zahabi & Arguin, 2014). A number of recent studies have shown how crowding not only deteriorates performance but also strongly changes stimulus appearance (Coates, Wagemans, & Sayim, 2017; Greenwood, Bex, & Dakin, 2010; Sayim & Wagemans, 2017).

A good predictor for the strength of crowding is the degree to which the target groups with the flankers: Strong target–flanker grouping yields strong crowding, and weak target–flanker grouping yields weak crowding (Banks, Larson, & Prinzmetal, 1979; Banks & White, 1984; Livne & Sagi, 2007, 2010; Malania, Herzog, & Westheimer, 2007; Manassi et al., 2012; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim & Cavanagh, 2013; Sayim et al. 2010, 2011; Prinzmetal & Banks, 1977). This effect of grouping has been shown for a large range of different stimuli, including verniers (Malania et al., 2007; Manassi et al., 2012; Sayim et al., 2010, 2011), Gabors (Livne & Sagi, 2007, 2010), and letters (Banks et al., 1979).

The deleterious effect of flankers on target perception when there is strong target–flanker grouping resembles the effect of grouping studied in other realms. For example, grouping often hinders access to the parts of a configuration (Baylis & Driver, 1992; Kramer & Jacobson, 1991; Poljac, de-Wit, & Wagemans, 2012). In contrast, target discrimination can also improve when the target is grouped with other elements (Pomerantz & Portillo, 2011; Pomerantz, Sager, & Stoever, 1977). In particular, arrangements of elements that elicit emergent features have been shown to be advantageous in discrimination tasks (see Pomerantz & Garner, 1973; Pomerantz & Portillo, 2011; see also "object superiority," Weisstein & Harris, 1974). For example, response times for discrimination of a

parenthesis stimulus in an odd-quadrant task have been shown to be more rapid when the oddball stimulus was embedded in a context that was uninformative on its own. The formation of an emergent feature in the context condition yielded an advantage compared to when the parenthesis was presented in isolation (Figure 1b; Pomerantz et al., 1977; Pomerantz & Garner, 1973). This effect was not observed when no emergent features were elicited between the context and the targets.

Crowding and grouping share many characteristics, including sensitivity to spacing and similarity. In fact, it has been proposed that the contextual influence of flankers on target perception could be used as a measure to quantify the strength of Gestalt laws (Sayim et al., 2010). Similar characteristics of crowding and grouping, and the strong dependence of crowding on grouping, might lead to the assumption that crowding and grouping are the same process; however, this is not the case. For example, it has been shown that grouping operates over a larger spatial extent than crowding (Sayim & Cavanagh, 2013). Importantly, grouping between a target and an additional item can also be beneficial. When an additional item with the same shape as the crowded target is presented at fixation (far outside the crowding zone of the target), crowding has been shown to be reduced compared to when the additional item has a different shape (Sayim, Greenwood, & Cavanagh, 2014; see also Geiger & Lettvin, 1986). These results show that the target signal is not entirely lost, and "uncrowding" may occur through long-range grouping between the target and a remote item. However, it is unclear if the grouping of a target with nearby items within the crowding zone can yield a similar improvement, or if strong grouping between the target and nearby flankers always deteriorates performance.

Hence, grouping of elements can be either harmful (nearby flankers impair a target in crowding) or helpful (nearby object parts can form emergent features; distal objects can group to enhance performance), depending on the stimuli and the tasks. Here we investigated the interplay between the two modulatory influences of grouping resulting in either impairment or enhancement using identification tasks in a crowding paradigm. To do so, we utilized stimuli similar to the parenthesis stimuli introduced by Pomerantz and Garner (1973; see also Figure 1b). With these stimuli, pairs of elements form configurations that may elicit emergent features when in close proximity. Importantly, these element pairs can also function as a target and a flanker in a crowding paradigm. Here we used chevrons (with identical horizontal and vertical extent) as targets and flankers. To isolate the factors of impairment and enhancement, we tested a set of target–flanker pairs that comprised configurations both amenable and immune to emergent-feature formation. Several differ-

ent experimental manipulations were used to vary crowding and emergent-feature strength.

In Experiments 1–3 the observers' task was to identify the orientation of a peripherally presented chevron target (pointing up or down). One of the flankers, the *critical flanker* (CF), formed configurations with the target, some of which were expected to elicit emergent features modulating identification performance (the CF itself was not informative about the orientation of the target). In Experiment 1, the observers were not given explicit information about these configurations. Emergent-feature cues would be available but not necessarily used. Although previous studies have shown that grouping can operate under conditions of inattention (e.g., Lamy, Segal, & Ruderman, 2006; Moore & Egeth, 1997), grouping between parts does not always happen involuntarily; it is modulated by factors such as attention (e.g., Mack, Tang, Tuma, Kahn, & Rock, 1992) and prior knowledge (Girgus, Rock, & Egatz, 1977). Our first experiment investigated whether emergent features would automatically modulate performance in crowding.

To test whether explicit knowledge about the configurations modulated performance, in Experiment 2 the observers were informed about the possible configurations of the target and the CF prior to the experiment. To preview our results: Configural effects were observed at close spacings, with stronger effects in Experiment 2 than in Experiment 1. Next, to keep the stimuli as similar as possible to Experiments 1 and 2 but at the same time break target–flanker grouping, we presented the CF before the rest of the configuration in Experiment 3. In contrast to the results of Experiments 1 and 2, the previously observed effects of configuration were no longer present. Instead, only the typical crowding effect was evident: Performance was worse when flankers were closer to the target.

In Experiments 1–3, the orientation of the CF was task irrelevant, as observers were required to identify the target only (not the configuration of the target and the CF). In Experiment 4 we investigated whether making the CF task relevant would increase the configuration effects. The observers were asked to identify the configuration that was formed between the target and the CF. Performance was high when the target and the CF were positioned close to each other, and decreased with increasing CF–target distance—the opposite of the pattern seen in crowding. Importantly, performance depended again on the orientation of the CF, with an advantage for good configurations (depending on the CF–target distance). Configurations with identical elements showed the greatest advantage when the task required attention to both elements.

Together, these experiments show the complexity of influences that the grouping of targets and flankers can

have on target identification. Strong target–flanker grouping does not necessarily result in a decline of performance. Emergent features resulting from the grouping of a target and a flanker can counteract the usual negative influence of nearby flankers on performance in crowding.

Experiment 1: No prior CF knowledge

In Experiment 1 we investigated whether target–flanker configurations modulated performance. A target-identification task with two alternatives was used to enable the calculation of discriminability (d') and bias. Observers reported the orientation of a chevron target (pointing up or down) flanked by four flankers. The flanker above the target—the Critical Flanker (CF)—formed different configurations with the target. Observers were not informed about either the orientation of the CF or the configurations between the target and the CF. We expected performance to be better in the conditions where the target and the CF formed *good* configurations (i.e., good Gestalts). This effect was expected to decrease with increasing spacing between the target and the CF.

Materials and methods

Observers

Seven observers (all women; age range: 20–36) participated in Experiment 1. All observers were unaware of the purpose of the experiment. They were familiarized with the task before the beginning of the experiment. All observers reported normal or corrected-to-normal vision. Experiments were carried out in accordance with ethical standards of the Declaration of Helsinki and were approved by the Ethics Committee of the University of Bern. All recruited observers provided informed consent prior to their participation. Two additional observers were tested but were excluded from the analysis because they did not sufficiently exceed chance performance levels (the exclusion criteria were determined prior to the experiment).

Apparatus

A 21-in. CRT color monitor set at a resolution of 1,024 × 768 pixels and a refresh rate of 70 Hz was used for stimulus presentation. The viewing distance was 57 cm. A chin- and headrest was used. A combination of Python 2.7 and the PsychoPy toolbox (Peirce, 2007) was used for stimulus presentation and data collection. Experiments took place in a dimly lit room. All stimuli
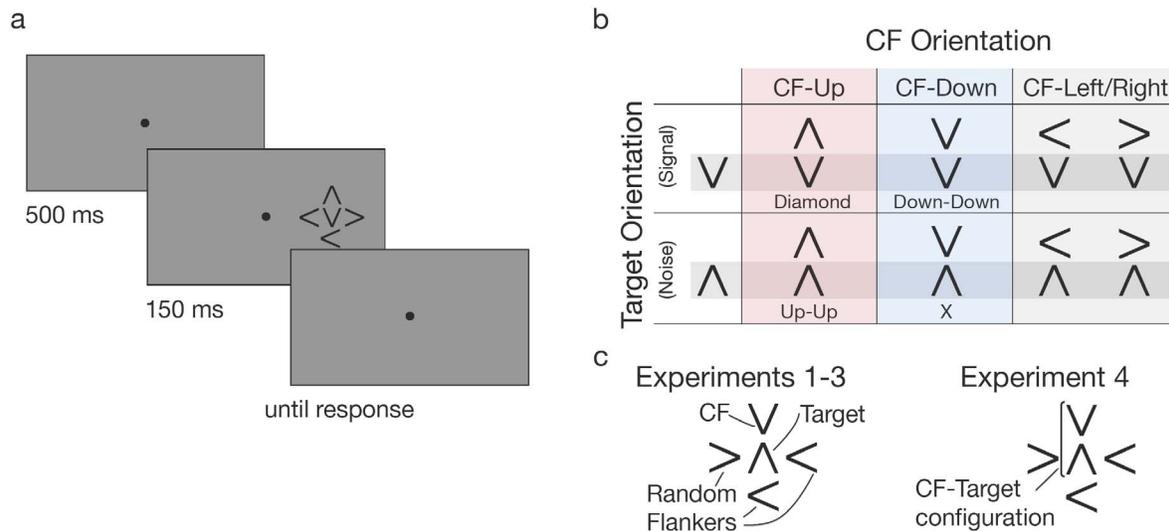
Figure 2. (a) Time course of Experiments 1, 2, and 4. After the fixation presentation, the stimulus appeared on the screen for 150 ms. Observers had to identify the orientation of the target (the central chevron; Experiments 1 and 2) or the configuration of the target and the critical flanker (CF; Experiment 4). (b) The configurations formed by the target (lower chevron in each pair) and the CF (upper chevron). The CF-Up condition comprised the Diamond and Up-Up configurations, and the CF-Down condition comprised the X and Down-Down configurations. The CF pointing to the left and to the right were combined in the CF-Left/Right condition. The CF-Absent condition is not included in the figure. (c) Stimuli used in Experiments 1–4. In Experiments 1–3, observers identified the orientation of the target (i.e., up or down). In Experiment 4, observers reported the configuration formed by the CF and the target.

were black (0.89 cd/m^2), presented on a gray (33.3 cd/m^2) background.

Stimuli

Stimuli consisted of a chevron target, pointing up or down, presented at 8° eccentricity in the right visual field (Figure 2a). The target was surrounded by four flankers. Three of the flankers, the *random* flankers—presented to the left, to the right, and below the target—varied randomly (pointing left or right). The fourth flanker, the CF, was presented above the target and fixed within each block to one of the four orientations (up, down, left, or right). Thus, the CF was uninformative about the orientation of the target. There were three different CF-conditions: CF-Up, CF-Down, and CF-Left/Right (combining the left- and right-pointing CFs; see Figure 2b). The size of the chevrons was determined in a separate experiment (see Size determination). The random flankers (to the left and right sides of the target) were positioned at a (center-to-center) distance of 1.5 times the size of the chevrons from the target (Figure 2c). (In an additional condition, the distance was 2 times the size of the chevrons, with similar results; results are not reported here). The flanker below the target was presented at the same distance from the target as the CF. There were four different CF–target distances (center-to-center): 1.17, 1.5, 2, and 2.5 times the chevron size. The CF–target distance was fixed in each block. Performance

without the CF (CF-Absent) and without flankers (i.e., target alone; baseline) was also measured.

Procedure

Stimuli were presented for 150 ms (Figure 2a). Observers indicated the orientation of the target by pressing the up or down key. Auditory feedback was given after each trial: A high-pitched sound was played after a correct response, and a low-pitched sound after an incorrect response. The first trial in the block was initiated by pressing the space bar; the following stimuli were presented after fixed intervals of 500 ms after observers' responses. Observers performed two blocks of 80 trials without CF, and two blocks with each CF orientation (Up, Down, Left, Right) and each CF–target distance (half with the target–flanker spacing of 1.5; 2,720 trials in total). In the first run the order of conditions was randomized; in the second run it was reversed. Observers were instructed to respond as fast and accurately as possible.

Size determination

Before the experiment, the chevron size was adapted for each observer separately using the same procedure as in the main experiment. The size of the chevrons was varied (0.4°, 0.6°, 0.8°, 1°, and 1.2°). All items (target, CF, and flankers) had the same size in a given trial. Size values were counterbalanced and randomly intermixed

within a block. The CF appeared randomly in all four orientations. Observers performed two blocks of 100 trials. Psychometric functions were fitted to the data using the maximum-likelihood method (Wichmann & Hill, 2001). Size at 65% correct performance was used in the main experiment. The mean size of the stimuli was $0.62° ± 0.06°$ (sizes for individual observers: $2 × 0.55°$, $0.6°$, $2 × 0.62°$, $2 × 0.7°$).

Data analysis

Trials in which the observers took longer than 3 s to respond were removed from the analysis (<1% of all trials). First, we calculated discriminability (and bias) for each CF condition and CF–target distance. Following the nomenclature of signal-detection theory (Macmillan & Creelman, 2005), we defined the target pointing down as signal and the target pointing up as noise (see Figure 2b). Correspondingly, the correct identification of the target pointing down was defined as a hit, and the correct identification of the target pointing up as a correct rejection. Reporting "down" when the target was pointing up was a false alarm, and reporting "up" when the target was pointing down was a miss.

Discriminability was calculated using the equation $d' = z(H) − z(F)$, where $z(H)$ stands for z transformation of hits and $z(F)$ for z transformation of false alarms (Macmillan & Creelman, 2005). Bias (i.e., criterion) was computed using the formula $c = −1/2[z(H) + z(F)]$. Following our definition of signal (target pointing down) and noise (target pointing up), a positive bias denotes the tendency to respond "up," and a negative bias the tendency to respond "down." The trials in which the CF pointed left or right were combined in the CF-Left/Right condition. Discriminability and bias data were analyzed with a repeated-measures analysis of variance (ANOVA), with the two factors of CF condition (3 levels: CF-Up, CF-Down, CF-Left/Right) and CF–target distance (4 levels: 1.17, 1.5, 2, 2.5 times the chevron size). Greenhouse–Geisser corrections were used when the sphericity assumption was violated. Paired comparisons were tested using the Least Significant Difference (LSD) procedure (if not stated otherwise).

Results

The results of Experiment 1 are summarized in Figure 3. We compared discriminability (d') and bias of the CF-Up, CF-Down, and CF-Left/Right conditions (Figure 3a). Discriminability for CF-Down and CF-Left/Right increased as a function of CF–target distance. Discriminability in the CF-Up condition, however, showed first a decrease and then an increase

with larger CF–target distances. A repeated-measures ANOVA revealed a main effect of CF condition, $F(2, 12) = 17.90$, $p < 0.001$, and a CF condition × CF-target distance interaction, $F(6, 36) = 2.61$, $p < 0.05$. There was no main effect of distance, $F(3, 18) = 2.00$, $p = 0.15$. Paired comparisons between the CF-Up and CF-Down conditions revealed higher discriminability in the CF-Up condition at the smallest spacing ($d' = 1.61$ vs. $d' = 0.62$), $t(6) = 2.48$, $p < 0.05$. There were no differences between the CF conditions at the other spacings. Overall, discriminability in CF-Left/Right ($d' = 1.79$) was greater than in CF-Down ($d' = 1.1$), $t(6) = 8.80$, $p < 0.001$, and CF-Up ($d' = 1.29$), $t(6) = 4.08$, $p < 0.01$.

We further investigated the dependence of performance on spacing within each condition. We observed a difference between the smallest ($d' = 0.62$) and largest spacings ($d' = 1.39$) in the CF-Down condition, $t(6) = 4.56$, $p < 0.05$, but not in the other conditions.

To test whether biases differed between the conditions, bias values were entered in a repeated-measures ANOVA. There was no main effect of CF condition ($p = 0.38$), no main effect of CF–target distance ($p = 0.52$), and no interaction between them ($p = 0.51$).

Next, to investigate how each individual configuration formed between the CF and the target modulated performance, we analyzed accuracy data (proportion correct; see Figure 3b) for the different CF–target configurations: Diamond, X, Up-Up, Down-Down, and CF-Left/Right (see Figure 2b), as well as CF-Absent. The configurations depended on the orientation of both the target and the CF. The Diamond configuration occurred when the CF was pointing up and the target down; the X configuration when the CF was pointing down and the target up; and the Up-Up and Down-Down configuration when the CF and the target were both pointing up or down, respectively. Accuracy values in the different configurations were calculated for each observer and CF–target distance. The data were analyzed with a repeated-measures ANOVA with the CF–target configuration (6 levels: Diamond, X, Up-Up, Down-Down, CF-Left/Right, CF-Absent), and CF–target distance (4 levels: 1.17, 1.5, 2, 2.5 times the chevron size) as factors.

The accuracy for the CF-Left/Right, Down-Down, and X configurations improved with increasing CF–target distance. The accuracy for the Diamond and Up-Up configurations showed a U-shaped function with higher accuracy at the smallest spacing, a decrease at intermediate spacings, and an increase at larger spacings. The repeated-measures ANOVA on the accuracy data revealed a main effect of configuration, $F(5, 30) = 9.07$, $p < 0.001$. Observers performed better in CF-Absent and CF-Left/Right compared to all other configurations (all ps < 0.05).
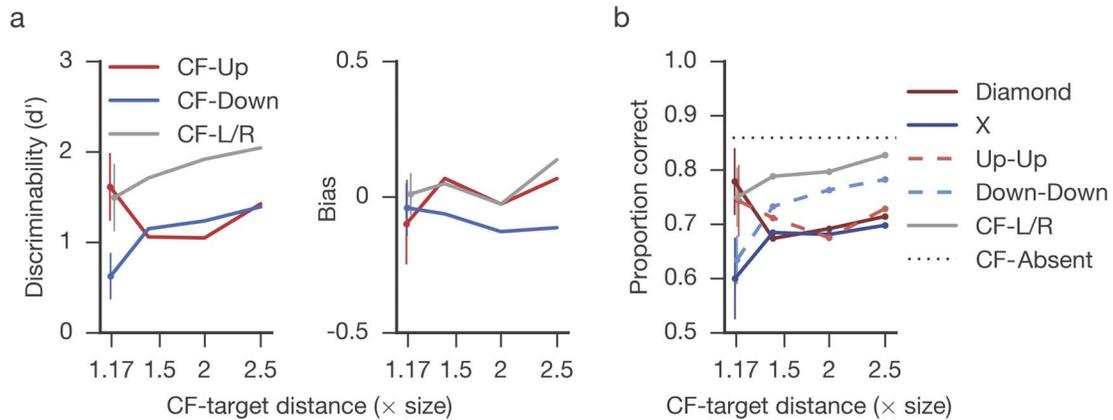
Figure 3. Experiment 1: (a) Discriminability and bias and (b) accuracy as functions of CF–target distance. Negative bias values denote a bias to respond "down," and positive values a bias to respond "up." Average unflanked performance was 96% correct. Error bars denote standard errors of the mean and are displayed only for the smallest spacing; error bars for the other spacings are similar and not shown here. The position of the markers at the smallest spacing was jittered to increase visibility. CF-L/R = CF-Left/Right.

Our main question was if the Diamond configuration differed from the X configuration, in particular, at close spacings. To explore if there was a trend for better performance in the Diamond than in the X configuration, we compared the two configurations at each CF–target distance; t tests between the X and Diamond configuration at each spacing revealed a trend at the smallest spacing (CF–target distance = $1.17 \times$ size), $t(6)$ = 2.06, p = 0.086, and no difference at the other spacings. However, the pattern of results differed among observers. The analysis of individual data showed that three of the seven observers achieved superior performance in the Diamond compared to the X configuration at the smallest spacing. Two observers showed either a trend for better performance in the Diamond compared to the X configuration or no difference, and one showed slightly better performance in the X configuration compared to the Diamond configuration. The Up-Up and Down-Down configurations did not differ at the smallest spacing; however, there was a strong trend for better performance in the Down-Down compared to the Up-Up configuration at the third spacing, $t(6)$ = 2.44, p = 0.05.

Overall, the results of Experiment 1 showed that increasing the CF–target distance improved performance, showing a standard crowding pattern. CF-Up was similar to CF-Down, but only for intermediate and larger spacings. At the smallest spacing, CF-Up was superior to CF-Down. Discriminability was higher when the CF was rotated (CF-Left/Right condition) compared to CF-Up and CF-Down, as expected from the similarity effect in crowding (dissimilar flankers are known to crowd less than similar flankers). There was a trend for better performance in the Diamond compared to the X configuration at the smallest spacing.

Experiment 2: Prior configuration information

The results of Experiment 1, in which the observers were not informed about the possible configurations, showed that the configurations moderately modulated performance. While some observers showed better performance in the Diamond configuration (i.e., when potentially helpful configural information was present), others did not. In Experiment 2, we informed the observers of the possible orientations of the CF and the resulting configurations with the target. Explicit instruction about the configurations was expected to increase the likelihood that observers would use the information available in the CF–target configurations to perform the task. Note that the orientation of the CF was still irrelevant to the task.

Materials and methods

Observers

Eight observers (seven women, one man; age range: 19–40) participated in Experiment 2. All observers were unaware of the purpose of the experiment.

Stimuli and procedure

The stimuli and procedure were the same as in Experiment 1, except for the following changes. Observers were informed before the experiment about the possible orientations of the CF and the configurations that the CF and the target could form. The stimulus size was constant for all observers (the horizontal and vertical extent of the chevrons was 0.6°). The flanker below the target was presented at the same
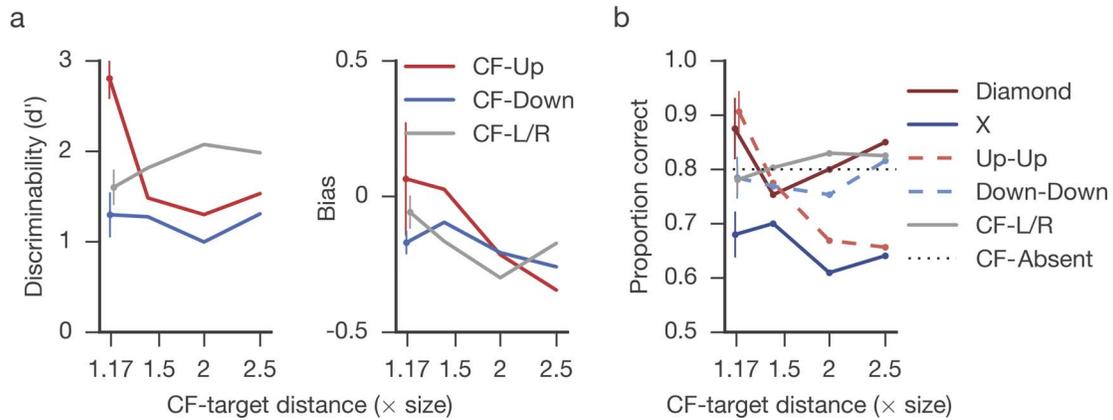
Figure 4. Experiment 2: (a) Discriminability and bias and (b) accuracy as functions of CF–target distance. Average unflanked performance was 99.7% correct. Error bars denote standard errors of the mean (displayed only for the smallest spacing; error bars for the other spacings are similar). The position of the markers at the smallest spacing was jittered to increase visibility. CF-L/R = CF-Left/Right.

distance as the flankers to the left and right of the target.

Results

The results of Experiment 2 are shown in Figure 4. The orientation of the CF strongly modulated discriminability (Figure 4a). The analysis followed that performed for Experiment 1. First, we performed a repeated-measures ANOVA on the discriminability data. The analysis revealed a main effect of CF condition, $F(2, 14) = 15.98$, $p < 0.001$; a main effect of distance, $F(1.36, 9.51) = 5.63$, $p < 0.05$; and an interaction between the factors, $F(6, 42) = 10.57$, $p < 0.001$. Discriminability was higher in the CF-Up condition ($d' = 1.78$) compared to the CF-Down condition ($d' = 1.22$), $t(7) = 6.59$, $p < 0.001$. Paired comparisons revealed that at the smallest CF–target distance, the discriminability was higher in the CF-Up condition ($d' = 2.81$) compared to the CF-Down condition ($d' = 1.30$), $t(7) = 7.74$, $p < 0.001$. The two conditions did not differ at any other spacing. Discriminability in the CF-Up condition was also higher than in the CF-Left/Right condition ($d' = 1.60$), $t(7) = 4.17$, $p < 0.01$, at the smallest spacing.

We further investigated the dependence of discriminability on CF–target distance within each CF condition. Comparison of the spacings in the CF-Up condition revealed higher discriminability at the smallest spacing ($d' = 2.81$) compared to all other spacings—1.5 × size ($d' = 1.48$): $t(7) = 4.05$, $p < 0.01$; 2 × size ($d' = 1.30$): $t(7) = 8.03$, $p < 0.01$; 2.5 × size ($d' = 1.53$): $t(7) = 4.79$, $p < 0.001$. A different pattern was observed in the CF-Left/Right condition: 1.17 × size ($d' = 1.6$) versus 2.5 × size ($d' = 1.98$), $t(7) = 2.77$, $p < 0.05$. The curve of the CF-Down condition was comparably

flat: Discriminability was only slightly higher at the fourth (2.5 × size, $d' = 1.31$) compared to the third spacing (2 × size, $d' = 1$), $t(7) = 2.96$, $p < 0.05$.

The bias values were submitted to a repeated-measures ANOVA with CF condition and CF–target distance as factors. There was no main effect of CF condition ($p = 0.51$), no main effect of CF–target distance ($p = 0.1$), and no interaction between them ($p = 0.37$). However, there was a trend for a more negative bias with increasing CF–target distance (see Figure 4a), presumably indicating a general response bias. While small biases driven by the CF could be expected, such biases do not invalidate any conclusions based on (bias-free) discriminability differences.

As in Experiment 1, we next investigated accuracy data for each of the CF–target configurations (Figure 4b). The accuracy of the Diamond and the Up-Up configurations showed a U-shaped function: High performance at the smallest spacing was followed by a decrease in performance, then a subsequent increase as the CF–target distance increased. Performance in the CF-Left/Right configuration improved as a function of CF–target distance. A repeated-measures ANOVA revealed a main effect of configuration, $F(5, 35) = 5.64$, $p < 0.001$; a main effect of distance, $F(3, 21) = 4.08$, $p < 0.05$; and an interaction between the two, $F(15, 105) = 3.07$, $p < 0.001$. Comparison between the Diamond (0.88) and the X (0.68) configurations revealed a difference at the smallest spacing (CF–target distance = 1.17 × size), $t(7) = 4.54$, $p < 0.01$. Performance in the Diamond configuration was also better compared to X at spacings 3 (2 × size), 0.8 versus 0.61, $t(7) = 4.6$, $p < 0.01$, and 4 (2.5 × size), 0.85 versus 0.64, $t(7) = 3.10$, $p < 0.05$.

The dependence of performance on spacings was then investigated within each configuration. Performance in the Up-Up configuration at the smallest
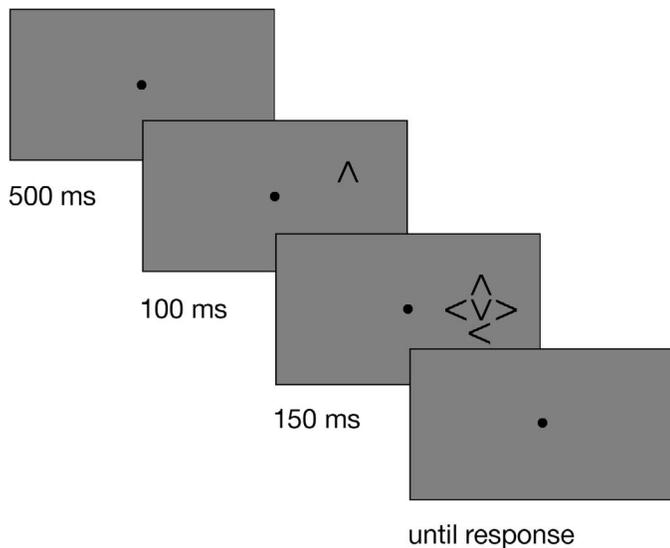
Figure 5. Time course of Experiment 3. Observers fixated on the dot in the center of the screen. After a preview of the CF for 100 ms, the rest of the stimulus appeared on the screen for 150 ms.

spacing (1.17 × size) was higher than in the other spacings (all $ps < 0.01$)—versus 1.5 × size: $t(7) = 6.10$, $p < 0.001$; versus 2 × size: $t(7) = 4.98$, $p < 0.01$; versus 2.5 × size: $t(7) = 4.55$, $p < 0.01$. Analysis of individual data also showed a strong trend for higher performance at the smallest spacing in the Diamond configuration for all observers except one. In the CF-Left/Right configuration, accuracy increased from the smallest spacing (1.17 × size; 0.78) to the largest (2.5 × size; 0.83), $t(7) = 2.44$, $p < 0.05$. The other comparisons did not show significant differences, but there was a trend for better performance in the X configuration at the smallest spacing compared to the third spacing (2 × size; $p = 0.075$).

Taken together, the CF strongly modulated the performance in the task. Discriminability in the CF-Up condition was better at the smallest spacings compared to the other spacings. Performance in the Diamond configuration was better compared to the X configuration at the smallest CF–target spacing.

Experiment 3: CF preview

In Experiments 1 and 2, we showed that the orientation of the CF modulated performance. In particular, discriminability in the condition when the CF and the target formed a good configuration was high at the smallest spacing. In addition to this, we observed different modulation patterns between the configuration which elicited only crowding (CF-Left/Right) and the configurations which could elicit emergent features. We suggest that the pattern of results was due to the grouping between the target and the CF and the corresponding emergent features. If grouping and emergent features underlie the observed effects, a disruption of the grouping between the target and the CF (i.e., a disruption of the emergent features) should abolish the difference between the CF conditions (and configurations) observed in the previous experiments. To disrupt emergent features but keep the experiment as similar as possible to Experiments 1 and 2, we presented the CF for 100 ms before the target and the flankers (flanker preview).

Materials and methods

Observers

Five observers (four women, one man; age range: 21–29) participated in Experiment 3. All were unaware of the purpose of the experiment.

Stimuli and procedure

The stimuli and procedure in Experiment 3 were the same as in Experiment 1 with the following changes. The CF appeared on the screen first (preview; see Figure 5). After 100 ms, the rest of the stimulus appeared and remained on the screen for 150 ms. The flanker below the target was presented at the same distance from the target as the CF (as in Experiment 1). Observer-specific chevron sizes were estimated using the method described for Experiment 1 (mean size = 0.71° ± 0.22°; sizes for individual observers: 0.56°, 0.57°, 0.58°, 0.76°, 1.07°).

Results

Figure 6 summarizes the results of Experiment 3. There was a general increase in discriminability in all conditions with increasing CF–target distance (Figure 6a). A repeated-measures ANOVA on the discriminability data revealed a main effect of CF condition, $F(2, 8) = 32.15$, $p < 0.001$, and a main effect of distance, $F(3, 12) = 4.87$, $p < 0.05$, but no interaction between the factors ($p = 0.78$). Discriminability in the CF-Left/Right condition ($d' = 2.32$) was higher compared to the discriminability in CF-Down ($d' = 1.16$), $t(4) = 4.89$, $p < 0.01$, and CF-Up ($d' = 0.99$), $t(4) = 7.43$, $p < 0.01$.

We then compared the dependence of discriminability on CF–target spacing within conditions. Discriminability in the CF-Up condition at the smallest spacing ($d' = 0.55$) was worse compared to the largest spacing ($d' = 1.14$), $t(4) = 9.21$, $p < 0.001$. In the CF-Down condition it increased between the second spacing (1.5 × size; $d' = 0.94$) and the largest (2.5 × size;
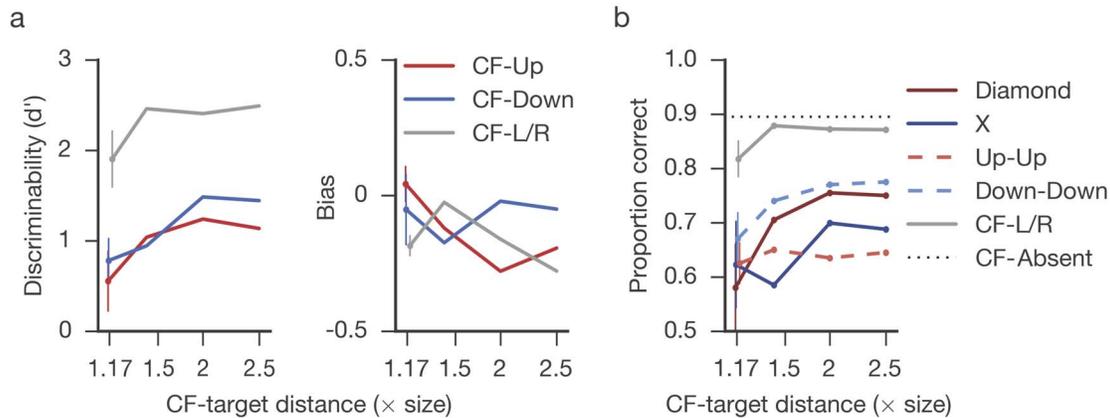
Figure 6. Experiment 3: (a) Discriminability and bias and (b) accuracy as functions of CF–target distance. Average performance in unflanked target discrimination was 96%. Error bars denote standard errors of the mean (displayed only for the smallest spacing; error bars for the other spacings are similar). The position of the markers at the smallest spacing was jittered to increase visibility. CF-L/R = CF-Left/Right.

$d' = 1.44$), $t(4) = 2.88$, $p < 0.05$. Discriminability in the CF-Left/Right condition also increased from the smallest spacing ($1.17 \times$ size; $d' = 1.91$) to all other spacings (all $ps < 0.05$)—versus $1.5 \times$ size ($d' = 2.46$): $t(4) = 3.97$, $p < 0.05$; versus $2 \times$ size ($d' = 2.41$): $t(4) = 4.03$, $p < 0.05$; versus $2.5 \times$ size ($d' = 2.49$): $t(4) = 3.86$, $p < 0.05$.

Bias values were submitted to a repeated-measures ANOVA with CF condition and CF–target distance as factors. There was no main effect of CF condition ($p = 0.88$), no main effect of CF–target distance ($p = 0.24$), and no interaction between the factors ($p = 0.16$).

Next we analyzed the accuracy data (Figure 6b), which revealed a main effect of configuration, $F(5, 20) = 8.25$, $p < 0.001$, and a trend for a main effect of distance, $F(3, 12) = 3.25$, $p = 0.06$, but no interaction between these factors. Performance of the Diamond and X configurations did not differ—$1.17 \times$ size: $p > 0.1$; $1.5 \times$ size: $p = 0.08$; $2 \times$ size: $p = 0.08$; $2.5 \times$ size, $p > 0.1$. Pairwise comparisons revealed better performance in CF-Left/Right (0.86) compared to all other configurations—Diamond (0.7): $t(4) = 3.20$, $p < 0.05$; Down-Down (0.74): $t(4) = 2.96$, $p < 0.05$; Up-Up (0.64): $t(4) = 14.19$, $p < 0.001$; X (0.65): $t(4) = 3.20$, $p < 0.05$.

Next, we investigated the dependence of performance on spacing within configurations. Performance increased as a function of CF–target distance in the Diamond configuration—$1.17 \times$ size (0.58) versus $1.5 \times$ size (0.71): $t(4) = 2.84$, $p < 0.05$; versus $2.5 \times$ size (0.75): $t(4) = 3.47$, $p < 0.05$. In the X configuration, there was no difference between the smallest spacings but a significant increase between the second spacing ($1.5 \times$ size; 0.59) and the third ($2 \times$ size; 0.70), $t(4) = 3.31$, $p < 0.05$. In the CF-Left/Right configuration, performance at the smallest spacing ($1.17 \times$ size) was worse than at all other spacings (all $ps < 0.05$)—versus $1.5 \times$ size: $t(4) = 3.40$, $p < 0.05$; versus $2 \times$ size: $t(4) = 3.67$, $p < 0.05$; versus $2.5 \times$ size: $t(4) = 2.87$, $p < 0.05$.

Taken together, performance increased with increasing CF–target distance. Discriminability and performance in CF-Left/Right were better compared to the other CF conditions. No difference in discriminability between CF-Up and CF-Down and no difference in performance between the X and Diamond configurations were observed. The preview removed the nonmonotonic effects seen in Experiments 1 and 2, leaving only a standard crowding curve.

Experiment 4: Configuration report

In Experiments 1–3 the observers' task was to report the orientation of the chevron target, and the orientation of the CF was task irrelevant. In Experiments 1 and 2, we observed that CF orientation strongly modulated performance. In Experiment 3, the preview of the CF disrupted the positive influence on performance, likely due to a lack of formation of emergent features. We next sought to increase the effect of grouping and emergent features of the CF–target configurations. In contrast to the previous experiments, observers reported the configuration between the target and the CF, making the CF a task-relevant item. We hypothesized an enhanced effect of grouping at small CF–target spacings and a reduction of configural effects with increasing spacings.

Materials and methods

Observers

Five observers (all women; age range: 21–25) participated in Experiment 4, including one of the observers from Experiment 3 and the first author. All
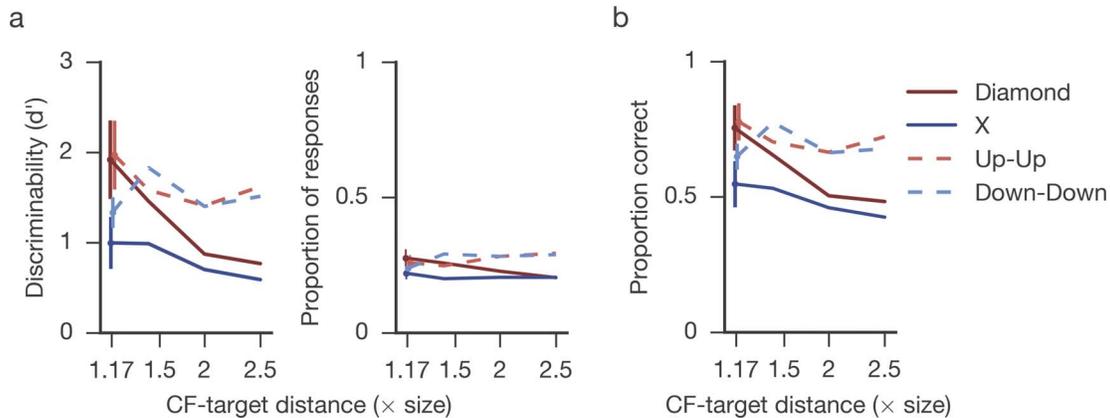
Figure 7. Experiment 4: (a) Discriminability and proportion of responses with each response category and (b) accuracy as functions of CF–target distance. Average performance in the unflanked condition was 94.6% (average of all four spacings; not shown). Error bars denote standard errors of the mean (displayed only for the smallest spacing; error bars for the other spacings are similar). The position of the markers at the smallest spacing was jittered to increase visibility.

observers except for the first author were unaware of the purpose of the experiment.

Stimuli and procedure

Observers were asked to report the configurations formed by the target and the CF. The arrangement of the CF and the single target in Experiments 1–3 created the following four configurations: Up-Up, Down-Down, Diamond, and X (see Figure 2b). There was no CF-Left/Right condition. To maintain consistent terminology with Experiments 1–3, the distance between the *parts* of the configuration (i.e., the distance between the CF and the targets) is referred to as the CF–target distance (although both are targets). The observers used a numeric keypad with one key assigned to each target configuration. Each block consisted of 80 trials. The target configurations were counterbalanced in each block (20 trials). The chevron size was constant for all observers (0.6°). The flanker below the target was presented at the same distance from the target as the flankers to the right and left of it. Before the crowded conditions, observers completed 160 trials for each CF–target distance without flankers. As in Experiment 1, trials lasting longer than 3 s were excluded from the analysis (less than 0.05% of the trials were excluded). To calculate discriminability values in this design with four response alternatives, we used the formula

$$P'_M(c, d') = \int_{-\infty}^{\frac{d'-m}{\sigma}} \phi(x)dx = \Phi\left(\frac{d'-m}{\sigma}\right),$$

where m (mean) and σ (standard deviation) are adjusted to yield the least mean square error between the values of $P_M'(c)$ and $P_M(c)$ (Green & Dai, 1991; implemented in the Psyphy package for R: Knoblauch, 2014). The discriminability data were analyzed using a

2×2 repeated-measures ANOVA with configuration (4 levels: Up-Up, Down-Down, Diamond, X) and CF–target distance (4 levels: 1.17, 1.5, 2, 2.5 times the chevron size) as factors. The calculation of discriminability assumes independent target responses and unbiased observers (for details, see Green & Dai, 1991; see also Macmillan & Creelman, 2005). To test whether any configuration was selected more often than the others, we analyzed the proportion of responses (as a measure of bias) using a repeated-measures ANOVA with the response category (4 levels: Diamond, X, Up-Up, Down-Down) and CF–target distance (4 levels: 1.17, 1.5, 2, 2.5 times the chevron size) as factors. We also analyzed accuracy with a 2×2 repeated-measures ANOVA with configuration (4 levels: Up-Up, Down-Down, Diamond, X) and CF–target distance (4 levels: 1.17, 1.5, 2, 2.5 times the chevron size) as factors.

Results

Results of Experiment 4 are summarized in Figure 7. A repeated-measures ANOVA was performed on the discriminability data, revealing a main effect of configuration, $F(3, 12) = 4.64$, $p < 0.05$; a main effect of CF–target distance, $F(3, 12) = 12.34$, $p < 0.01$; and an interaction between them, $F(9, 36) = 3.74$, $p < 0.01$. Paired comparisons revealed a difference between the Diamond ($d' = 1.92$) and X ($d' = 1$) configurations at the smallest spacing, $t(4) = 3.68$, $p < 0.05$. We also found a decrease in discriminability between the smallest spacing (1.17 × size) and all other spacings in the Diamond configuration (all ps < 0.05)—versus 1.5 × size: $t(4) = 3.36$, $p < 0.05$; versus 2 × size: $t(4) = 12.43$, $p < 0.05$; versus 2.5 × size: $t(4) = 3.85$, $p < 0.05$.

We then analyzed whether the observers used any of the four response categories more often than the others

(see Figure 7a). The ANOVA showed no main effect of response category and no main effect of distance. However, there was an interaction between them, $F(9, 36) = 3.21$, $p < 0.01$, with incidental, small biases at larger spacings. At the third spacing ($2 \times$ size), the number of responses for Down-Down was higher compared to X, $t(4) = 3.15$, $p < 0.05$. Additionally, at the largest spacing the number of X responses was lower than the number of Up-Up responses, $t(4) = 2.9$, $p < 0.05$.

Next we analyzed the accuracy data (Figure 7b). A repeated-measures ANOVA revealed a main effect of configuration, $F(3, 12) = 4.62$, $p < 0.05$; a main effect of distance, $F(3, 12) = 13.94$, $p < 0.001$; and an interaction between them, $F(9, 36) = 2.99$, $p < 0.01$. Paired comparisons revealed a difference between the Diamond (0.76) and X (0.55) configurations at the smallest spacing, $t(4) = 3.82$, $p < 0.05$, but not at the other spacings. We further investigated the dependence of performance on CF–target spacing within configurations, and found a decrease in accuracy in the Diamond configuration between both the smallest spacing ($1.17 \times$ size) and the third ($2 \times$ size), $t(4) = 7.42$, $p < 0.01$, and the smallest spacing and the fourth ($2.5 \times$ size), $t(4) = 5.18$, $p < 0.01$. The slow decrease of accuracy with distance in the Down-Down and Up-Up configurations manifested in several comparisons as well—Down-Down: $1.5 \times$ size (0.78) versus $2 \times$ size (0.66), $t(4) = 5.25$, $p < 0.05$; Up-Up: $1.17 \times$ size (0.78) versus $2 \times$ size (0.67), $t(4) = 16.91$, $p < 0.01$.

To summarize, overall discriminability and performance were high at the smallest spacing, particularly in the Diamond and Up-Up configurations. Performance was better in the Diamond compared to the X configuration. There was a pronounced difference between the configurations. In the Up-Up and the Down-Down configurations, discriminability and accuracy changed only gradually with increasing spacing between the two parts (CF and target), suggesting that grouping between the parts operated beneficially over a long range. This pattern was not observed for the Diamond and the X configurations, where performance clearly decreased as the distance between the parts of the configurations increased.

Discussion

Studies investigating the relation between crowding and grouping have usually shown that strong target–flanker grouping yields strong crowding. Outside of crowding research, studies of perceptual organization have focused more generally on how constituent parts combine together into wholes, showing that configural relationships between elements provide additional perceptual cues, for example, in the form of emergent features. Here we asked if emergent features can overcome crowding.

We found strong variations between conditions that were designed to elicit different emergent features. The results from the CF-Left/Right conditions in Experiments 1–3 exhibited the typical hallmark of crowding: Performance was most compromised with nearby flankers, with weakening influence as the CF–target distance increased. Experiment 3 was designed to decrease the effects of grouping (by violating the principles of common fate and synchrony in perceptual organization; Wagemans et al., 2012) and crowding (by flanker preview; Huckauf & Heller, 2004; Scolari, Kohnen, Barton, & Awh, 2007). Here we expected the typical crowding pattern not only in CF-Left/Right but also in the configurations that elicited emergent features in Experiments 1 and 2. Our results showed the usual pattern of improvement with increasing CF–target spacing, and clearly no advantage for the smallest spacings (Figure 6).

Qualitatively different performance patterns were observed when configural influences on target perception were possible (Experiment 1), encouraged (Experiment 2), or mandatory (Experiment 4). In Experiment 1, the typical proximity effect was observed with all four emergent-feature configurations at larger spacings ($1.5–2.5 \times$ size). However, at the smallest spacings, the Diamond and Up-Up configurations exhibited a clear trend for an *enhancement* effect compared to the larger spacings. A similar, more pronounced pattern was observed in Experiment 2, where the observers were informed about the existence of the possible CF–target configurations. The effect was particularly strong in the CF-Up condition (comprising the Up-Up and Diamond configurations): Discriminability at the smallest spacing was about twice as high as with the larger spacings, showing a distinct reversal of the usual effect of spacing in crowding. In accuracy data, this effect was mostly manifested in the Up-Up and Diamond configurations. Moreover, at the smallest spacing, discriminability in the CF-Up condition exceeded that in the CF-Left/Right condition even though left- and right-pointing chevrons are clearly less similar to the target than up- or down-pointing chevrons. Hence, this relative alleviation of crowding shows a reversal of the usual effect of target–flanker similarity. Finally, in Experiment 4 the task required the identification of both the target and the CF. As expected, performance worsened as the spacing between the target and the CF increased in all configurations—again the opposite of the typical crowding pattern. This effect was strongest in the X and Diamond configurations, with performance in the Up-Up and Down-Down configurations decreasing at a much slower rate with increasing flanker distance, indicating that grouping of repeating

elements operates over a larger spatial scale than grouping into good Gestalts (at least with the stimuli used here; see also Butcher & Cavanagh, 2008; Sayim et al., 2014; Sayim & Cavanagh, 2013). As the requirement to extract target information from two locations (target and CF) was the same in all configurations, differences between the configurations are likely due to the strength of the (mandatory) grouping and emergent features of the target and the CF.

While the stimuli were almost identical in all four experiments, the task relevance of the CF was manipulated using different instructions and task requirements. In Experiments 1–3, the observers' task was to report the orientation of the target, and thus the CF could hinder, help, or have no effect on its identification. Interestingly, although the CF was fixed within a block (therefore constituting irrelevant information), performance depended strongly on the orientation of both the target and the CF. When observers were explicitly informed about the possible spatial configurations formed by the target and the CF (Experiment 2), the effects on performance (a relative enhancement of performance at closer spacings, summarized earlier) were stronger than when observers were unaware of the configurations (Experiment 1). Informal subjective reports revealed that a small majority of observers perceived the Diamond and Up-Up configurations as more salient than the X configuration, and only two of the eight observers in Experiment 2 reported that they were able to see all four configurations. These reports support the notion that Diamond configurations were more salient than X configurations. Interestingly, even some observers in Experiment 1 benefited from the CF, although no explicit instructions about the potential groupings and available configural cues were given.

We hypothesize that the grouping between the target and the CF modulates performance because of different emergent features elicited by the configurations, including collinearity (in the X configuration), closure (the Diamond configuration), and translational symmetry (the Up-Up and Down-Down configurations; Pomerantz & Garner, 1973). All four configurations (Diamond, X, Up-Up, and Down-Down) showed strong qualitative and quantitative differences, indicating that emergent features can also have a strong influence in identification tasks and complementing previous research showing the potency of emergent features using discrimination tasks (e.g., Fox, Harel, & Bennett, 2017; Pomerantz & Garner, 1973).

All four of these configurations contained emergent features. Hence, the observed differences between configurations possibly reflect the relative strengths of the different emergent features. In comparing the Diamond and X configurations, we saw that observers exhibited superior performance overall in the Diamond

configuration. We suggest that this pattern of results is due to a more salient emergent feature, and the goodness of the Diamond compared to the X configuration. Earlier results support this interpretation: Pomerantz and Garner (1973) informally collected goodness ratings for the grouped-parentheses stimuli (Figure 1b). A circlelike configuration similar to our Diamond—()—was reported to be "better" than an X-like configuration—)(. Interestingly, the circlelike and X-like configurations were both judged as "better" configurations than identically oriented parentheses—((and)). Recent evidence suggests that configural superiority is not perceived in an all-or-none manner, such that the effects of grouping are still observed when configurations have small distortions induced by graded variations of the stimuli (Fox et al., 2017). Hence, the better the Gestalts are, the stronger is their expected effect on performance. The advantages we found for the Diamond compared to the X configuration are well in line with these findings. However, our results suggest that the goodness of a pattern and the distance over which the parts of the pattern are grouped diverge, as is apparent in the results with identical target and CF (Up-Up and Down-Down configurations).

These two configurations (Up-Up and Down-Down) exhibited several results that differentiated them from the other two configurations (Diamond and X). As we measured discriminability, a simple bias to respond with the (less crowded and fixed) CF, which would yield correct responses in Up-Up and Down-Down but not in X and Diamond, cannot explain any (discriminability) advantages in the Up-Up and Down-Down configurations. In Experiment 4 (configuration report), performance in these two configurations was approximately the same, and overall clearly better compared to the other two configurations. One explanation for this effect could be that the Down-Down and Up-Up configurations elicit an emergent feature of translational symmetry. The fact that the discriminability stays high over much larger CF–target distances suggests that translational symmetry is highly salient to human vision and operates over a larger spatial scale than other emergent features. This is in agreement with the Gestalt law of grouping by similarity (see, e.g., Wertheimer, 1923). In line with this explanation, the grouping of identical target–flanker pairs has been shown to operate over large spatial scales in crowding paradigms (Sayim & Cavanagh, 2013; Sayim et al., 2014). For the experiments where the CF was irrelevant to the task (Experiments 1 and 2), results in the Up-Up configuration were different from those in the Down-Down configuration. Specifically, at closer distances, performance in the Up-Up configuration was superior to the Down-Down configuration. As the two configurations are the same except for the (presumably

irrelevant) orientation up or down, we suggest that differences between the configurations are largely due to the fact that they appeared in blocks together with the X and Diamond configurations, respectively. The similarity between the Up-Up and the Diamond curve, together with their difference compared to the Down-Down curve (see Figures 3 and 4), suggests that the effect is indeed due to the Diamond configuration. As the Diamond configuration has the aforementioned good Gestalt characteristics hypothesized to improve performance, the other response alternative in the same block (Up-Up) should benefit as well. Specifically, because the correct response for Up-Up coincides with the absence of the salient Diamond configuration, processing Up-Up as "not Diamond" would entail an advantage—observers could simply report Up-Up when no Diamond was present. The weaker X configuration, on the other hand, would not improve performance in the Down-Down configuration as strongly. Hence, the observed differences between the Up-Up and Down-Down configurations may be attributed to differences between the X and Diamond configurations.

In summary, we have shown that the influence of flankers on crowded target identification is not necessarily a simple monotonic relationship with flanker distance. Instead, configural effects resulting from the grouping of targets and flankers counteract the typically harmful influence of nearby flankers in crowding. The advantage of configurations with salient emergent features shows that strong target–flanker grouping can be beneficial, potentially even without awareness of the specific target–flanker configurations. We propose that these results, taken together, reveal processes involved in the automatic processing of cluttered scenes, whereby the visual system organizes spatial patterns based on inherent rules of Gestalt goodness.

Keywords: emergent features, crowding, periphery, perceptual organization, grouping

Acknowledgments

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References

Banks, W. P., Larson, D. W., & Prinzmetal, W. (1979). Asymmetry of visual interference. *Perception & Psychophysics*, *25*(6), 447–456, https://doi.org/10.3758/BF03213822.

Banks, W. P., & White, H. (1984). Lateral interference and perceptual grouping in visual detection. *Perception & Psychophysics*, *36*(3), 285–295, https://doi.org/10.3758/BF03206370.

Baylis, G. C., & Driver, J. (1992). Visual parsing and response competition: The effect of grouping factors. *Perception & Psychophysics*, *51*(2), 145–162, https://doi.org/10.3758/BF03212239.

Bernard, J.-B., & Chung, S. T. L. (2011). The dependence of crowding on flanker complexity and target-flanker similarity. *Journal of Vision*, *11*(8):1, 1–16, https://doi.org/10.1167/11.8.1. [PubMed] [Article]

Bouma, H. (1970, April 11). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241), 177–178, https://doi.org/10.1038/226177a0.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research*, *13*(4), 767–782, https://doi.org/10.1016/0042-6989(73)90041-2.

Butcher, S. J., & Cavanagh, P. (2008). A unilateral field advantage for detecting repeated elements. *Perception & Psychophysics*, *70*(4), 714–724, https://doi.org/10.3758/PP.70.4.714.

Coates, D. R., Wagemans, J., & Sayim, B. (2017). Diagnosing the periphery: Using the Rey–Osterrieth Complex Figure drawing test to characterize peripheral visual function. *i-Perception*, *8*(3), 1–20, https://doi.org/10.1177/2041669517705447.

Fox, O. M., Harel, A., & Bennett, K. B. (2017). How configural is the Configural Superiority Effect? A neuroimaging investigation of emergent features in visual cortex. *Frontiers in Psychology*, *8*, 32.

Girgus, J. J., Rock, I., & Egatz, R. (1977). The effect of knowledge of reversibility on the reversibility of ambiguous figures. *Perception & Psychophysics*, *22*(6), 550–556, https://doi.org/10.3758/BF03198762.

Geiger, G., & Lettvin, J. Y. (1986). Enhancing the perception of form in peripheral vision. *Perception*, *15*(2), 119–130.

Green, D. M., & Dai, H. (1991). Probability of being correct with 1 of *M* orthogonal signals. *Perception & Psychophysics*, 49(1), 100–101, https://doi.org/10.3758/BF03211621.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2010). Crowding changes appearance. *Current Biology*, 20(6), 496–501, https://doi.org/10.1016/j.cub.2010.01.023.

He, S., Cavanagh, P., & Intriligator, J. (1996, September 26). Attentional resolution and the locus of visual awareness. *Nature*, 383(6598), 334–337, https://doi.org/10.1038/383334a0.

Huckauf, A., & Heller, D. (2004). On the relations between crowding and visual masking. *Perception & Psychophysics*, 66(4), 584–595, https://doi.org/10.3758/BF03194903.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology*, 43(3), 171–216, https://doi.org/10.1006/cogp.2001.0755.

Knoblauch, K. (2014). *Psyphy: Function for analyzing psychophysical data in R* (R package v. 0.1-5) [Computer software]. Retrieved from cran.r-project.org/package=psyphy

Kooi, F. L., Toet, A., Tripathy, S. P., & Levi, D. M. (1994). The effect of similarity and duration on spatial interaction in peripheral vision. *Spatial Vision*, 8(2), 255–279.

Kramer, A. F., & Jacobson, A. (1991). Perceptual organization and focused attention: The role of objects and proximity in visual processing. *Perception & Psychophysics*, 50(3), 267–284, https://doi.org/10.3758/BF03206750.

Lamy, D., Segal, H., & Ruderman, L. (2006). Grouping does not require attention. *Perception & Psychophysics*, 68(1), 17–31.

Latham, K., & Whitaker, D. (1996). A comparison of word recognition and reading performance in foveal and peripheral vision. *Vision Research*, 36(17), 2665–2674, https://doi.org/10.1016/0042-6989(96)00022-3.

Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in peripheral vision: Peripheral crowding is neither size invariant nor simple contrast masking. *Journal of Vision*, 2(2):3, 167–177, https://doi.org/10.1167/2.2.3. [PubMed] [Article]

Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Research*, 25(7), 963–977, https://doi.org/10.1016/0042-6989(85)90207-X.

Levi, D. M., Klein, S. A., & Hariharan, S. (2002). Suppressive and facilitatory spatial interactions in foveal vision: Foveal crowding is simple contrast masking. *Journal of Vision*, 2(2):2, 140–166, https://doi.org/10.1167/2.2.2. [PubMed] [Article]

Livne, T., & Sagi, D. (2007). Configuration influence on crowding. *Journal of Vision*, 7(2):4, 1–12, https://doi.org/10.1167/7.2.4. [PubMed] [Article]

Livne, T., & Sagi, D. (2010). How do flankers' relations affect crowding? *Journal of Vision*, 10(3):1, 1–14, https://doi.org/10.1167/10.3.1. [PubMed] [Article]

Mack, A., Tang, B., Tuma, R., Kahn, S., & Rock, I. (1992). Perceptual organization and attention. *Cognitive Psychology*, 24(4), 475–501.

Macmillan, N. A., & Creelman, C. D. (2005). *Detection theory: A user's guide* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum Associates.

Malania, M., Herzog, M. H., & Westheimer, G. (2007). Grouping of contextual elements that affect vernier thresholds. *Journal of Vision*, 7(2):1, 1–7, https://doi.org/10.1167/7.2.1. [PubMed] [Article]

Manassi, M., Sayim, B., & Herzog, M. H. (2012). Grouping, pooling, and when bigger is better in visual crowding. *Journal of Vision*, 12(10):13, 1–14, https://doi.org/10.1167/12.10.13. [PubMed] [Article]

Manassi, M., Sayim, B., & Herzog, M. H. (2013). When crowding of crowding leads to uncrowding. *Journal of Vision*, 13(13):10, 1–10, https://doi.org/10.1167/13.13.10. [PubMed] [Article]

Moore, C. M., & Egeth, H. (1997). Perception without attention: Evidence of grouping under conditions of inattention. *Journal of Experimental Psychology: Human Perception and Performance*, 23(2), 339–352.

Peirce, J. W. (2007). PsychoPy: Psychophysics software in Python. *Journal of Neuroscience Methods*, 162(1–2), 8–13, https://doi.org/10.1016/j.jneumeth.2006.11.017.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, 4(12):12, 1136–1169, https://doi.org/10.1167/4.12.12. [PubMed] [Article]

Petrov, Y., & Meleshkevich, O. (2011). Asymmetries and idiosyncratic hot spots in crowding. *Vision Research*, 51(10), 1117–1123, https://doi.org/10.1016/j.visres.2011.03.001.

Petrov, Y., Popple, A. V., & McKee, S. P. (2007). Crowding and surround suppression: Not to be confused. *Journal of Vision*, 7(2):12, 1–9, https://doi.org/10.1167/7.2.12. [PubMed] [Article]

Põder, E. (2007). Effect of colour pop-out on the

recognition of letters in crowding conditions. *Psychological Research*, 71(6), 641–645, https://doi.org/10.1007/s00426-006-0053-7.

Poljac, E., de-Wit, L., & Wagemans, J. (2012). Perceptual wholes can reduce the conscious accessibility of their parts. *Cognition*, 123(2), 308–312, https://doi.org/10.1016/j.cognition.2012.01.001.

Pomerantz, J. R., & Garner, W. R. (1973). Stimules configuration in selective attention tasks. *Perception & Psychophysics*, 14(3), 565–569, https://doi.org/10.3758/BF03211198.

Pomerantz, J. R., & Portillo, M. C. (2011). Grouping and emergent features in vision: Toward a theory of basic Gestalts. *Journal of Experimental Psychology: Human Perception and Performance*, 37(5), 1331–1349, https://doi.org/10.1037/a0024330.

Pomerantz, J. R., Sager, L. C., & Stoever, R. J. (1977). Perception of wholes and of their component parts: Some configural superiority effects. *Journal of Experimental Psychology: Human Perception and Performance*, 3(3), 422–435.

Prinzmetal, W., & Banks, W. P. (1977). Good continuation affects visual detection. *Perception & Psychophysics*, 21(5), 389–395, https://doi.org/10.3758/BF03199491.

Saarela, T. P., Sayim, B., Westheimer, G., & Herzog, M. H. (2009). Global stimulus configuration modulates crowding. *Journal of Vision*, 9(2):5, 1–11, https://doi.org/10.1167/9.2.5. [PubMed] [Article]

Sayim, B., & Cavanagh, P. (2013). Grouping and crowding affect target appearance over different spatial scales. *PLoS One*, 8(8), e71188, https://doi.org/10.1371/journal.pone.0071188.

Sayim, B., Greenwood, J. A., & Cavanagh, P. (2014). Foveal target repetitions reduce crowding. *Journal of Vision*, 14(6):4, 1–12, https://doi.org/10.1167/14.6.4. [PubMed] [Article]

Sayim, B., & Wagemans, J. (2017). Appearance changes and error characteristics in crowding revealed by drawings. *Journal of Vision*, 17(11):8, 1–16, https://doi.org/10.1167/17.11.8. [PubMed] [Article]

Sayim, B., Westheimer, G., & Herzog, M. H. (2008). Contrast polarity, chromaticity, and stereoscopic depth modulate contextual interactions in vernier acuity. *Journal of Vision*, 8(8):12, 1–9, https://doi.org/10.1167/8.8.12. [PubMed] [Article]

Sayim, B., Westheimer, G., & Herzog, M. H. (2010). Gestalt factors modulate basic spatial vision. *Psychological Science*, 21(5), 641–644, https://doi.org/10.1177/0956797610368811.

Sayim, B., Westheimer, G., & Herzog, M. H. (2011). Quantifying target conspicuity in contextual modulation by visual search. *Journal of Vision*, 11(1):6, 1–11, https://doi.org/10.1167/11.1.6. [PubMed] [Article]

Scolari, M., Kohnen, A., Barton, B., & Awh, E. (2007). Spatial attention, preview, and popout: Which factors influence critical spacing in crowded displays? *Journal of Vision*, 7(2):7, 1–23, https://doi.org/10.1167/7.2.7. [PubMed] [Article]

Strasburger, H., Harvey, L. O., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception & Psychophysics*, 49(6), 495–508, https://doi.org/10.3758/BF03212183.

Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research*, 32(7), 1349–1357.

Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., & von der Heydt, R. (2012). A century of Gestalt psychology in visual perception: I. Perceptual grouping and figure–ground organization. *Psychological Bulletin*, 138(6), 1172–1217.

Weisstein, N., & Harris, C. S. (1974, November 22). Visual detection of line segments: An object-superiority effect. *Science*, 186(4165), 752–755, https://doi.org/10.1126/science.186.4165.752.

Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt II. *Psychologische Forschung*, 4, 301–350. (Translated extract reprinted as "Laws of organization in perceptual forms." In W. D. Ellis (Ed.), (1938). *A source book of Gestalt psychology* (pp. 71–94). London, UK: Routledge & Kegan Paul Ltd.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, 15(4), 160–168, https://doi.org/10.1016/j.tics.2011.02.005.

Wichmann, F. A., & Hill, N. J. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics*, 63(8), 1293–1313, https://doi.org/10.3758/BF03194544.

Zahabi, S., & Arguin, M. (2014). A crowdful of letters: Disentangling the role of similarity, eccentricity and spatial frequencies in letter crowding. *Vision Research*, 97, 45–51, https://doi.org/10.1016/j.visres.2014.02.001.