Contrast dissimilarity effects on crowding are not simply another case of target saliency

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Previous studies have shown crowding alleviation when target and flankers similarity is reduced. However, in the case of contrast dissimilarity, the findings were inconsistent. This study examined the effect of stimulus contrast, particularly contrast dissimilarity, on both overall performance under crowded conditions and the critical distance—the spatial extent of crowding. To this end, we measured orientation identification of a rotated T presented with and without flankers. Target contrast was either the same as the flankers or different: higher in Experiment 1 and lower in Experiment 2. Experiment 3 investigated the hypothesis that higher target contrast reduces crowding through attraction of attention to the salient target. Thus, this experiment included orthogonal manipulations of transient attention, via attentional precues, and contrast. The results show reduced crowding effects—better performance and smaller critical distance—when target contrast was higher than its flankers and increased crowding effects when target contrast was lower. In addition, the effects of attention did not interact with those of contrast, suggesting that the effect of high target contrast is not solely due to attraction of attention. Our results suggest that contrast dissimilarity effects reflect a differential contribution of the target and flankers to the faulty integration process underlying crowding.

Introduction

The identification of a target presented in the periphery of the visual field is often impaired when flankers are presented nearby. This impairment, termed "crowding," becomes smaller as the distance between the target and flankers grows, and the critical distance is typically defined as the distance beyond which the flankers no longer impair target identification (e.g., Bouma, 1970; Chung, Levi, & Legge, 2001; Pelli, Palomares, & Majaj, 2004). It has been repeatedly shown that the identification of crowded targets is better when the target and its flankers are dissimilar. This "dissimilarity benefit" was found both in terms of higher overall performance (e.g., Felisberti, Solomon, & Morgan, 2005; Poder, 2006, 2007) and reduction of the critical distance (e.g., Chakravarthi & Cavanagh, 2007; Kooi, Toet, Tripathy, & Levi, 1994; Levi & Carney, 2009; Scolari, Kohnen, Barton, & Awh, 2007). Moreover, this dissimilarity benefit was found with various stimulus attributes including color (Kooi et al., 1994; Poder, 2007; Scolari et al., 2007), size (Levi & Carney, 2009; Saarela, Sayim, Westheimer, & Herzog, 2009), contrast polarity (Chakravarthi & Cavanagh, 2007; Kooi et al., 1994), and shape (Kooi et al., 1994). However, when considering stimulus contrast, the pattern of results is more complex. When the target has a higher contrast than the flankers, the typical dissimilarity benefit is found (Chung et al., 2001; Felisberti et al., 2005; Kooi et al., 1994; Livne & Sagi, 2007). For example, Chung et al. (2001) reported a decrease in contrast threshold for letter identification as the contrast of the flankers decreased relative to that of the target, and Felisberti et al. (2005) reported the same pattern of results in an orientation discrimination task using Gabor patches. Yet, when the target had a lower contrast than its flankers, crowding was worse than when both had equal contrast (Chung et al., 2001; Felisberti et al., 2005).

The effect of contrast dissimilarity on the critical distance, however, is not clear because thus far inconsistent results were reported. For instance, Kooi et al. (1994) measured the accuracy of four observers in an orientation discrimination task while manipulating the contrast of the target and flankers. Four contrast conditions were used: (a) both target and flankers had an equally high contrast; (b) the target had high contrast, and the flankers had low

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contrast; (c) the target had low contrast, and the flankers had high contrast; and (d) both target and flankers had equally low contrast. They found that when the target had a higher contrast than its flankers, the critical distance was the smallest for all four observers. However, when the target had lower contrast than its flankers, the critical distance was found to be either smaller than the corresponding equal-contrast condition, larger, or unchanged, depending on the observer. Thus, there is no clear view of the role stimulus contrast plays in crowding, particularly not with regard to the spatial extent of crowding. This is likely due to the fact that previous studies often used contrast threshold as their dependent variable (e.g., Chung et al., 2001; Pelli et al., 2004), which is problematic when evaluating the effect of contrast on the critical distance (Coates, Chin, & Chung, 2013). Additionally, as Coates and Levi (2014) indicate, most of the previous studies, which evaluated the effect of target and flankers contrast on the critical distance, have covaried the size and contrast of the stimuli, making it impossible to single out the role played by contrast. Given this unresolved issue, one goal of this study was to evaluate the effect of stimulus contrast, particularly contrast dissimilarity, on crowding and its critical distance. To that end, in Experiments 1 and 2, we measured identification accuracy under crowded conditions and evaluated the critical distance while systematically varying the contrast of the target and flankers.

The dissimilarity benefit described above could be explained in several different ways. Scolari and her colleagues (2007) found that color dissimilarity reduced both overall crowding effects and the critical distance. They suggested that when the target is different from its flankers bottom-up grouping cues (e.g., the Gestalt cue of similarity) encourage the segregation of the target and flankers into two separate groups, and this reduces the probability of faulty or excessive integration of target and flankers, which is the common explanation of crowding effects. This account of the dissimilarity benefit can also be applied to the contrast dissimilarity benefit found with a target of higher contrast than the flankers, but it does not fit well with Kooi et al.'s (1994) finding that, with some observers, crowding increases for targets of lower contrast. This is because, according to this account, crowding should be maximal when the target and flankers have the same contrast (i.e., when target–flankers similarity maximizes target–flankers grouping) rather than when the target has a lower contrast (e.g., Chung et al., 2001).

Felisberti and colleagues (2005) found both a benefit and a cost with contrast dissimilarity, depending on whether the target or the flankers had a higher contrast. They offered a different explanation for their dissimilarity effects. According to their account, a similar inappropriate integration or pooling of target and flankers takes place when the target has a different contrast than its flankers and when all stimuli have the same contrast. However, when the target has a higher contrast, its contribution to this integration process is larger than that of the flankers due to its higher contrast, and the representation that is the outcome of this process is "biased" toward the target. The opposite occurs when the flankers have a higher contrast.

Poder (2007), like Scolari et al. (2007), also found a color dissimilarity benefit but proposed yet another account, in which attention is the main factor mediating the effect. Specifically, Poder suggested that the alleviation of crowding observed when the target is different from its flankers could be attributed to attentional capture by the salient target to its location. This attention allocation to the target relieves crowding by facilitating target processing. The idea that the allocation of attention to the target location alleviates crowding is consistent with our previous finding that the attraction of transient attention—the stimulus-driven component of spatial attention—to the target location via peripheral cues improved target identification and diminished the critical distance (Yeshurun & Rashal, 2010). As with the other account of color dissimilarity benefit, this account can also be applied to contrast dissimilarity because a target that differs in contrast from its flankers may attract attention to its location, which may then improve target identification. This account fits well with the smaller critical distance found for targets of higher contrast. Additionally, it is not in conflict with the lack of dissimilarity benefit found with some observers for targets of lower contrast because a low-contrast target is less conspicuous and therefore may be a less efficient attention attractor. Still, a target with equal contrast to its flankers may not be a better attractor of attention than a target of lower contrast because its similarity to the flankers reduces its saliency. Hence, this account of the dissimilarity benefit does not seem to have clear predictions for the equal-contrast versus lower-contrast comparison. Thus, another goal of this study was to examine the hypothesis that the contrast dissimilarity effect reflects the attraction of attention to the salient target. To that end, in Experiment 3, we orthogonally manipulated the target–flankers contrast similarity and the allocation of transient attention by a spatial precue. If the dissimilarity effect is indeed a result of allocation of transient attention to the target, then an interaction between the two factors should emerge. Otherwise, we should observe additive effects.

Experiment 1

In this experiment, we compared performance with crowded displays when (a) both the target and flankers

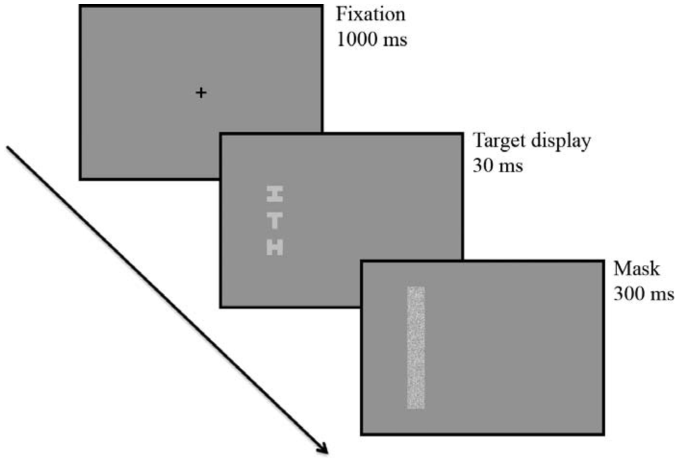

Figure 1. A schematic depiction of the sequence of events in Experiment 1.

had high contrast (20%) – Equal-High condition, (b) both had low contrast (10%) – Equal-Low condition, or (c) the target had a higher contrast (20%) than the flankers (10%) – High-Target condition. This allowed us to examine effects that are due to modifying the contrast of both target and flankers without changing their relative contrast (i.e., effects of "absolute contrast") as well as effects that are due to modifying the relative contrast of target and flankers (i.e., effects of "relative contrast"). The target was the letter T presented at the periphery in various orientations, and it was either flanked by two other stimuli or appeared in isolation (Figure 1). The task was to indicate the target orientation, and identification accuracy served as the dependent variable. Target–flanker distance was varied systematically to allow the assessment of the critical distance. Given previous studies (Chung et al., 2001; Felisberti et al., 2005; Kooi et al., 1994; Livne & Sagi, 2007), we expected to find higher overall accuracy and a smaller critical distance in the higher contrast condition than both equal contrast conditions.

Methods

Observers

Fifteen students from the University of Haifa with normal or corrected-to-normal vision participated in this experiment; all were naive to the purpose of the study. This study adhered to the Declaration of Helsinki.

Stimuli and apparatus

The stimuli were presented using PsyScope™ (Cohen, MacWhinney, Flatt, & Provost, 1993) on a 21-in. monitor of a PowerMac G4 computer. The target was the capital letter T oriented upright, inverted, or tilted 90° to the left or to the right (Figure 1). Flankers were capital Hs, either upright or with a 90° tilt, positioned one above and one below the target. Targets and flankers subtended 0.9° × 0.9° of visual angle each. Viewing distance was 57 cm. The various stimuli were always presented on a middle gray background (20.5 cd/m^2). In the Equal-High condition, both target and flankers had 20% contrast (stimuli luminance: 31 cd/m^2). In the Equal-Low condition, both target and flankers had 10% contrast (stimuli: luminance 24.8 cd/m^2). In the High-Target condition, the target had 20% contrast and the flankers had 10% contrast. There were nine possible distances between the center of a flanker and the center of the target, varying randomly from one to nine in units of target width (0.9°–8.1° of visual angle). In approximately 7% of the trials, the target appeared without flankers to provide a baseline. The target appeared at 9° of eccentricity, randomly positioned to the left or right of fixation. The fixation mark was a black cross (0.3° × 0.3°, 0.01 cd/m^2) presented at the center of the screen, and the mask was a 23.3° × 1.1° gray and white random dot rectangle. In the two equal-contrast conditions, the average mask contrast was matched to the stimulus contrast. In the High-Target condition, the average mask contrast was high (i.e., similar to the target contrast) at the central segment with a size equal to the target size and low (i.e., similar to the flankers contrast) at the other segments of the mask.

Procedure

Each trial started with the fixation cross, and after 1000 ms, the target and flankers appeared. The duration of the target and flankers display was chosen individually for each observer based on performance in the practice blocks to ensure performance level of about 75% correct averaged across all trial types. Display duration in a given practice block was adjusted based on the overall accuracy level in the previous practice block. Final display duration ranged between 30 and 80 ms with a median of 50 ms. This short exposure duration assured prevention of eye movements (e.g., Mayfrank, Kimmig, & Fischer, 1987). Finally, the mask was presented for 300 ms. Target and flankers orientation was randomized between trials. The various conditions (i.e., target–flankers distance and contrast conditions) appeared equally often but in a randomized order.

The observers had to report the orientation of the target. Auditory feedback followed their response. Each observer participated in two to three blocks of 116 practice trials and 1,392 experimental trials.

Results

The data from two observers were removed from further analysis because the overall accuracy of one of these observers was 0.56, and the mean R^2 of the

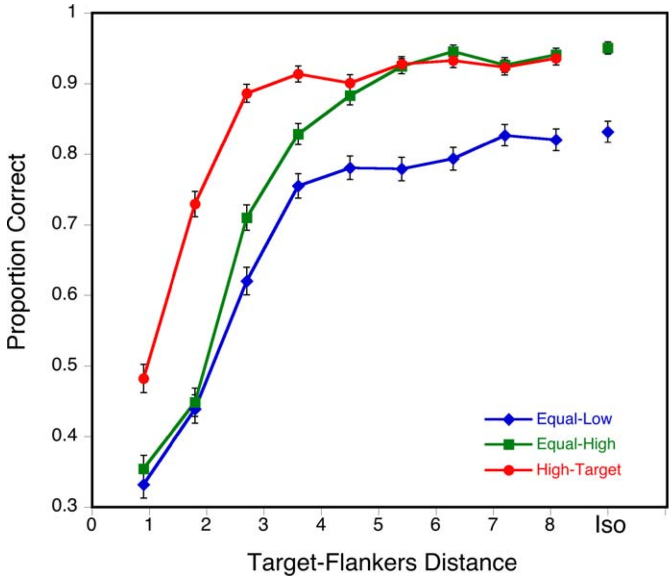

Figure 2. Proportion correct in Experiment 1 as a function of contrast condition and target–flankers distance (in degrees). Iso: no flankers condition (isolated target). Error bars correspond to one standard error of the means across observers.

exponential fit (see below) of the other observer was lower than 0.8.

Accuracy

A two-way, repeated-measures ANOVA (contrast condition × target–flankers distance) was performed on the accuracy data, excluding the trials in which the target appeared without flankers. A significant main effect of contrast condition was found, $F(2, 24) = 33.92$, $p < 0.001$; accuracy was highest for the High-Target condition and lowest for the Equal-Low condition (Figure 2). Post hoc analysis with Bonferroni correction yielded significance for all contrast condition comparisons ($p < 0.005$). A significant main effect was also found for target–flankers distance, $F(8, 96) = 238.47$, $p < 0.001$; accuracy increased as target–flankers distance increased. A significant interaction was found between contrast condition and target–flankers distance, $F(16, 192) = 11.92$, $p < 0.001$. This interaction emerged because (a) the accuracy difference between the two equal-contrast conditions was smaller for smaller target–flankers distances and close to absent for the two smallest distances, and (b) the accuracy difference between the High-Target and Equal-High conditions was more pronounced with the smaller target–flankers distances.

Finally, paired t test performed on the trials with no flankers indicated significantly higher accuracy for high-contrast (95%) than low-contrast targets (83%), $t(12) = 4.35$, $p < 0.001$.

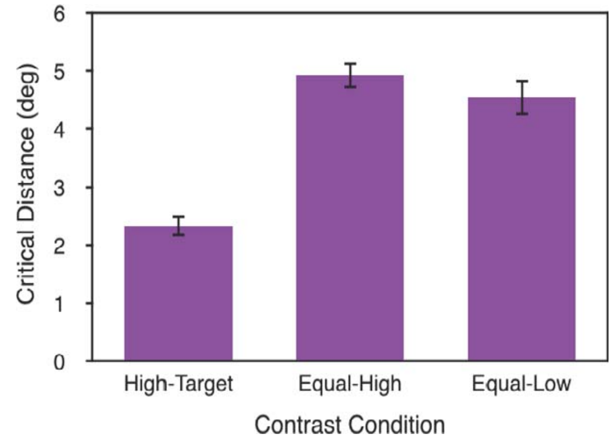

Figure 3. Mean critical distance values (in degrees) as a function of contrast condition in Experiment 1. Error bars correspond to one standard error of the means across observers.

Critical distance

To evaluate the critical distance, an exponential function was fitted to the data of each observer. We employed the following equation (e.g., Scolari et al., 2007):

$$pc = a\left(1 - e^{(-s(d-i))}\right), \quad d > i \tag{1}$$

where pc is proportion correct, a is the asymptote, s is the scaling factor, d is the target–flankers distance, and i is the x-intercept. The asymptotic value, scaling factor, and x-intercept were adjusted using the nonlinear least squares fitting method (with a Trust-Region algorithm provided in MATLAB Curve Fitting Toolbox™). The critical distance c was defined as the target–flankers distance at which accuracy achieved 90% of the asymptotic value, and it was calculated using this equation (e.g., Scolari et al., 2007):

$$c = i - \frac{\ln(0.1)}{s} \tag{2}$$

The exponential model fits the data well (mean $R^2 = 0.92$). A one-way, repeated-measures ANOVA (contrast condition) was conducted on the critical distance values calculated based on the individual data. We found a significant effect of contrast condition, $F(2, 24) = 69.17$, $p < 0.001$ (Figure 3). Post hoc analysis with Bonferroni correction indicated that the critical distance of the High-Target condition was significantly smaller than those of the other two conditions ($p < 0.001$ for both comparisons). There was no significant difference in critical distance between the two equal contrast conditions ($p = 0.32$). Table 1 includes the mean critical distance values.

	Experiment 1	Experiment 2	Experiment 3
Contrast condition			
High-Target	2.33 (0.18)	-	2.29 (0.12)
Low-Target	-	8.13 (0.55)	-
Equal-Low	4.54 (0.3)	4.06 (0.22)	4.43 (0.24)
Equal-High	4.93 (0.22)	4.2 (0.23)	-
Cue condition			
Cued	-	-	3.04 (0.23)
Neutral	-	-	3.69 (0.26)

Table 1. Mean critical distance values (in degrees) and mean standard errors (in parenthesis) for the different conditions of Experiments 1–3.

Discussion

We found that increasing the absolute contrast improved overall performance even though the increase in target contrast was accompanied by an increase in flankers contrast. However, increasing absolute contrast did not affect the critical distance. Unlike absolute contrast, increasing relative contrast affected both overall accuracy as well as the spatial extent of crowding. That is, increasing the contrast of both target and flankers resulted in a similar critical distance to when both target and flankers had lower contrast. In both cases, the critical distance was slightly above half the eccentricity, consistent with previous studies in which similar stimuli were used (e.g., Scolari et al., 2007; Yeshurun & Rashal, 2010). Yet, when only the target contrast was increased, the critical distance was markedly reduced to half that size (i.e., about 0.25 of the eccentricity). As detailed above, the finding that increasing target contrast relative to its flankers improves overall accuracy and reduces the critical distance is consistent with previous studies (Chung et al., 2001; Felisberti et al., 2005; Kooi et al., 1994; Livne & Sagi, 2007). Moreover, it is consistent with all the accounts for the alleviation of crowding due to dissimilarity: reduced target–flankers grouping, enhanced contribution of the target to the pooling process, and attraction of attention. These different accounts were further explored in Experiment 2.

Experiment 2

In this experiment, we employed the same equal-contrast conditions used in Experiment 1: the Equal-High condition in which both target and flankers had high contrast (20%) and Equal-Low condition in which both had low contrast (10%), but performance in these conditions was compared to a Low-Target condition in which the target had a lower contrast (10%) than the flankers (20%). All other aspects of this experiment were similar to Experiment 1. As in Experiment 1, this design allowed us to examine the effects of both absolute and relative contrast. Critically, it allowed us to examine whether the reduction in critical distance that was found in the dissimilar-contrast condition of Experiment 1 (i.e., the High-Target condition) will be replicated when the dissimilar condition includes a target of lower contrast. If the reduction in critical distance found in Experiment 1 reflects a decrease in target–flankers grouping due to their dissimilarity, we should see a similar reduction in the critical distance for the Low-Target condition. Alternatively, an opposite effect should be found if the reduction in critical distance is due to the greater contribution of the higher contrast target to the target–flankers integration process. Specifically, the critical distance should be larger in the dissimilar Low-Target condition than in the equal-contrast conditions because in the former the target contribution is smaller than that of the flankers. Note that, as mentioned above, the "attention allocation" hypothesis does not have clear predictions for the equal-contrast versus lower contrast comparisons tested in this experiment.

Methods

Observers

Sixteen students from the University of Haifa with normal or corrected-to-normal vision participated in this experiment; all were naive to the purpose of the study, and none of them participated in Experiment 1.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure were identical to Experiment 1 except for the following: Instead of the High-Target contrast condition, there was a Low-Target contrast condition in which the target contrast was 10% and the flankers contrast was 20%. The mask used in this condition was the higher contrast mask with a central segment of lower contrast whose size was equal to the target size. An isolated target appeared in 10% of the trials. The duration of the target and flankers display ranged between 50 and 80 ms with a median of 80 ms. A practice session included 120 trials, and the experimental session included 1,440 trials.

Results

Accuracy

A two-way, repeated-measures ANOVA (contrast condition × target–flankers distance) was performed on the accuracy data, excluding the trials in which the target appeared without flankers. A significant main effect of contrast was found, $F(2, 30) = 101.76$, $p <$

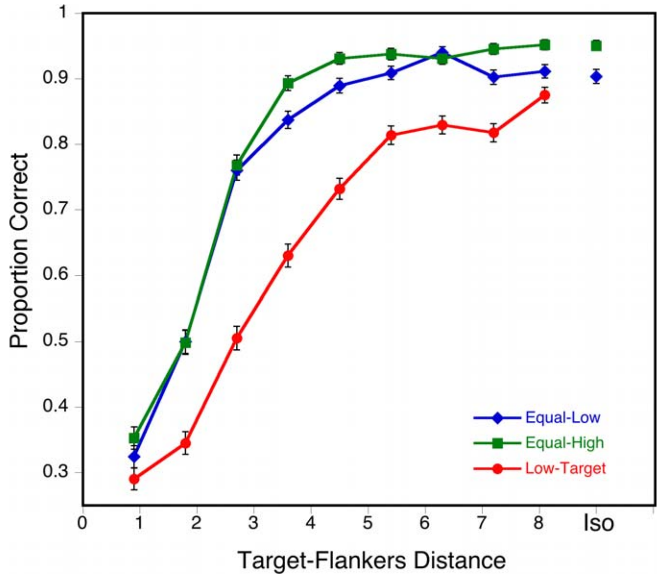

Figure 4. Proportion correct in Experiment 2 as a function of contrast condition and target–flankers distance (in degrees). Iso: no flankers condition (isolated target). Error bars correspond to one standard error of the means across observers.

0.001; accuracy was lowest in the Low-Target condition and highest in the Equal-High condition (Figure 4). Post hoc analysis with Bonferroni corrections yielded significance for the comparisons of both equal-contrast conditions with the Low-Target condition ($p < 0.001$). The difference between Equal-Low and Equal-High conditions was marginally significant ($p < 0.09$). As in Experiment 1, a significant main effect was also found for target–flankers distance, $F(8, 120) = 380.41$, $p < 0.001$; accuracy increased with increased target–flankers distance. A significant interaction was found between contrast condition and target–flankers distance, $F(16, 240) = 10.61$, $p < 0.001$. This interaction emerged because accuracy differences between the Low-Target and the other two conditions were larger at intermediate target–flanker distances than at the smallest and largest ones. In addition, accuracy differences between the two equal-contrast conditions only emerged with larger target–flankers distances.

Finally, a paired t test performed on the trials with no flankers indicated significantly higher accuracy for targets with higher (95%) than lower (89%) contrast, $t(15) = 4.08$, $p < 0.001$.

Critical distance

The exponential model fits the data well (mean $R^2 = 0.93$). Table 1 includes the mean critical distance values. A one-way, repeated-measures ANOVA (contrast condition) was conducted on the critical distance values calculated based on the individual data. We found a significant effect of contrast condition, $F(2, 30) = 53.36$, $p < 0.001$. As can be seen in Figure 5 and confirmed by post hoc analysis with Bonferroni correction, the critical distance for the Low-Target condition was significantly larger than the critical distance of the other two equal-contrast conditions ($p < 0.001$ for both comparisons). There was no significant difference between the critical distance values of the two equal-contrast conditions ($p = 0.99$).

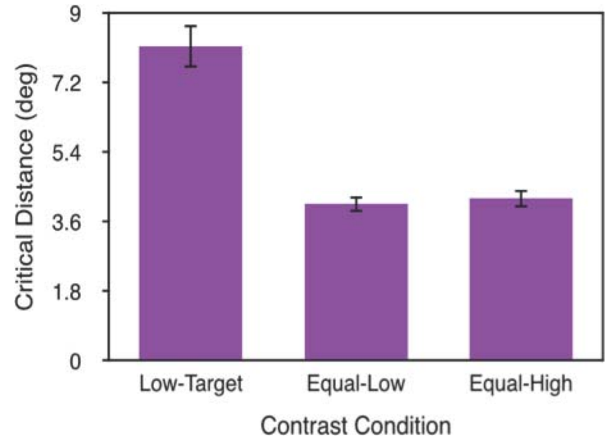

Figure 5. Mean critical distance values (in degrees) as a function of contrast condition in Experiment 2. Error bars correspond to one standard error of the means across observers.

Discussion

As in Experiment 1, a change in both the absolute and relative contrast affected overall performance, but only a change in relative contrast between target and flankers affected the spatial extent of crowding. Specifically, decreasing both target and flankers contrast decreased overall accuracy but did not affect the critical distance; the critical distance in both high and low equal-contrast conditions was about half the eccentricity. Decreasing only the target contrast similarly decreased accuracy, but it also dramatically affected the critical distance as it practically doubled the size of the critical distance.[1] Thus, in both experiments, the dissimilar-contrast condition had a unique effect on the critical distance, yet the nature of this effect was opposite: A target with a higher contrast than its flankers reduced the critical distance, and a target with a lower contrast than its flankers increased the critical distance. These findings are consistent with Kooi et al. (1994), who found a decrease in overall performance and an increase in critical distance in their lower-target condition, but this pattern of results was found only for some of their participants. The effects of dissimilar contrast that were found in our Experiments 1 and 2 are more robust. As can be seen in Figure 6, the critical distance of all the participants of Experiment 1

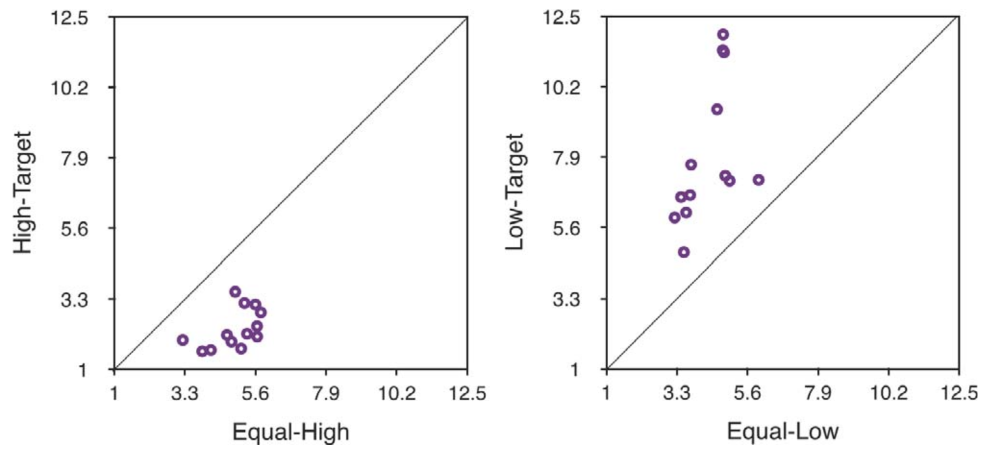

Figure 6. The critical distance (in degrees) in the dissimilar-contrast condition as a function of the critical distance in its corresponding equal-contrast condition for each participant of Experiment 1 (left panel) and Experiment 2 (right panel).

was smaller in the dissimilar-contrast than equal-contrast condition (i.e., High-Target vs. Equal-High condition, respectively), and the critical distance of all the participants of Experiment 2 was larger in the dissimilar-contrast than equal-contrast condition (i.e., Low-Target vs. Equal-Low condition, respectively).

The finding that the effect of dissimilar contrast on crowding depends on the dissimilarity direction (i.e., whether the target has a higher or lower contrast than its flankers) is not consistent with the hypothesis that crowding alleviation that is due to target–flankers dissimilarity reflects reduced target–flankers grouping. This is because the target was different from its flankers in both the High-Target and Low-Target conditions of Experiments 1 and 2, respectively, but only with the former did crowding alleviation emerge. With the latter, crowding was even exacerbated. Nonetheless, this hypothesis is likely valid for other types of target–flankers dissimilarity, such as color or size dissimilarities (e.g., Scolari et al., 2007), but it does not seem to hold for contrast dissimilarity.

Unlike the "reduced grouping" hypothesis, the findings of both Experiments 1 and 2 are consistent with the hypothesis that the effect of contrast dissimilarity reflects modification of the relative contribution of the target and flankers to the faulty integration process (Felisberti et al., 2005). When the target has a higher contrast than its flankers, its contribution to this process is larger than that of the flankers, and the final outcome of this process is "biased" toward the target identity. This leads to better target identification than when target and flankers contrast is equal as was found in Experiment 1. However, when the target has a lower contrast than its flankers, its contribution to the integration process is smaller than that of the flankers, and the outcome is "biased" toward the flankers identity. This leads to reduced target identification as was found in Experiment 2.

Finally, we return to the hypothesis that crowding alleviation that is due to target–flankers dissimilarity reflects attention allocation to the target (Poder, 2007). As discussed in the Introduction section, the predictions of this hypothesis when dealing with contrast dissimilarity are not trivial. That is, for the case of a higher contrast target, the predictions are straightforward: The target is clearly more salient than its flankers and should therefore attract attention. A target of lower contrast is also different from its flankers, and dissimilarity is often translated to high saliency. Still, such a target is also less conspicuous due to its low contrast and, therefore, may not be an effective attractor of attention. Thus, the finding that in the Low-Target condition crowding was not reduced in comparison to the equal-contrast condition is compatible with the attention-attraction hypothesis. However, to account for the fact that in this condition crowding was worsened, it requires the additional assumption that in the Low-Target condition more attentional resources were allocated to the flankers than the target, and in the Equal-Low condition, attention was equally allocated to all items. Thus, the comparison between the Low-Target and Equal-Low conditions cannot answer the question of whether or not the dissimilarity effect reflects attentional attraction. A different, more direct test of the hypothesized connection between attention and dissimilarity effects on crowding is performed in Experiment 3.

Experiment 3

This experiment examined more closely the relationships between the effects of attention and contrast-dissimilarity on performance under crowded conditions. Specifically, we examined whether the effect of high-contrast targets can be explained in terms of attentional capture by target salience as suggested by Poder (2007). We have tested directly the effect of transient spatial attention on crowding in a previous study (Yeshurun & Rashal, 2010) and found that directing transient attention to the target location via peripheral precues improved overall performance and reduced the critical distance. The findings of the two previous experiments of the current study, particularly those of Experiment 1 in which the target had a higher contrast than the flankers, may also be due to attention allocation. However, as discussed above, these findings could also be due to a differential contribution of the target and flankers to the integration process. To disentangle the effects of contrast dissimilarity, specifically high target contrast, from that of transient attention, we introduced in this experiment an orthogonal manipulation of transient attention and target contrast. Target contrast was either equal to that of the flankers (Equal-Contrast condition) or higher (High-Target condition). Independently, the target location was either cued with a peripheral cue prior to the target onset, attracting attention in advance to the target location (Cued condition), or target presentation was preceded by a neutral cue that did not indicate a location (Neutral condition). If the effects of contrast dissimilarity on overall performance and the critical distance are due to attraction of attention by the dissimilar target, then an interaction should emerge between the manipulations of contrast and attentional cueing. Specifically, higher accuracy and a smaller critical distance should be found with the target of higher contrast but only in the Neutral condition, not in the Cued condition. This is because, in the latter case, attention is already allocated to the target location due to the peripheral cue, and so the target is attended regardless of its contrast. Alternatively, if evidence of additivity (i.e., no such interaction) were to be found, it might suggest that the effects of contrast dissimilarity and spatial attention are mediated by different mechanisms.

Methods

Observers

Twenty-five students from the University of Haifa with normal or corrected-to-normal vision participated in this experiment; all were naive to the purpose of the study, and none of them participated in the former experiments.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure were identical to Experiment 1 except for the following. Only two contrast conditions were used: (a) Both target and flankers had 10% contrast – Equal-Contrast condition, or (b) the target had 20% contrast, and the flankers had 10% contrast – High-Target condition. In addition, targets were precued by a peripheral cue, Cued condition, or a neutral cue, Neutral condition. As in Yeshurun and Rashal (2010), the peripheral cue was a green dot with a diameter of 0.35°, positioned 1° closer to fixation than the target. The neutral cue was a green disk with a diameter of 0.55°, presented at the center of the screen. The cue followed the fixation mark and appeared for 50 ms. Target and flankers were displayed after an interstimulus interval of 70 ms. Precueing and contrast conditions were randomized between trials and appeared equally often throughout the experiment. The peripheral cue was always valid. An isolated target appeared in 10% of the trials. The duration of the target and flankers display ranged between 30 to 80 ms with a median of 50 ms. A practice session included 128 trials, and the experimental session included 1,280 trials.

Results and discussion

Data from three observers were removed from further analysis because their mean R^2 of the exponential fit was lower than 0.80.

Accuracy

A three-way, repeated measures ANOVA (cueing condition × contrast condition × target–flankers distance) was performed on the accuracy data, excluding the trials in which the target appeared without flankers. This analysis revealed a significant main effect for contrast condition, $F(1, 21) = 130.25$, $p < 0.001$; as in Experiment 1, accuracy was higher for the High-Target than for the Equal-Contrast condition. A significant main effect of cueing condition was also found, $F(1, 21) = 5.01$, $p < 0.05$; accuracy was higher for the Cued than the Neutral condition. This cueing effect is similar to that found in previous studies, demonstrating that directing attention to the target location leads to better overall performance in crowded displays (Felisberti et al., 2005; Huckauf & Heller, 2002; Scolari et al., 2007; Strasburger, 2005; Yeshurun & Rashal, 2010). Importantly, these two factors—cueing and contrast—did not interact ($F < 1$, $p = 0.398$).

As in previous experiments, accuracy increased significantly with increased target–flankers distance, $F(8, 168) = 465.83$, $p < 0.001$. The two-way interaction of this factor with the factor of contrast was significant, $F(8, 168) = 14.84$, $p < 0.001$, and its interaction with the factor of cueing was marginally significant, $F(8, 168) = 1.92$, $p = 0.06$. Both two-way interactions were qualified by a significant three-way (cueing × contrast × distance)

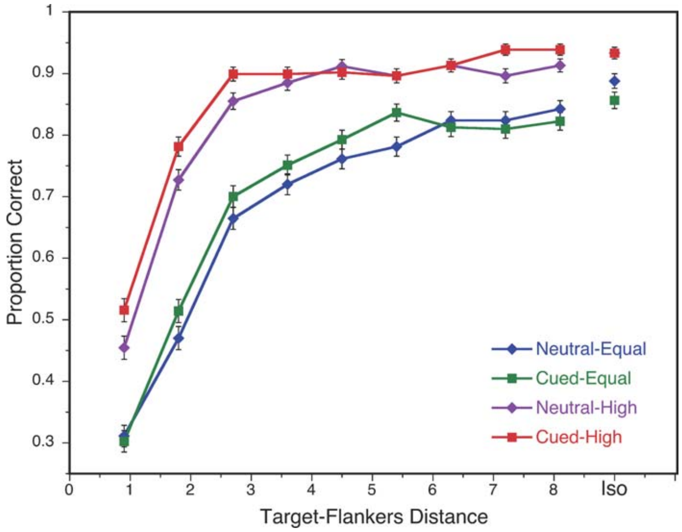

Figure 7. Accuracy in Experiment 3 as a function of target contrast (high vs. equal), cueing condition (cued vs. neutral), and target–flankers distance (in degrees). Iso: no flankers condition (isolated target). The isolated Neutral-High data point is not seen because it is equal to the isolated Cued-High data point. Error bars correspond to one standard error of the means across observers.

interaction, $F(8, 168) = 2.56$, $p < 0.05$. As can be seen in Figure 7, a contrast-dissimilarity effect was present in both cueing conditions, and a cueing effect was present in both contrast conditions, but the size of these effects was different for the different target–flankers distances.

A two-way, repeated-measures ANOVA (cueing condition × contrast condition) was performed on the accuracy data for isolated targets. A significant main effect of contrast was found, $F(1, 21) = 19.3$, $p < 0.001$; accuracy was higher for targets with higher (93%) compared with lower contrast (88%). There were no other significant effects. The lack of cueing effect with isolated targets likely reflects ceiling effects.

Critical distance

The model fits the data well (mean $R^2 = 0.91$). A two-way, repeated-measures ANOVA (cueing condition × contrast condition) was conducted on the critical distance values calculated based on individual data. Table 1 includes the mean critical distance values for the two factors. As in Experiments 1 and 2, we found a significant main effect of contrast condition, $F(1, 21) = 55.16$, $p < 0.001$; the critical distance was smaller for the higher contrast target (Figure 8, left panel). In addition, a significant main effect of cueing condition emerged, $F(1, 21) = 6.31$, $p < 0.05$; the critical distance was smaller for targets preceded by a peripheral than a neutral cue (Figure 8, middle panel). A similar attentional reduction of the critical distance was found in our previous study (Yeshurun & Rashal, 2010) and was replicated recently by Strasburger and Malania (2013). Most critical for the current study, the interaction between cueing and contrast conditions did not reach statistical significance ($p = 0.19$; Figure 8, right panel). The fact that these two factors did not interact might suggest that their effects are mediated by different mechanisms.

General discussion

The present study examined the role of contrast dissimilarity in crowding when measured by orientation identification accuracy and the critical distance. Experiments 1 and 2 demonstrate that changing the absolute contrast of the target without changing its relative contrast in comparison to the flankers modifies overall performance—increasing or decreasing accuracy in accordance with contrast increment or decrement, but it does not affect the critical distance. Only a change in the target and flankers relative contrast modifies the critical distance. Specifically, increasing the target contrast in comparison to its flankers reduced the critical distance (Experiments 1 and 3), and decreasing the target contrast in comparison to its flankers increased the critical distance (Experiment 2).

The finding that increasing the target contrast in comparison to the flankers alleviates crowding, and reducing it worsens crowding, is consistent with several previous studies (Chung et al., 2001; Felisberti et al., 2005; Kooi et al., 1994; Livne & Sagi, 2007). The finding

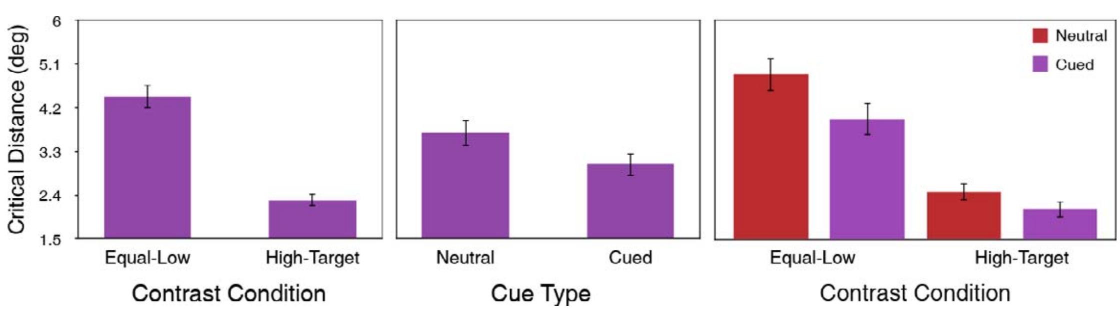

Figure 8. Mean critical distance values (in degrees) as a function of contrast condition (left panel), cueing condition (middle panel), and both factors (right panel) in Experiment 3. Error bars correspond to one standard error of the means across observers.

that increasing the target contrast also reduces the critical distance is consistent with Kooi et al.'s (1994) study. However, previous studies did not portray a clear picture regarding the effect of decreasing target contrast in comparison to its flankers on the critical distance. Kooi et al. reported that low target contrast affected the critical distance differently for the different observers (i.e., reduced, increased, or left unchanged). The effects we found of changing the relative contrast of target and flankers on the critical distance were highly robust for both the higher-contrast condition as well as the lower-contrast condition. Both effects are consistent with the view that the same processes mediate the opposing findings observed in the similar-contrast and dissimilar-contrast conditions. According to this view, in both cases, a similar inappropriate integration or pooling of target and flankers takes place, and this faulty integration leads to the observed performance impairment under crowded conditions (e.g., Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004). The effects of dissimilarity are simply due to differential contribution of the target and flankers to the integration process, depending on their relative contrast (Felisberti et al., 2005). Thus, when the target has a higher contrast than the flankers, its contribution to this integration process is larger, and the representation that is the outcome of this process is skewed toward the target properties, resulting in better identification. Following the same logic, when the target contrast is lower than the flankers, its contribution to the integration process is smaller, and the final representation leans toward the flankers properties, interfering with target identification. Note that because modifying the relative contrast also affected the critical distance, not just overall performance, an additional assumption seems to be required in order to keep the view that the similar-contrast and dissimilar-contrast conditions only differ in the relative contributions of the target and flankers to the pooling process. In particular, one has to assume that the contribution of a given item to the pool decreases as its distance from the target increases (van den Berg, Roerdink, & Cornelissen, 2010). Such a gradual decrease in item weights with increasing target–flankers distance can account for the observed changes in critical distance because it generates the following predictions: A flanker that is relatively far from the target will have a relatively small contribution to the pool. Lowering its contrast relative to the target will further reduce its contribution and may eliminate it altogether. This will effectively reduce the area over which flankers impair performance (i.e., decreasing the critical distance). Likewise, a flanker that is too far from the target will typically have only a negligible contribution to the pool. Increasing its contrast relative to the target may result in a more noticeable contribution. This will effectively increase the observable area of flankers interference (i.e., increasing the critical distance).

The fact that contrast dissimilarity affected performance differently depending on the direction of dissimilarity (i.e., whether the target had a higher or lower contrast than the flankers) is not consistent with the hypothesis that contrast-dissimilarity effects reflect reduced target–flankers grouping. This is because, according to this hypothesis, when the target and its flankers are similar, bottom-up Gestalt cues encourage grouping the target and its flankers into a single group, facilitating their faulty integration or pooling. When the target is different than its flankers, the Gestalt cues encourage a different perceptual organization in which the target and flankers belong to separate groups, and the tendency to pool together their signal is reduced. Hence, this hypothesis predicts that crowding should be worst when the target contrast is similar to the flankers. Yet crowding was worst when the target had a lower contrast than the flankers. Thus, unlike other stimulus attributes, such as color and size, in which the grouping principle of similarity seems to play an important role (e.g., Manassi, Sayim, & Herzog, 2012; Saarela et al., 2009; Scolari et al., 2007), and notwithstanding the central role played by other grouping principles in crowding (e.g., Livne & Sagi, 2007; Saarela, Westheimer, & Herzog, 2010; Sayim, Westheimer, & Herzog, 2010), when dealing with stimulus contrast, mere similarity does not seem to be a critical factor.

Another explanation that was offered for dissimilarity effects attributes these effects to attention allocation. Specifically, it suggests that the dissimilarity grants the target higher saliency, and this makes it a more efficient attractor of spatial attention (Poder, 2007). This allocation of attention to the target facilitates its processing, resulting in reduced crowding effects. This explanation can easily account for the findings of Experiment 1. It may also be able to account for the findings of Experiment 2 with the additional assumption that more attention is allocated to the flankers than the target when target contrast is lower. However, this explanation cannot account for the findings of Experiment 3 that increasing target contrast reduced the critical distance even when target location was precued. This is because, in this case, transient attention was attracted to the target by the precue regardless of target contrast. Hence, if the only effect of contrast increment was the attraction of transient attention, the critical distance reduction should have been eliminated or at least considerably decreased when a precue preceded the target. The findings, however, did not follow the prediction of this "attention allocation" hypothesis: Not only did the effect of contrast increment persist, it also maintained its magnitude, reducing the critical distance by half. Thus, given the outcome of Experiment 3, it seems that the contrast-dissimilarity effect does not merely reflect a more efficient allocation of attention to the target.

Still, a significant precueing effect emerged in Experiment 3. As was previously found, transient attention improved target identification (e.g., Felisberti et al., 2005; Scolari et al., 2007; Yeshurun & Rashal, 2010) and reduced the critical distance (Strasburger & Malania, 2013; Yeshurun & Rashal, 2010). The fact that these attentional effects were found regardless of the target contrast relative to its flankers (i.e., for both equal-contrast and high-contrast targets) suggests that the effects of attention are mediated by a different mechanism than the effects that are due to contrast-dissimilarity. In our previous study (Yeshurun & Rashal, 2010), we found a robust effect of transient attention: Similar effects of precueing attention were found for targets presented at different eccentricities with or without backward masking and whether or not the peripheral precue was informative. Because previous studies demonstrated that transient attention enhances spatial resolution by reducing the area over which information is processed (e.g., Yeshurun & Carrasco, 1998, 1999, 2000), we suggested that the attentional reduction of the critical distance might reflect information integration over smaller areas. Given the similarity of the effects of transient attention on the critical distance found in our current and previous studies, both in terms of direction and size, this account of the effect of attention on the critical distance (i.e., attentional reduction of the integration area) may also be relevant for our current findings. It is important, however, to note that the effect of transient attention on the critical distance was considerably smaller than that of contrast modification. Increasing the target contrast relative to its flankers reduced the critical distance by about 50% whereas directing transient attention to the target location reduced the critical distance by about 20%. This striking difference suggests that the role of transient attention in defining the spatial extent of crowding may be secondary to the role of stimulus contrast, but this outcome may be different with different levels of contrast and different cueing parameters.

Conclusions

Changing the absolute or relative contrast of the target and its flankers affected overall performance: Increasing the contrast of all stimuli or only that of the target increased accuracy, and decreasing it reduced accuracy. However, only a change in relative contrast affected the spatial extent of crowding, reducing or increasing the critical distance depending on whether the target contrast was higher or lower than that of the flankers. Moreover, an effect of contrast dissimilarity of a similar magnitude was found even when a peripheral precue attracted transient attention in advance to the target location. Taken together, the results of the three experiments performed in this study suggest that the contrast-dissimilarity effect does not reflect less target–flankers grouping or a more efficient attraction of transient attention to the target. Instead, they suggest that the contrast-dissimilarity effect reflects a differential contribution of the target and flankers to the faulty integration process.

Keywords: crowding, contrast, attention, critical distance

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Footnote

[1] An anonymous reviewer suggested that the increased critical distance found with the Low-Target condition is due to the presence of a mask. However, Vickery, Shim, Chakravarthi, Jiang, and Luedeman (2009) also found that crowding extends over larger areas with a target of lower contrast (experiment 2) than with target and flankers of equal contrast (experiments 1b and 5) even though, in all these cases, there was no mask.

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