Multidimensional feature interactions in visual crowding: When configural cues eliminate the polarity advantage

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Crowding occurs when surrounding objects (flankers) impair target perception. A key property of crowding is the weaker interference when target and flankers strongly differ on a given dimension. For instance, identification of a target letter is usually superior with flankers of opposite versus the same contrast polarity as the target (the "polarity advantage"). High performance when target-flanker similarity is low has been attributed to the ungrouping of target and flankers. Here, we show that configural cues can override the usual advantage of low target-flanker similarity, and strong target-flanker grouping can reduce – instead of exacerbate – crowding. In Experiment 1, observers were presented with line triplets in the periphery and reported the tilt (left or right) of the central line. Target and flankers had the same (uniform condition) or opposite contrast polarity (alternating condition). Flanker configurations were either upright (| |), unidirectionally tilted (\\ or //), or bidirectionally tilted (\/ or /\). Upright flankers yielded stronger crowding than unidirectional flankers, and weaker crowding than bidirectional flankers. Importantly, our results revealed a clear interaction between contrast polarity and flanker configuration. Triplets with upright and bidirectional flankers, but not unidirectional flankers, showed the polarity advantage. In Experiments 2 and 3, we showed that emergent features and redundancy masking (i.e. the reduction of the number of perceived items in repeating configurations) made it easier to discriminate between uniform triplets when flanker tilts were unidirectional (but not when bidirectional). We propose that the spatial configurations of uniform triplets with unidirectional flankers provided sufficient task-relevant information to enable a similar performance as with alternating triplets: strong-target flanker grouping alleviated crowding. We suggest that features which modulate crowding strength can interact non-additively, limiting the validity of typical crowding rules to contexts where only single, independent dimensions determine the effects of target-flanker similarity.

Introduction

Context strongly modulates our perception of objects and their features. For instance, a letter presented in the periphery is usually harder to identify when surrounded by other letters than in isolation. This deleterious effect of surrounding clutter (flankers) on target perception is called crowding (e.g. Bouma, 1970; Chung, Levi, & Legge, 2001; Coates, Chin, & Chung, 2013; Coates, Ludowici, & Chung, 2021; He, Cavanagh, & Intriligator, 1996; Pelli, Palomares, & Majaj, 2004; Sayim, Greenwood, & Cavanagh, 2014; Sayim & Wagemans, 2017; Strasburger, Harvey, & Rentschler, 1991; Stuart & Burian, 1962; Toet & Levi, 1992, for reviews see Herzog, Sayim, Chicherov, & Manassi, 2015; Levi, 2008; Whitney & Levi, 2011). Crowding mainly manifests itself in peripheral vision (for foveal crowding, see Coates, Levi, Touch, & Sabesan, 2018; Malania, Herzog, & Westheimer, 2007; Sayim, Westheimer, & Herzog, 2008a; Sayim et al., 2010; Sayim et al., 2011), limiting various capacities, ranging from reading (Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007; Pelli & Tillman, 2008), to visual search (Carrasco, Evert, Chang, & Katz, 1995; Reddy & VanRullen, 2007; Rosenholtz, Huang, Raj, Balas, & Ilie, 2012; Sayim, Westheimer & Herzog, 2011; Vlaskamp & Hooge, 2006), and object recognition (Levi, 2008; Pelli & Tillman, 2008; Wallace & Tjan, 2011; Whitney & Levi, 2011). Although crowding is usually assumed not to affect target detection (Chung, 2010; Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004), parts of targets or even entire targets are often lost in crowded displays (Coates, Bernard, & Chung, 2019; Sayim & Taylor, 2019; Sayim & Wagemans, 2017; Taylor & Sayim, 2020; Yildirim, Coates, & Sayim, 2019; Yildirim, Coates, & Sayim, 2020; Yildirim, Coates, & Sayim, 2021; Yildirim, Coates, & Sayim, 2022). A particularly strong loss was found in repeating patterns, for example,

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when observers report only two of three presented lines (Yildirim, Coates, & Sayim, 2020; Yildirim, Coates, & Sayim, 2021). This reduction of the number of perceived items is called redundancy masking (Sayim & Taylor, 2019), and has been suggested to contribute to the impaired recognition of crowded targets (Yildirim, Coates, & Sayim, 2020).

Crowding has several key properties. Typically, crowding is stronger when flankers are located closer to the target (Bouma, 1970; Toet & Levi, 1992). Another signature characteristic of crowding is its dependence on target-flanker similarity. Target identification is generally better when the similarity between the target and its surrounding flankers is low. For instance, it was shown that identifying a crowded letter was superior with opposite compared to same contrast polarity flankers (Chung & Mansfield, 2009; Kooi, Toet, Tripathy, & Levi, 1994; Rosen & Pelli, 2015; Rummens & Sayim, 2019; Rummens & Sayim, 2021), a benefit referred to as the "polarity advantage" (Chakravarthi & Cavanagh, 2007). Similarly, previous studies revealed that flanker tilts closer to the target orientation yielded stronger crowding than flanker tilts further away (Andriessen & Bouma, 1976; Hariharan, Levi, & Klein, 2005; He, Wang, & Fang, 2019; Levi, Hariharan, & Klein, 2002; Solomon, Felisberti, & Morgan, 2004; Wilkinson, Wilson, & Ellemberg, 1997). This "similarity rule" of crowding has been shown for a broad range of other features, such as binocular disparity (Astle, McGovern, & McGraw, 2014; Kooi et al., 1994; Sayim et al., 2008a), color (Greenwood & Parsons, 2020; Kooi et al., 1994; Manassi, Sayim, & Herzog, 2012; Põder, 2007; Sayim, Westheimer, & Herzog, 2008a), complexity (Bernard & Chung, 2011; Sayim & Wagemans, 2017), motion (Greenwood & Parsons, 2020), and shape (Kooi et al., 1994; Nazir, 1992; Manassi et al., 2012; Sayim, Westheimer, & Herzog, 2010; but see Melnik, Coates, & Sayim, 2020).

The similarity rule suggests that crowding is always weaker when the closest flankers strongly differ from the target on a given dimension. However, purely local interactions between the target and the innermost flankers do not reliably predict crowding. Instead, performance depends on the whole configuration, and, more specifically, on how strongly a target groups with its global context (the target and all its flankers; e.g. Choung, Bornet, Doerig, & Herzog, 2021; Doerig, Bornet, Rosenholtz, Francis, Clarke, & Herzog, 2019; Herzog & Manassi, 2015; Sayim, Westheimer, & Herzog, 2010; Sayim et al., 2011). For example, offset discrimination for a black vernier was worse when embedded in an array of alternating black and white flanking lines compared to when all flanking lines were white (Sayim et al., 2008a). The innermost flankers were white in both conditions, hence, not the local but the global target context accounted for the different results. In general, local target-flanker similarity falls short when predicting performance in crowding tasks. Instead, how strongly the target groups with its global context needs to be taken into account. Several measures have been proposed to quantify target-flanker grouping. When observers rated how much the target stood out from its flankers, higher target conspicuity was associated with weaker crowding (Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim & Cavanagh, 2013). Similarly, performance in a visual search task was predictive of crowding: targets that "popped out" in visual search were less crowded (Gheri, Morgan, & Solomon, 2007; Sayim, Westheimer, & Herzog, 2011). Moreover, contextual modulation itself was proposed as a measure of grouping strength, with performance in a crowding task quantifying the strength of (target-flanker) grouping (Sayim, Westheimer, & Herzog, 2010). In general, it was shown that when target-flanker grouping was weak, the target stood out from its context, resulting in better performance than when grouping was strong (Banks, Larson, & Prinzmetal, 1979; Livne & Sagi, 2007; Livne & Sagi, 2010; Malania, Herzog, & Westheimer, 2007; Manassi, Sayim, & Herzog, 2012; Rosen & Pelli, 2015; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim, Westheimer, & Herzog, 2010; Sayim et al., 2011).

Conventional crowding rules of spacing, similarity, and grouping have typically been shown using task-irrelevant flankers: observers were asked to report a single target, while processing of the flankers was not required. However, when the context was task-relevant, previous studies showed that conventional crowding rules did not readily apply (Melnik, Coates, & Sayim, 2018; Rummens & Sayim, 2021). For instance, when all letters of a trigram had to be reported, the recognition of the central letter was only minimally better (Chung & Mansfield, 2009) or similar (Rummens & Sayim, 2021) when neighboring letters had opposite compared to identical contrast polarity. These findings are consistent with high target-flanker similarity being less costly when all letters were targets instead of a single letter only (Huckauf & Heller, 2002; Rummens & Sayim, 2021; Zhang, Zhang, Liu, & Yu, 2012). Furthermore, word recognition, a task in which all letters are task-relevant, has been shown to benefit from strong (compared to weak) grouping between adjacent word parts. Specifically, performance was better for words consisting of parts with the same compared to opposite polarity, revealing benefits of uniformity when multiple crowded items were task-relevant (Rummens & Sayim, 2019). Conventional crowding rules were also called into question when target and flankers combined into a configuration with particular emergent features. For example, when stimuli comprised a central target chevron (pointing up or down) flanked by chevrons on all four sides, crowding was surprisingly weaker at closer than at larger spacings between the target and a flanking chevron (Melnik, Coates, & Sayim, 2018). This reversal of the typical effect of target-flanker spacing was attributed to emergent features of the target and the (critical) flanker. The effect of strong grouping yielding weak crowding was increased when observers reported the entire target-flanker configuration (making the critical flanker task-relevant). In a subsequent study, a diamond shape was better recognized among diamonds versus Xs, again showing a reversal of the similarity rule (Melnik, Coates, & Sayim, 2020). These findings suggested that strong grouping of the target with the flankers can – contrary to the generally deleterious effect – alleviate crowding. Taken together, when flankers were task-relevant or informative about target identity by forming a salient configuration with the target, key properties of crowding did no longer apply.

Effects of target-flanker similarity and grouping have typically been investigated by varying similarity on a single feature dimension, while controlling for target-flanker differences on other dimensions. For instance, studies that revealed the polarity advantage with a rotated T-task typically compared performance between stimuli comprising Ts of same versus opposite contrast polarity (e.g. Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Rummens & Sayim, 2021). As all items were Ts, potential effects of shape differences between target and flankers were minimized. When target and flankers did vary on several dimensions (color, spatial frequency, and orientation), multiple features interacted in an additive fashion: performance improved with increasing number of feature dimensions on which the target differed from its flankers (Põder & Wagemans, 2007). Similarly, whereas temporal (i.e. flanker preview; Huckauf & Heller, 2004; Scolari, Kohnen, Barton, & Awh, 2007) and figural ungrouping (Manassi, Sayim, & Herzog, 2013; Sayim, Westheimer, & Herzog, 2010) have been shown to individually reduce – but usually not abolish – crowding, crowding was absent when both types of ungrouping were combined (Sayim, Westheimer, & Herzog, 2008b). Additive effects of features in multiple dimensions were also suggested with foveal studies, revealing that the combined effect of grouping by proximity and (luminance) similarity (Kubovy & van den Berg, 2008) or proximity and collinearity (Claessens & Wagemans, 2005) was equal to the sum of both individual effects.

By contrast, recent crowding studies suggested that multiple features may also interact in a non-additive manner. For instance, as outlined above, whether close target-flanker spacing hindered or helped performance depended on the emergent feature elicited by the combination of the target and flankers (Melnik, Coates, & Sayim, 2018). Similarly, configural cues have been suggested to counteract the typical benefit for target identification when flankers were of opposite compared to same contrast polarity as the target (Rummens & Sayim, 2021; Experiment 3). In the latter study, observers were instructed to report the tilt of the central line (left or right) of three horizontally arranged lines (i.e. triplets), with each line having a left- or rightward tilt (8 possible configurations; see Figure 1A for an example). Interestingly, both with 100 ms and 150 ms presentation duration, there was no polarity advantage: Identification of the central line tilt was similar when target and flankers had the same contrast polarity (uniform condition) compared to the opposite contrast polarity (alternating condition; see Figure 1B). Similar performance in the uniform and alternating conditions suggested that uniform triplets benefitted from configural cues not available in alternating triplets. Hence, the validity of the similarity rule seemed contingent on orientation cues of the stimulus. The lack of an advantage for alternating compared to uniform triplets contrasted with earlier studies showing a polarity advantage with similar stimuli (e.g. a vernier flanked by same or opposite contrast polarity lines; Sayim, Westheimer, & Herzog, 2008a).

In the current study, we examined how the interaction of multiple features – contrast polarity and orientation – conjointly affected crowding. Specifically, we examined whether – and how – flanker orientations affected the polarity advantage in crowding. To this aim, we measured tilt discrimination of a crowded line (Experiment 1). Stimuli comprised three horizontally arranged lines (line triplets). Observers were asked to report the tilt of the central line (either left- or rightward). The orientations of the flanking lines were varied: upright (||), unidirectionally tilted (\\ and //), or bidirectionally tilted (\/ and /\). In two conditions, the flankers had either the same contrast polarity as the target (uniform condition), or the opposite contrast polarity (alternating condition). Within each block, contrast polarity and flanker tilt were kept constant, and only the central line tilt was randomized (left or right). Bidirectional flankers yielded stronger crowding and unidirectional flankers weaker crowding than upright flankers. The polarity advantage was observed with upright and bidirectional but not unidirectional flankers, demonstrating a clear interaction between contrast polarity and orientation.

In two follow-up experiments, we investigated to what extent the two factors "emergent features" (Experiment 2) and "redundancy masking" (Experiment 3) contributed to the absence of the polarity advantage with unidirectional flankers. In Experiment 2, observers performed an odd quadrant task, indicating which line triplet differed from the other three triplets presented. As in Experiment 1, line triplets had unidirectional or bidirectional flankers (no upright flankers), and were uniform or alternating in contrast polarity. The odd line triplet differed from the other three triplets by the central line tilt only. Our results revealed better discrimination between triplets with unidirectional flankers (e.g. \\\ versus \/\) compared to

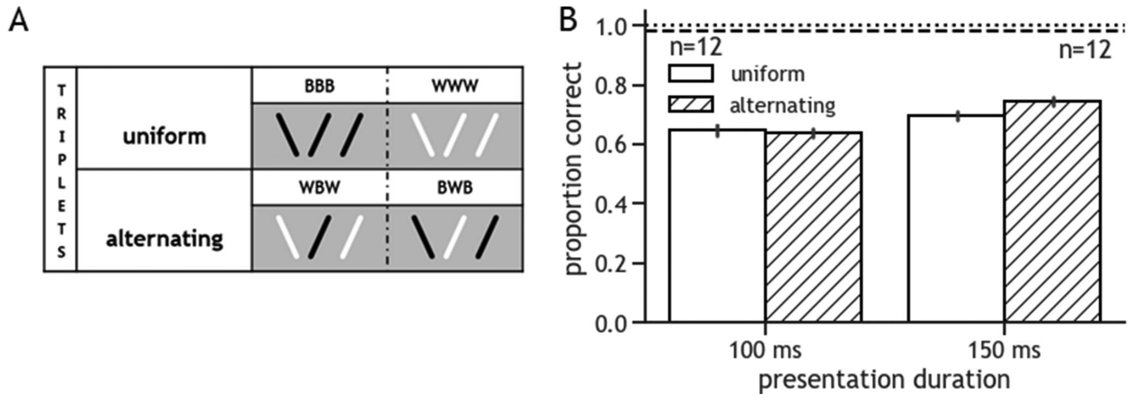

Figure 1. (**A**) Examples of stimuli as used in Rummens and Sayim (2021). Stimuli consisted of three tilted lines that were either uniform or alternating in contrast polarity. Uniform triplets were all white ("WWW") or all black ("BBB"), alternating triplets consisted of a black central line with white flanking lines ("BWB"), or vice versa ("WBW"). Each line was either tilted to the left or right from vertical, resulting in eight possible configurations. (**B**) In two experiments (100 and 150 ms presentation duration; 12 participants each), the polarity advantage was absent when reporting the tilt of the central line. Error bars represent the standard error of the mean. The dotted (dashed) line denotes unflanked performance for 100 (150) ms. Adapted from Rummens and Sayim (2021).

bidirectional flankers (e.g. \\/ versus \//). Specifically, a configural superiority effect was found for triplets with unidirectional flankers, as observers were faster to report the odd-one-out with triplets than with single lines. Triplets with bidirectional flankers did not show a configural superiority effect. Taken together, our findings suggested that emergent features benefitted performance for line triplets with unidirectional flankers only. Importantly, the benefit of emergent features was greater when discriminating between uniform than between alternating triplets with unidirectional flankers.

In Experiment 3, we investigated whether redundancy masking contributed to the good performance with uniform triplets flanked by unidirectional lines in Experiment 1. As redundancy masking most strongly affects highly regular stimuli (Yildirim, Coates, & Sayim, 2020), it is likely that it affected triplets comprised of three similarly tilted lines (\\\- or ///-triplets) but not when the central line was of opposite tilt than both its flankers (\/\- or /\/-triplets). A reduction of the perceived number of identical lines may have provided task-relevant information that facilitated the discrimination of uniform triplets with unidirectional flankers. In Experiment 3, observers reported the number of lines of stimuli comprising three to five tilted black lines. Critically, uniform triplets with uni- and bidirectional flankers, identical to those of Experiment 1, were included. Our findings revealed a reduction of the number of reported lines when all lines were tilted in the same direction (e.g. \\\) but not when triplets contained opposite tilt directions (e.g. \/\). These findings suggested that redundancy masking – similarly to emergent features – benefitted the discrimination between \\\- and \/\-triplets but not between \\/- and \//-triplets.

In sum, we showed that the often-replicated polarity advantage was absent when triplets had flankers with unidirectional tilts. We propose that spatial characteristics of the stimulus – emergent features (Experiment 2) and the susceptibility to redundancy masking (Experiment 3) – likely provided observers with cues that contributed to the good performance with uniform triplets comprising unidirectional flankers (Experiment 1). Spatial configurations formed by only three lines may contain sufficiently potent cues to overcome the usual cost of same versus opposite contrast polarity.

Experiment 1: Tilt discrimination task

Method

Subjects

Eight observers (men = 3, women = 5; age range = 21–28 years) with self-reported normal or corrected-to-normal vision participated. Prior to the experiment, all participants provided their written informed consent. Experiments were in accordance with the ethical standards of the Declaration of Helsinki, and approved by the Ethics Committee of the University of Bern.

Apparatus

A custom-written Python program was run by Psychopy2 (Peirce, Gray, Simpson, MacAskill,

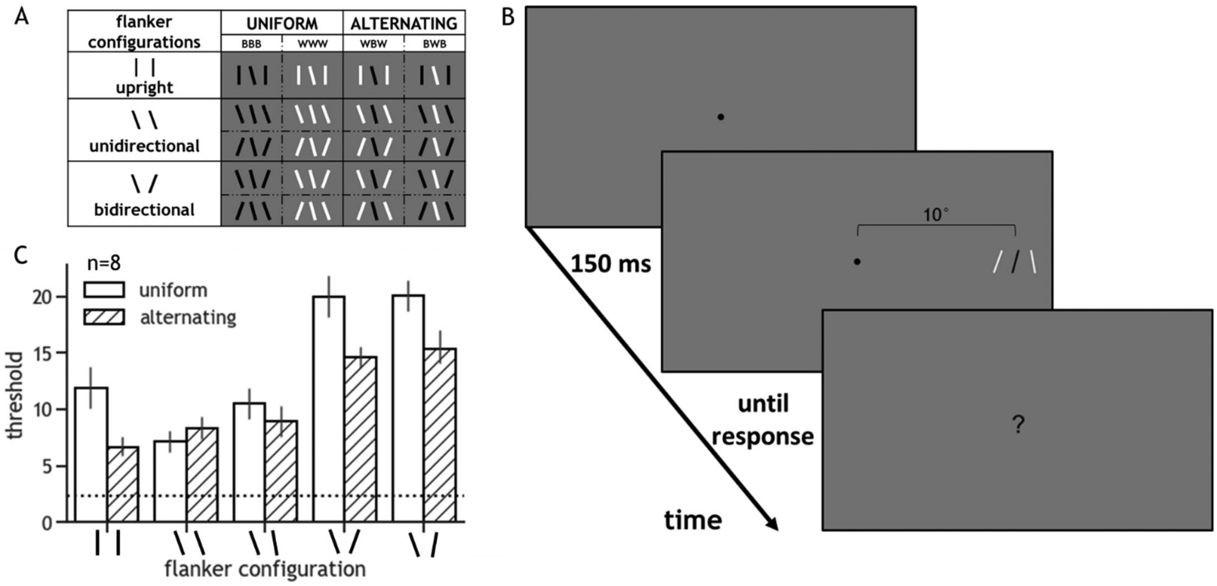

Figure 2. Overview of the stimuli (**A**), procedure (**B**), and results (**C**). (**A**) Stimuli were line triplets, either uniform or alternating in contrast polarity. Uniform triplets consisted of all black (BBB) or all white (WWW) lines. Alternating triplets comprised a black central line with white flankers (WBW) or vice versa (BWB). Flanker tilts were either upright (||), unidirectional (\\ or //), or bidirectional (\/ or /\). Upright flankers had no tilt, uni- and bidirectional flankers had tilts of −20 degrees, -10 degrees, 10 degrees, or 20 degrees. Uni- and bidirectional flanker tilts were either symmetrical (same absolute values) or asymmetrical (different absolute values). (Only symmetrical configurations with tilts of 20 degrees in absolute value are depicted.) (**B**) Time course of a trial, showing an alternating triplet with non-symmetrical bidirectional flankers. (**C**) Results of the tilt discrimination experiment. Thresholds are displayed as a function of flanker configurations, separately for uniform and alternating triplets. Error bars indicate the standard error of the mean. The dotted line denotes the 75 percent correct threshold of the unflanked condition. With uniform and alternating triplets combined, performance was superior with unidirectional compared to upright and bidirectional flankers. The polarity advantage was shown for triplets with upright and bidirectional flankers, but was surprisingly absent when flankers had unidirectional tilts.

Höchenberger, Soso, Kastman, & Lindeløv, 2019) on a PC computer. Stimuli were displayed on a 22 inch CRT monitor (HP, p1230, refresh rate = 110 Hz, resolution = 1152 × 864). Supported by a head- and chinrest, observers were seated at 57 cm distance from the screen in a dimly lit room.

Stimuli

Stimuli (see Figure 2A) were line triplets comprising three adjacent lines, each of 1 degree height and 0.07 degrees width. Lines were 0.75 degrees apart, horizontally arranged, and centered on the horizontal meridian. Line triples were centered at 10 degrees eccentricity, and randomly shown in the left or right hemifield. The tilt of the central target line was varied with an adaptive QUEST-procedure (Watson & Pelli, 1983), with a random clockwise or counterclockwise tilt of 15 degrees from vertical as the starting value. There were three types of flanker configurations: flanking lines were either vertical (*upright* flankers: ||), were both tilted to the left or right (*unidirectional* flankers: \\ or //), or had one leftward and one rightward tilt (*bidirectional* flankers: \/ or /\). When tilted, flanker orientations comprised all possible combinations of 10 degrees or 20 degrees counterclockwise or clockwise tilts from vertical. Uni- and bidirectional flankers were *symmetrical* when identical in absolute value, or *non-symmetrical* when absolute values of the left and right flanker differed. Overall, seventeen flanker configurations (1 upright, 8 unidirectional, and 8 bidirectional flanker configurations), and a no-flanker condition were included. Lines were either *uniform* or *alternating* in contrast polarity. Uniform stimuli consisted of all black (0.02 cd/m^2; “BBB”) or all white (89.9 cd/m^2; “WWW”) lines. Alternating stimuli consisted of a black central line with white outer lines (“WBW”), or vice versa (“BWB”). Line triplets were displayed on a middle grey background (45.0 cd/m^2).

Procedure

We measured orientation discrimination for the central line within a line triplet. Line triplets varied in contrast polarity and flanker configurations. Neighboring lines were of the same contrast polarity in uniform triplets, and of opposite contrast polarity in alternating triplets. Both for uniform and for alternating triplets, we measured tilt discrimination for the central line when surrounded by the different flanker configurations introduced above.

The experiment comprised two sessions of approximately 75 minutes each, which were separated by a 30-minute break. At the beginning of each session, we measured performance for unflanked black or white lines. In each session, observers completed all flanker configurations for two contrast polarity conditions. Trials were blocked by contrast polarity and flanker configuration. Each block consisted of 50 trials, preceded by four practice trials that were not part of the QUEST-staircase. The contrast polarity condition switched after every block. The order of contrast polarity conditions and the order of flanker configurations for each contrast polarity condition were randomized. Each participant completed 3500 trials (3400 flanked; 100 unflanked) in total.

Task

Observers were asked to judge the tilt direction, either left- or rightward relative to the vertical, of the central line within a line triplet. The experimental procedure is depicted in Figure 2B. First, a black fixation dot was presented in the center of the screen. Participants were instructed to focus on the fixation dot throughout each trial. Upon key press, a triplet was presented for 150 ms at 10 degrees eccentricity randomly to the left or right of the fixation dot. After stimulus presentation, the fixation dot remained on the screen for 50 ms. Next, a question mark was presented until observers pressed “s” for a leftward or “k” for a rightward tilt.

Results

Per participant, we obtained the 75% correct thresholds for each condition of contrast polarity by flanker configuration. Thresholds for uniform BBB- and WWW-triplets were averaged as well as for alternating WBW- and BWB-triplets. Results are displayed in Figure 2C. We conducted a repeated measures ANOVA including the thresholds as dependent variable, and both contrast polarity (uniform and alternating) and flanker configurations (upright, and both the symmetrical and nonsymmetrical variants of unidirectional and bidirectional flanker configurations) as factors. All post hoc pairwise comparisons were Tukey tests.

We found a main effect of contrast polarity. All flanker configurations taken together, tilt discrimination for the central line was better for alternating compared to uniform line triplets ($F(1,7) = 45.80$, $p < 0.001$, $\eta^2 = 0.07$). A main effect of flanker configuration ($F(4,28) = 29.13$, $p < 0.001$, $\eta^2 = 0.50$) was characterized by worse performance for bidirectional flanker tilts (symmetrical and asymmetrical) compared to both unidirectional (symmetrical and asymmetrical) and upright flankers (p values for all six comparisons: < 0.001). Performances of the upright, symmetrical unidirectional, and asymmetrical unidirectional flankers did not differ (all p values > 0.52), neither did performances of symmetrical and asymmetrical bidirectional flankers ($p > 0.99$). The effect of contrast polarity depended on flanker configurations ($F(4,28) = 4.15$, $p < 0.001$, $\eta^2 = 0.05$). Performance for alternating compared to uniform line triplets was superior for upright ($p < 0.02$) and bidirectional flankers (symmetrical: $p = 0.01$; asymmetrical: $p < 0.04$), but similar for unidirectional flankers (symmetrical: $p = 1.0$; asymmetrical: $p = 0.98$).

Next, we examined whether the magnitude of flanker tilts in the uni- and bidirectional flankers condition affected thresholds (see Figure 3). Uni- and bidirectional flanker configurations had absolute average deviations from the vertical of 10, 15, and 20 degrees. Absolute tilts averaged to 10 and 20 degrees when symmetrical, and to 15 degrees when asymmetrical. For example, asymmetrical bidirectional flankers with one flanker tilted by 10 degrees to the left and the other by 20 degrees to the right have an average absolute tilt of 15 degrees. To test for any differences in threshold depending on tilt magnitude of the flankers, we ran a repeated measures ANOVA with flanker configuration (uni- and bidirectional tilts), absolute deviation from vertical (10 degrees, 15 degrees, and 20 degrees), and contrast polarity (uniform and alternating) as factors, and thresholds as dependent variable. A main effect of deviation from vertical ($F(2,14) = 6.94$, $p < 0.01$, $\eta^2 = 0.02$) indicated better performance with 10 degree tilts compared to both other tilts (10 degrees versus 15 degrees: $p < 0.05$; 10 degrees versus 20 degrees: $p < 0.05$). Thresholds were lower for alternating compared to uniform triplets ($F(1,7) = 17.70$, $p < 0.01$, $\eta^2 = 0.04$), and for uni- relative to bidirectional tilts ($F(1,7) = 46.84$, $p < 0.001$, $\eta^2 = 0.51$). As shown in our first analysis, the effect of contrast polarity depended on flanker configuration ($F(1,7) = 16.81$, $p < 0.01$, $\eta^2 = 0.05$). Furthermore, we found a three-way interaction between flanker configuration, average flanker tilt, and contrast polarity ($F(2,14) = 5.07$, $p < 0.05$, $\eta^2 = 0.02$).

With unidirectional flankers, the flankers' absolute deviation from vertical affected thresholds neither for uniform (p values of all three comparisons above 0.19) nor for alternating triplets (p values of all three comparisons above 0.99). With bidirectional flankers, we found a linear increase in thresholds with increasing average tilt for uniform bidirectional triplets (10 degrees versus 20 degrees: $p < 0.01$) but no difference between tilts for its alternating counterparts (10 degrees versus 20 degrees: $p = 1.0$).

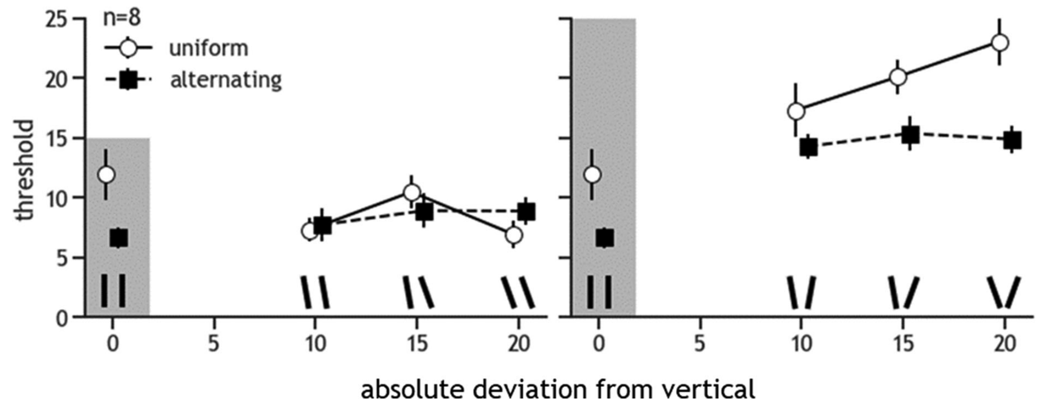

Figure 3. Thresholds plotted as a function of the flankers' average absolute deviation from vertical (in degrees), separately for uniform (left graph) and alternating (right graph) triplets. Thresholds for unidirectional and bidirectional flankers are shown in the left and right graph, respectively. Both graphs show the thresholds of upright flankers (0 degrees average tilt) on a grey background. With unidirectional flankers, thresholds for neither uniform nor alternating triplets were affected by the flankers' absolute deviation from the vertical. With bidirectional flankers, the polarity advantage increased with larger absolute deviations from vertical.

Discussion

The findings of Experiment 1 revealed that the effect of contrast polarity strongly depended on the flanker configuration. When flankers were upright or bidirectional, the typical polarity advantage was found, with superior tilt discrimination in alternating compared to uniform triplets. Surprisingly, there was no polarity advantage when flankers were unidirectional, with no difference in performance between uniform and alternating triplets. In fact, with unidirectional flankers, the polarity advantage was absent for all average absolute flanker deviations from the vertical (10, 15, and 20 degrees). Interestingly, with bidirectional flankers, there was a clear polarity advantage, which increased linearly with larger absolute deviation of the flankers from the vertical.

Despite good overall performance for uniform triplets with unidirectional flankers, the absence of the polarity advantage with unidirectional flankers cannot be explained by ceiling performance. The thresholds for uniform triplets with unidirectional flankers (both for asymmetrical and symmetrical) are above 2.5 times the single line performance, leaving plenty of margin for improvement. Instead, we propose that the spatial configuration formed by the central line and both flankers played a key role for the absence of the polarity advantage with unidirectional flankers. Importantly, because flanker tilts and contrast polarity did not vary within a block, one out of two possible triplets was presented on each trial. Therefore, if performance for one of the triplets within a block benefitted from a salient configural cue, performance for the other triplet could similarly gain from the absence of such a cue. Specifically, we hypothesized that observers could use configural cues that facilitated discriminating between uniform triplets with unidirectional flankers (\\\ versus \/\ and /// versus /\/) but not (or to a lesser extent) between uniform triplets with bidirectional flankers (\\/ versus \// and //\ versus /\\). If so, the advantage of configural cues for uniform triplets with unidirectional flankers may have enabled similar performance as with alternating triplets. The presence of the polarity advantage with bidirectional flankers seems to indicate that performance for uniform triplets with bidirectional flankers could not – or only minimally – benefit from configural cues, resulting in the typical worse performance for uniform compared to alternating stimuli.

Experiment 2: Odd quadrant task

In Experiment 2, we used an odd quadrant task (e.g. Pomerantz, Sager, & Stoever, 1977) to examine whether emergent features facilitated discriminating between uniform triplets with unidirectional (\\\ versus \/\ and /// versus /\/) but not with bidirectional flankers (\\/ versus \// and /\\ versus //\).

Method

Subjects

Ten new observers (9 women and 1 man) between 19 and 47 years old participated for course credit. All subjects had normal or corrected-to-normal vision, and provided informed consent prior to the experiment.

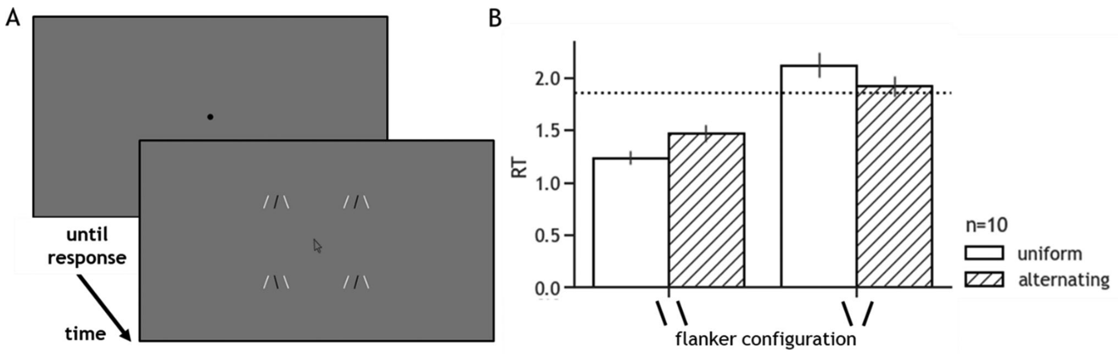

Figure 4. Procedure (**A**) and results (**B**) of the odd quadrant task in experiment 2. (**A**) Each trial of the odd quadrant task started with a central fixation dot. Upon key press, four-line triplets were presented in a two-by-two configuration. One of the four triplets was unique, and observers were instructed to click the "odd" triplet as fast and accurate as possible with the mouse. (**B**) Separately for uniform and alternating triplets, correct RT was plotted as a function of flanker tilt, with unidirectional flankers on the left (\\ and //) and bidirectional flankers on the right (\/ and /\). The dotted line shows the performance for unflanked lines (black and white combined). Performance below the dotted line indicates configural superiority. Error bars indicate the standard error of the mean. Better performance for triplets with unidirectional tilts compared to single lines indicated a configural superiority effect. There was no configural superiority for triplets with bidirectional flankers. The effect of contrast polarity depended on flanker configuration: RTs for uniform compared to alternating triplets were faster with unidirectional flankers, but slower with bidirectional flankers.

Apparatus

Apparatus was identical to Experiment 1.

Stimuli

Stimuli consisted of four simultaneously presented line triplets, each centered in a six-by-six degrees quadrant. Quadrants were arranged in a two-by-two matrix. A line triplet appeared 4.24 degrees away from the screen center (see Figure 4A for an example). Line triplets were identical to those of Experiment 1: three horizontally arranged, near-vertical lines of 1 degree height and 0.07 degrees width were separated by a spacing of 0.75 degrees. The tilt of the central line was 15 degrees clockwise or counterclockwise from vertical, and – different from Experiment 1 – only absolute flanker tilts of 20 degrees but not 10 degrees were included. Uniform triplets consisted of all black (BBB-triplets) or white lines (WWW-triplets), alternating triplets had a black central line with white flankers (WBW-triplets) or the other way around (BWB-triplets). Luminance values of black (0.02 cd/m^2), white (45.0 cd/m^2), and grey (89.9 cd/m^2) were the same as in Experiment 1. Four flanker configurations were included: \\ and // had unidirectional tilts, and \/ and /\ had bidirectional tilts. Each stimulus consisted of three quadrants with identical line triplets, and of one "odd quadrant" containing a triplet differing from the other triplets by the central line tilt only. In the baseline condition, each quadrant contained a single tilted line, with one line of opposite tilt compared to the three other lines. Single lines were either all black or all white. The location of the odd quadrant was randomized.

Procedure

Observers were instructed to indicate the line triplet (or single line in the baseline condition) that differed from the others as fast and accurate as possible. Every trial began with a fixation dot presented in the center of the screen. When pressing the spacebar, the stimulus was presented until response, and the fixation dot was replaced by the mouse pointer. Participants responded by clicking one of the four triplets with the mouse. The experimental procedure is shown in Figure 4A.

Trials were blocked in identical fashion to Experiment 1 (i.e. by flanker configuration \\, //, \/, and /\ and contrast polarity WWW, BBB, BWB, and WBW), resulting in 16 different conditions. Additionally, observers completed two baseline conditions, one with single black lines and one with single white lines. All conditions were performed in randomized order. Overall, 18 blocks of 50 trials (900 trials) were completed. We registered accuracy (correct or incorrect) and reaction time (i.e. the time between stimulus onset and response).

Results

Results for BBB- and WWW-triplets were combined (uniform condition), as well as those for WBW- and BWB-triplets (alternating condition). After the removal of incorrect responses (1.9 percent of all trials), trials with reaction times (RTs) of more than two standard deviations below or above the individual mean were excluded. If subtracting two standard deviations from the individual mean had an outcome below 100 ms, 100 ms was used as a cutoff as such fast RTs would not reflect the process of interest (Luce, 1991). Overall, 3.9 percent of the accurate trials were excluded. We performed a repeated-measures ANOVA with RT as the dependent variable, and contrast polarity (uniform or alternating) and flanker configuration (unidirectional or bidirectional) as factors. All post hoc pairwise comparisons were Tukey tests.

We found a main effect of flanker configuration ($F(1,9) = 120.98$, $p < 0.001$, $\eta^2 = 0.81$): RTs were faster for triplets with unidirectional compared to bidirectional tilts, and Tukey tests revealed this unidirectional advantage both for uniform ($p < 0.001$) and alternating ($p < 0.001$) triplets. Furthermore, the interaction between flanker configuration and contrast polarity ($F(1,9) = 24.09$, $p < 0.001$, $\eta^2 = 0.08$) was characterized by better performance for uniform compared to alternating triplets with unidirectional flankers ($p < 0.01$), and worse performance with bidirectional flankers ($p = 0.01$).

Discussion

The findings of the odd quadrant task demonstrated that, regardless of stimulus uniformity, discriminating between triplets when flankers were unidirectional was superior than when bidirectional. Triplets with unidirectional flankers showed a clear configural superiority effect: Compared to performance with single lines, discrimination was markedly enhanced when unidirectional flankers were added. In particular, the better discrimination between triplets with unidirectional flankers (e.g. \\\ versus \/\) compared to without flankers suggested that performance could benefit from emergent features: the absence versus the presence of all parallel lines was rather easy to detect. As performance was not better with bidirectional flankers than without flankers, there was no configural superiority for triplets with bidirectional flankers. Similar performance for triplets with bidirectional flankers versus single lines suggested that the addition of flanking lines did not elicit configural cues that facilitated discrimination. In fact, all triplets with bidirectional flankers (\\/ and \// and //\ and /\\) were similarly characterized by the emergent features of parallelism and mirror symmetry (Stupina, 2011), which may explain why these configural cues were not particularly helpful for their discrimination. Taken together, emergent features seem to have benefitted performance for triplets with unidirectional flankers but not bidirectional flankers.

Furthermore, the effect of contrast polarity was dependent on flanker configuration. Triplets with unidirectional flankers showed a clear configural superiority effect, with worse performance for alternating compared to uniform triplets. The smaller configural superiority effect for alternating compared to uniform triplets suggested that the advantage of emergent features weakened when lines alternated in contrast polarity. With bidirectional flankers, where performance did not benefit from emergent features, performance was worse with uniform compared to alternating triplets. Hence, flanking lines of opposite contrast polarity compared to same contrast polarity benefitted performance in the absence of relevant emergent features (bidirectional flankers), but deteriorated performance when present (unidirectional flankers).

The results of the odd quadrant task showed a clear configural superiority effect for triplets with unidirectional flankers but not with bidirectional flankers. Importantly, when flankers were unidirectional, the configural superiority effect was greater for uniform compared to alternating triplets. The larger benefit of emergent features when unidirectional flankers had the same compared to the opposite contrast polarity as the target may well play a role in the absence of the polarity advantage with identical stimuli in Experiment 1. Specifically, the greater advantage of emergent features in uniform compared to alternating triplets revealed in Experiment 2 seems to have overcome the usual stronger crowding cost of same versus opposite contrast polarity flankers, resulting in similar performance for uniform and alternating triplets with unidirectional flankers in Experiment 1. With bidirectional flankers, there was no configural superiority effect, suggesting that observers did not benefit from any configural cues. Performance was better with alternating compared to uniform triplets with bidirectional flankers, similar to the polarity advantage revealed with identical stimuli in Experiment 1.

Experiment 3: Enumeration task

In Experiment 3, we investigated whether redundancy masking (Sayim & Taylor, 2019; Yildirim, Coates, & Sayim, 2020) may have contributed to the good performance for uniform triplets with unidirectional flankers in Experiment 1. Because redundancy masking is usually stronger with highly regular stimuli (Yildirim, Coates, & Sayim, 2020), we predicted that a reduction in the number of perceived lines would mainly occur for highly regular \\\- and ///-triplets, but not for the less regular \/\- and /\/-triplets. Therefore, redundancy masking might have improved the discrimination between triplets of three similarly tilted lines and triplets with the central line of opposite tilt to both its flankers. By contrast, redundancy masking should not differentially affect the enumeration of triplets with bidirectional flankers. In fact, given the low regularity of triplets with bidirectional flankers, redundancy masking would be expected not to occur at all. If –

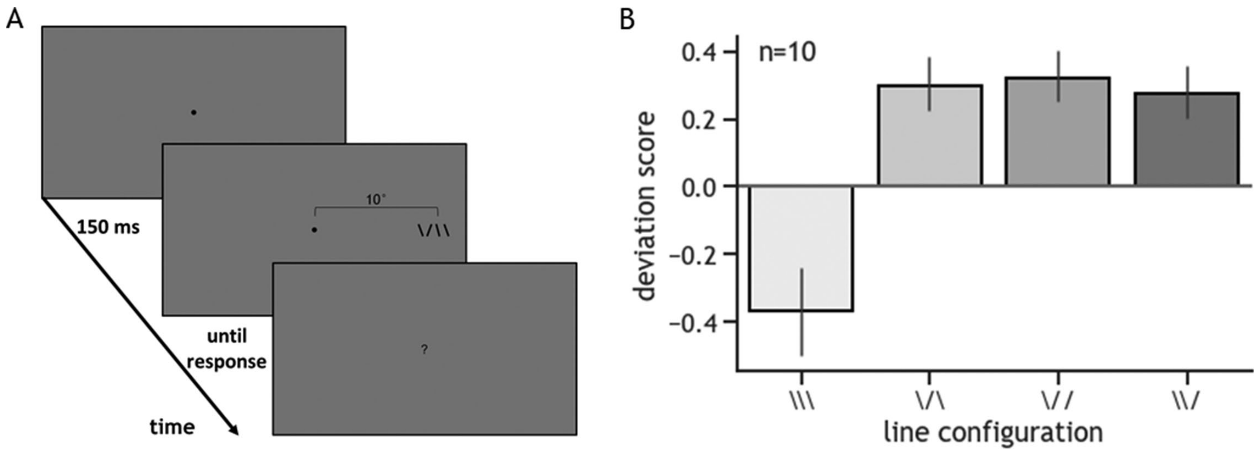

Figure 5. Procedure (**A**) and results (**B**) of the enumeration task in experiment 3. (**A**) Each trial began with a central fixation dot. Upon key press, a three-, four-, or five-line stimulus was presented for 150 ms in the left or right visual field. Following the stimulus presentation, observers responded with a number between zero and nine. (**B**) Deviation scores of triplets – calculated as the number of lines presented subtracted from the number of lines reported – are shown for each line configuration. Four- and five-line stimuli were shown as fillers and thus discarded. Scores were combined for equivalent triplets (\\\ and ///; \/\ and /\/; \// and /\\; and \\/ and //\). A deviation score of below zero (below the green line) indicates reporting less than the number of lines presented ("under-reporting"), and a deviation score larger than zero (above the green line) means reporting more than the number of presented lines ("over-reporting"). On average, \\\- and ///-triplets were under-reported, suggesting that these triplets were affected by redundancy masking. All other triplets were over-reported, showing no redundancy masking.

despite the limited regularity - redundancy masking were to affect triplets with bidirectional flankers, we would expect a similar effect on the enumeration of all triplet variants with bidirectional flankers as they all possess an equal amount of repetitions. Thus, we did not expect redundancy masking to improve the differentiation between triplets with bidirectional flankers. To probe our hypothesis, observers were presented with three to five tilted black lines and asked to report the number of lines.

Method

Subjects

All 10 observers of Experiment 2 participated in Experiment 3.

Apparatus

Apparatus was identical to Experiments 1 and 2.

Stimuli

Stimuli consisted of three to five near-vertical black lines that were horizontally arranged. Triplets were identical to those of Experiment 1, comprising tilted lines each of 1 degree height and 0.07 degrees width. The spacing between lines was 0.75 degrees. The left- or rightward tilt was again 15 degrees for the central line and 20 degrees for the flanking lines, resulting in eight possible line configurations: four configurations had unidirectional flanking lines (\\\, ///, \/\, and /\/) and four had bidirectional flanking lines (\//, \\/, /\\, and //\). The central line of a line triplet was centered at 10 degrees eccentricity, and presented in either the left or right visual field. Four-line stimuli were generated by randomly adding a line on the left or right side of a triplet, and five-line stimuli had an additional line on both sides of a triplet. The tilt(s) of the additional line(s) of four- and five-line stimuli were randomly chosen from the tilts of the triplet's outer lines (without replacement). All stimuli thus had one of the eight triplets at its core (i.e. "core triplets"), to which zero, one, or two tilted lines were added. Given the study objective, we were only interested in the performance with regard to the three-line stimuli. Four- and five-line stimuli were only included as fillers to obtain a certain variance in the correct number response.

Procedure

The procedure of the enumeration task is shown in Figure 5A. The task was to report the number of presented lines. Observers were instructed to focus on the fixation dot in the center of the screen. When pressing the spacebar, a line stimulus was presented for 150 ms, randomly in the left or right hemifield. After stimulus presentation, a question mark replaced the fixation dot, indicating that a response between zero and nine needed to be given with the number pad.

Stimuli varied in the number of lines and their core triplet. Trials were blocked by the tilt of the core triplets' outer lines (unidirectional or bidirectional). Half of the observers started with a unidirectional block, the other half with a bidirectional block. Blocks alternated between uni- and bidirectional. Each block consisted of 120 trials, with 30 trials – equally divided among three-, four-, and five-line stimuli – for each of the four core triplets. Within each block, trials were presented in random order. Observers performed 8 blocks or 960 trials (320 test and 640 filler trials) in total.

Results

Our aim was to investigate whether redundancy masking contributed to the discriminability of uniform triplets with unidirectional outer lines (\\\ & /// versus \/\ & /\/), but not between triplets with bidirectional outer lines (\\/ & //\ versus \// & /\\). We calculated the average deviation scores for triplets, subtracting the number of lines presented from the number of lines perceived. The deviation scores for equivalent triplets (\\\ & ///; \/\ & /\/; \\/ & //\; & \// & /\\) were combined. Deviation scores below zero indicated "under-reporting," with observers reporting less than the number of presented lines. Deviation scores above zero indicated "over-reporting," with observers reporting more than the number of presented lines.

A repeated measures ANOVA with deviation scores as dependent variable revealed a main effect of line configuration ($F(3,27) = 26.98$, $p < 0.001$, $\eta^2 = 0.75$), the only factor included in the model. Tukey tests revealed different deviation scores for \\\- & ///-triplets (negative deviation scores) compared to \/\- & /\/-triplets (positive deviation scores; $p < 0.001$), and no difference between \\/- & //\-triplets versus \//- & /\\-triplets (both positive deviation scores; $p = 0.60$; see Figure 5B).

Discussion

Our results showed that the number of perceived lines strongly depended on the tilt of the triplets' constituting lines. Redundancy masking – as indicated by deviation scores below zero – occurred for \\\-triplets but not for \/\-triplets. On average, triplets of three similarly tilted lines were under-reported, whereas triplets with a central line of opposite tilt to its flanking lines were over-reported. Redundancy masking did not occur for triplets with bidirectional flankers, as the reported number of lines was larger than the presented number of lines for both \//- and \\/-triplets.

Enumeration errors thus differed between \\\- and \/\-triplets: whereas \\\-triplets were under-reported, \/\-triplets were over-reported. Such differences in enumeration errors – and thus in the perceived number of lines – may have been beneficial when discriminating between triplets with unidirectional flankers. Although the task of Experiment 1 required reporting the tilt of the central triplet line only, performance may have benefitted from the surplus in task-relevant information provided by the presence (\\\-triplets) versus absence (\/\-triplets) of redundancy masking. We suggest that performance for uniform triplets with unidirectional flankers in Experiment 1 benefitted from the differential effect of redundancy masking, likely contributing to a similar performance level between uniform and alternating triplets. As the number of lines in \\/- and \//-triplets were equally overestimated, tilt discrimination of the central line in Experiment 1 could not benefit from systematic differences in the number of perceived lines between both line configurations.

General discussion

We investigated whether the usual deleterious effect of high target-flanker similarity in crowding is dependent on the spatial configuration formed by target and flankers. With an orientation discrimination experiment (Experiment 1), we tested whether flanker orientations influenced the usual advantage of opposite versus same contrast polarity flankers. Our findings demonstrated that the orientation of the flanking lines modulated the effect of contrast polarity. The polarity advantage was observed when flankers were upright and bidirectionally tilted. However, when flankers had unidirectional tilts, the polarity advantage was absent: Performance did not differ between alternating and uniform triplets. We hypothesized that the absence of the polarity advantage was due to task-relevant information available in uniform triplets with unidirectional flankers, sufficiently advantageous to compensate for the usual cost of same contrast polarity flankers. In particular, we propose that configural cues elicited by uniform triplets with unidirectional flankers enabled similar performance as with alternating triplets. Because our findings did show the polarity advantage with upright and bidirectional flankers, we suggest that observers could not benefit from configural cues when uniform triplets had these flanker configurations.

To test these hypotheses, we investigated if emergent feature differences between the configurations could have contributed to the pattern of results observed in Experiment 1. In Experiment 2, we examined whether emergent features may have facilitated discriminating between triplets with unidirectional but not with bidirectional flankers. In an odd-quadrant experiment, a standard paradigm to study emergent features (Pomerantz et al., 1977), observers indicated the line triplet with a central line tilt different from the other three triplets. Triplets identical to those of Experiment 1 were tested. As all four triplets had identical flankers on every trial, flanker configurations by themselves did not possess any informational value for the task at hand. The better discrimination between triplets with unidirectional flankers than between single lines indicated a clear configural superiority effect: emergent features elicited by the target and flankers benefitted performance. With bidirectional flankers, there was no configural superiority effect. Performance was not better with than without flankers, showing no benefit of emergent features. Hence, emergent features seemed to affect performance when discriminating between triplets with unidirectional flankers but not with bidirectional flankers.

In Experiment 3, with an enumeration task, we investigated whether redundancy masking may have contributed to the good performance for uniform triplets with unidirectional flankers in Experiment 1. Observers were presented with three to five black tilted lines, and had to report the number of lines. We were particularly interested in how redundancy masking affected the enumeration of uniform triplets with uni- and bidirectional flankers, identical to the stimuli used in Experiment 1. Our findings showed that redundancy masking – as indicated by under-reporting the number of lines – occurred for triplets of lines with similar tilts (\\\- and ///-triplets) but not for triplets containing opposite line tilts. Redundancy masking thus differentially affected triplets with unidirectional flankers: triplets of similarly tilted lines were under-reported, whereas triplets with a central line of opposite tilt to both its flanking lines were over-reported. With bidirectional flankers, redundancy masking did not affect performance, as both \\/- and \//-triplets were over-reported. Taken together, we propose that redundancy masking as well as emergent features provided additional task-relevant information when discriminating between uniform triplets with unidirectional flankers, enabling similar performance in uniform and alternating triplets with unidirectional flankers in Experiment 1.

In Experiment 1, for triplets with upright flankers, thresholds were clearly higher in the uniform condition than in the alternating condition. This finding replicated the usual advantage for conditions in which the flankers differed from the target compared to flankers similar to the target (e.g. Kooi et al., 1994; Manassi et al., 2012; Nazir, 1992; Põder, 2007; Sayim et al., 2008a). In particular, the results replicated the "polarity advantage" – flankers of opposite contrast polarity than the target interfered less with target discrimination than flankers of the same contrast polarity. The polarity advantage has been reported for various stimuli, including verniers (Sayim et al., 2008a), rotated Ts (Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Rummens & Sayim, 2021), and letters (Rosen & Pelli, 2015; Rummens & Sayim, 2019; Rummens & Sayim, 2021). In a previous study, vernier targets were flanked by upright lines, resembling the tilted targets flanked by upright flankers used here (Sayim et al., 2008a). The results were similar in the two studies: better offset discrimination of a vernier with opposite than with same contrast polarity flankers (Sayim et al., 2008a), and better orientation discrimination when upright flanking lines were of opposite contrast compared to same contrast polarity (present experiment). The same pattern of results was found when similar stimuli varied in color (red and green), in foveal (Sayim et al., 2008a) and peripheral (Manassi et al., 2012) vision. Hence, the effect of contrast polarity was as expected when flankers were upright: the orientation of a crowded line was better recognized with opposite compared to same contrast polarity flankers.

The polarity advantage was also revealed when flankers were bidirectional. However, the overall performance level in the bidirectional and upright condition differed greatly: tilt discrimination was much worse with bidirectional compared to upright flankers. In the uniform condition, thresholds were nearly twice as high for bidirectional as for upright flankers, and in the alternating condition, more than twice as high. In both conditions (upright and bidirectional), the *absolute* polarity advantage was comparable – thresholds were about 6 degrees lower with alternating than with uniform flankers. Consequently, the *relative* polarity advantage differed markedly: While thresholds for triplets with upright flankers were about half as high in the alternating condition compared to the uniform condition, the relative improvement in the bidirectional condition was only about 25 percent. In the bidirectional condition, the opposite contrast polarity of the flankers was clearly not sufficient to reduce thresholds to the same level as with upright flankers. Spatial factors that were counteracted only to a limited degree by opposite polarity flankers must underlie the still relatively poor performance with bidirectional flankers in the alternating condition.

The overall performance with unidirectional flankers was best, with thresholds in the uniform and alternating condition similarly low (7.14 and 8.31 degrees, respectively). Performance in the alternating condition here was similar as in the alternating condition with upright flankers. This result was not surprising and well in line with what would be expected if the polarity advantage did not strongly interact with orientation cues of the flankers. However, in contrast to upright flankers, thresholds were similarly low with uniform as with alternating contrast polarity in the unidirectional condition. Like the overall bad performance with bidirectional flankers, the high performance with uniform, unidirectional flankers must be due to (facilitating) spatial factors. If spatial factors and contrast polarity independently modulated performance, one prediction would be that their effects add up (as long as there were no ceiling or floor effects). Hence, performance with unidirectional flankers would be expected to improve when the target was flanked by opposite instead of same contrast polarity flankers. However, this was not what we found. Instead, it seems that the spatial factors that improved performance with unidirectional compared to upright flankers were only helpful when the target and the flankers were of the same contrast polarity. Alternatively, opposite contrast polarity flankers simply may not have improved performance compared to the same contrast polarity flankers because of a ceiling effect. However, because unflanked performance showed that there was still a large margin for improvement, we can exclude that the absence of the polarity advantage was due to ceiling performance.

The good performance for uniform triplets with unidirectional flankers assumes excellent tilt discrimination both when all lines had the same tilt direction as well as when the central line tilt was opposite to its flankers. Good performance for the central item of three tilted, parallel items has been shown before, with near perfect tilt discrimination of Gabors (Petrov & Popple, 2007) and lines (Rummens & Sayim, 2021). An important factor for the good performance with \\\- and ///-triplets may well be display uniformity, which has been identified as a source of task-relevant information strong enough to counteract the usual cost of high target-flanker similarity (Melnik, Coates, & Sayim, 2020). Furthermore, the good performance for \/\- and /\/-triplets might be attributed to the absence of tilt uniformity that is easily detectable: when a crowded noise patch was replaced by a tilted Gabor, the change went unnoticed only when the tilt was similar but not when dissimilar to the tilt of the flanking Gabors (Greenwood, Bex, & Dakin, 2010). At the same time, the low thresholds for triplets with targets tilted in the opposite direction from the flankers (\/\- and /\/-triplets) are seemingly at odds with previous findings of poor performance in similar configurations (Petrov & Popple, 2007; Rummens & Sayim, 2021). For example, when observers reported the central item of a line triplet, performance was worse for \/\- and /\/-triplets than for all other configurations (Rummens & Sayim, 2021). However, unlike the present experiment where flanker tilts were kept constant within blocks, they were randomized in the previous study (Rummens & Sayim, 2021; see also Petrov & Popple, 2007). Thus, with flankers of fixed orientation and only two response alternatives, the absence of the \\\- or ///-triplet seemed sufficient to infer that the target line was of opposite tilt to its flankers, explaining the different performances for \/\- and /\/-triplets between these studies. Hence, tilt uniformity – and the absence of uniformity – may have provided strong configural cues that could be used to help target discrimination in uniform triplets with unidirectional flankers.

In Experiment 2, we investigated whether emergent features could explain the advantage of uniform tilts (present versus absent) for target discrimination when all lines were of the same contrast polarity. An emergent feature refers to the salient property of a spatial configuration resulting from the combination of basic features (Pomerantz & Cragin, 2014). Previous studies have already shown that specific line configurations may elicit emergent features such as parallelism or collinearity (Pomerantz, Chapman, Flynn, Noe, & Yingxue, 2017; Stupina, 2011). Crucially, the basic features themselves are perceived less promptly than the emergent configurations. Such configural superiority generally facilitates the identification of its constituting parts, as a tilted line was better identified when part of an organized object than within a less coherent context (Weisstein & Harris, 1974). Similarly, determining which of four lines had a different tilt compared to three other identical lines was facilitated when the addition of a non-informative line created four-line pairs, of which three were parallel and one non-parallel (or vice versa) (Pomerantz, Chapman, Flynn, Noe, & Yingxue, 2017). These findings are well in line with the results of Experiment 2, showing a configural superiority effect for three-line configurations with unidirectional flankers. Specifically, discrimination between line tilts was superior when flankers were unidirectional compared to when flankers were absent. Because triplets with unidirectional flankers consisted either of all lines similarly tilted or of neighboring lines with opposite tilts, the presence versus absence of the emergent feature of parallelism seems to have facilitated discrimination, yielding better performance than with single lines. By contrast, emergent features did not benefit the discrimination between triplets with bidirectional flankers, as performance did not improve compared to single lines. Hence, configural cues – in particular the presence or absence of parallelism – induced by a task-irrelevant context can strongly benefit discriminating between single line tilts.

In Experiment 3, we examined whether redundancy masking – in addition to emergent features – may have enhanced the discrimination between uniform \\\- and \/\-triplets, contributing to the low thresholds with unidirectional flankers in Experiment 1. Redundancy masking has been shown to strongly alter the perception of highly uniform stimuli (Sayim & Taylor, 2019; Yildirim, Coates, & Sayim, 2019; Yildirim, Coates, & Sayim, 2020; Yildirim, Coates, & Sayim, 2021). For example, when presented with three identical lines, observers frequently reported only two lines. Regularity, for instance in spacing, has been shown to strongly modulate redundancy masking, with irregular compared to regular spacing yielding less (or no) redundancy masking (Yildirim, Coates, & Sayim, 2020). The results of Experiment 3 revealed a similar dependence of redundancy masking on regularity in line tilts. Redundancy masking occurred only in triplets with uniformly tilted lines but not in triplets containing lines of opposite tilt: observers frequently under-reported the number of lines in the repeating pattern of \\\- and ///-triplets, while the less repetitive \/\- and /\/-triplets were over-reported. This difference in the perceived number of lines may have been a strong cue that facilitated the discrimination between uniform triplets with unidirectional flankers: perceiving two versus three lines could have been a systematic confound used to decide on the target tilt. Moreover, redundancy masking has been shown to go hand in hand with a compression of space where the perceived spacing between lines is changed (Yildirim, Coates, & Sayim, 2019), possibly further contributing to high performance in discriminating between \\\- and \/\-triplets. Because both line configurations with bidirectional flankers were similarly over-reported, discrimination could not benefit from any cues provided by redundancy masking. Based on the results of Experiments 2 and 3, we propose that emergent features and redundancy masking provided observers with cues benefitting the discrimination between triplets with unidirectional flankers but not with bidirectional flankers.

In Experiment 1, we showed that flanker tilts strongly modulated crowding: Thresholds were highest with bidirectional flankers, and substantially lower for upright and unidirectional flankers. Here, we discuss whether these findings can be explained by prominent accounts of crowding. A simple pooling account of crowding would predict that the perception of the target tilt would result from an averaging process with the flankers (e.g. Greenwood, Bex, & Dakin, 2010; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). With upright and bidirectional flankers both averaging to zero, interference by upright and bidirectional tilts should thus result in similar performance levels. However, the mean threshold for uniform triplets with upright flankers was 11.94 degrees, while almost double (22.57 degrees) with bidirectional flankers (+20 and −20 degrees, respectively). Simple pooling can thus not account for the strongly divergent thresholds for upright and bidirectional flankers. Furthermore, it remains to be tested whether more complex pooling models, such as the Texture Tiling Model ("TTM"; Balas, Nakano, & Rosenholtz, 2009; Keshvari & Rosenholtz, 2016; Rosenholtz, Yu, & Keshvari, 2019) would adequately capture the current results. Consistent with the similarity rule, TTM has been suggested to provide a better representation of a tilted line when flankers have a dissimilar compared to a similar orientation (Rosenholtz, Yu, & Keshvari, 2019). In Experiment 1, with only two response alternatives, the difference in representational quality may have facilitated discriminating between uniform triplets with unidirectional flankers, as \\\-triplets would be characterized by a worse representation of the central line and \/\-triplets by a better representation. Both for triplets with upright (|\| versus |/|) and bidirectional flankers (e.g. \\/ versus \//), no systematic differences in the representation of the central line would be expected. Although TTM could thus well predict the results of Experiment 1, there are some factors that may render TTM inadequate. In the current study, we proposed that the differential effect of redundancy masking may have facilitated discriminating between uniform triplets with unidirectional flankers. However, TTM does not seem to produce redundancy masking. For instance, when presented with three identical letters I, the output of TTM clearly preserves three Is (Keshvari & Rosenholtz, 2016). Similarly, most often three Ts were preserved when creating mongrels of a T-trigram (Block, 2013). Therefore, it seems unlikely that TTM would predict redundancy masking to occur with uniform \\\- or ///-triplets, a stimulus that is highly similar to three repeating letters I. Furthermore, Bornet et al. (2021) recently highlighted another important limitation of TTM, namely its limited capability for capturing grouping cues. Such grouping cues (and how these interact) seem of utmost importance for explaining the current results.

Other accounts have proposed a prominent role for attention in crowding (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001), with limited attentional resolution impairing target individuation when flankers are at closer than critical spacing. Petrov and Popple (2007) suggested that only the pre-attentive feature contrast is preserved, while other information is lost during subsequent pooling of features within the attentional region. In their study, observers were instructed to report the tilts of three Gabors, with each having a left- or rightward tilt. A larger amount of confusion errors was revealed between triplets that contained the same compared to a different number of orientation contrasts (OCs; relative to the more outward element), suggesting that the number of OCs was available to observers. In the current study, OC may account for better performance when uniform triplets had unidirectional compared to both upright and bidirectional flankers. Indeed, discriminating between \\\- or ///-triplets (no OC) versus \/\- or /\/-triplets (two OCs) should be relatively easy, as the mere detection of an OC would be sufficient to infer the target tilt. Triplets with bidirectional flankers (\\/ and \//; each with one OC) or upright flankers (|\| and |/|; each with two OCs) both share the same number of OCs, and should be less easily discriminated. Indeed, we observed worse performance for uniform triplets with bidirectional flankers compared to unidirectional flankers. However, performance for uniform triplets with upright flankers and with unidirectional flankers did not differ, suggesting that differences in the number of OCs cannot adequately capture the results for uniform triplets. With alternating triplets, the similar thresholds for unidirectional (\\\- and \/\-triplets: zero versus two OCs) and upright flanker tilts (|\|- and |/|-triplets: both two OCs) suggested that OC was not predictive for performance with alternating triplets either. Furthermore, the number of feature contrasts in contrast polarity cannot account for the performance for alternating triplets. For all flanker configurations, adjacent lines in uniform versus alternating triplets were characterized by, respectively, zero and two alternations in contrast polarity. Therefore, if feature contrast predicted performance, contrast polarity would be expected to similarly affect all flanker configurations. Instead, we observed that the effect of contrast polarity depended on flanker tilt. Not only did the *relative* polarity advantage differ between upright and bidirectional flankers, the polarity advantage was even completely absent when flankers were unidirectional. Hence, contrast polarity and flanker tilt interactively determined performance. A simple additive combination of the effects of feature contrasts in separate dimensions cannot fully capture our results.

In crowding, flanker features are usually task-irrelevant and their integration detrimental. Any sufficient decrease of target-flanker integration would therefore be expected to benefit performance. Yet, the absence of the polarity advantage in uniform triplets with unidirectional flankers shown here suggests otherwise: the integration of flanker tilts seems to have benefitted performance to the extent that performance for alternating triplets was matched. Despite the task-irrelevancy of the flankers in the current study, high target-flanker similarity helped when flankers were unidirectional, and enabled a similar performance for uniform and alternating triplets. Our results suggest that the spatial configuration of uniform triplets with unidirectional flankers was informative on the tilt of the central target line, with the effects of emergent features and redundancy masking likely providing potent cues to override the similarity rule. When the triplets with unidirectional flankers consisted of alternating polarity lines, the reduction of stimulus uniformity in alternating compared to uniform triplets seems to have diminished the effect of emergent features. Emergent features, grouping, and Gestalts have been proposed to be strongly related: when elements group into a Gestalt and new features emerge, these features are perceived more promptly than its constituent basic features (Pomerantz & Cragin, 2014). The smaller configural superiority effect in the alternating compared to the uniform condition, as revealed in Experiment 2, seems to suggest that contrast reversals may decrease the presence of emergent features and weaken the grouping of elements into a Gestalt. Contrast reversals might therefore underlie the often-revealed worse identification of complex configurations when their uniformity is disrupted than when intact. Previous studies already suggested that the Gestalt is preserved when all parts have the same contrast polarity, but often appears qualitatively different when parts differ in contrast polarity. For instance, a convex target among concave distractors was detected more slowly when consisting of opposite versus same contrast polarity lines (Elder & Zucker, 1993; see Goldfarb & Treisman, 2011, for costs of disrupting uniformity by color). Furthermore, search efficiency was similarly low when target and distractors were closed configurations of alternating polarity lines compared to open configurations, suggesting that perceptual closure was likely reduced for configurations with contrast-reversing contours. Similar costs of disrupted uniformity were revealed in word recognition, with worse identification of a peripheral word when word segments alternated in contrast polarity than when all word segments had the same contrast polarity (Rummens & Sayim, 2019, see Pinna & Deiana, 2018, for costs of disrupting word uniformity by color). Hence, contrast reversals may have weakened the configural cues provided by triplets with unidirectional flankers, possibly contributing to the absence of the polarity advantage for alternating triplets with unidirectional flankers.

In sum, our results demonstrated that both orientation and contrast polarity strongly modulated crowding. Performance could not be explained by combining the separate effects of the individual features, but was instead determined by the interaction between contrast polarity and flanker configuration. In particular, the polarity advantage differed in magnitude between bidirectional and upright flankers, and was eliminated with unidirectional flankers. The absence of the polarity advantage with unidirectional flankers suggested that, when triplet lines strongly grouped due to same contrast polarity, performance benefitted from a configural advantage that enabled a similar performance level as with opposite polarity flankers. Hence, strong grouping of the target with unidirectional flankers yielded high instead of the usual low performance. To explain the configural advantage, we attribute a pivotal role to redundancy masking and emergent features, as both factors seemed to enhance the availability of task-relevant information when flankers were unidirectional. Our findings show that compulsory integration of flanker and target features can either hurt or benefit performance, depending on task-relevant information provided by the spatial configuration. We propose that strong target-flanker grouping in crowding may benefit performance when target-relevant information emerges from target-flanker configurations.

Keywords: Crowding, orientation discrimination, contextual modulation, contrast polarity, features

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