Precueing attention to the target location diminishes crowding and reduces the critical distance

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The identification of a peripheral target surrounded by flankers is often harder than the identification of an identical isolated target. This study examined whether this crowding phenomenon, and particularly its spatial extent, is affected by the allocation of spatial attention to the target location. We measured orientation identification of a rotated T with and without flankers. The distance between the target and the flankers and their eccentricity varied systematically. We manipulated attention via peripheral precues: in the cued condition, a dot indicated the target location prior to its onset. On the neutral condition, a central disk conveyed no information regarding the target location (Experiments 1–2), and on the invalid condition (Experiment 3), an invalid cue attracted attention to a nontarget location. We found, across all experiments, at all eccentricities, a significant attentional enhancement of identification accuracy. Most importantly, we found a significant attentional reduction of the critical distance (i.e., the target–flankers distance at which the flankers no longer interfere with target identification). These attentional effects were found regardless of the presence or absence of a backward mask and whether the attentional cue was informative or not. These findings suggest that attention reduces the spatial extent of crowding.

Keywords: crowding, transient attention, spatial attention, critical distance, precue, flankers

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Introduction

It is often harder to identify a peripheral stimulus when it is surrounded by flankers than when it appears in isolation. This phenomenon is termed crowding. The effects of crowding depend mainly on target eccentricity and the distance between the target and flankers (e.g., Bouma, 1970; Pelli, Palomares, & Majaj, 2004). The critical distance is typically defined as the distance between the target and flankers required for target identification at a similar level to that without flankers. Although the operational definition of the critical distance employed by various studies is different, this distance typically scales with target eccentricity regardless of the exact definition (e.g., Bouma, 1970; Latham & Whitaker, 1996; Pelli et al., 2004; Strasburger, 2005; Toet & Levi, 1992).

This study explored the effects of peripheral precues on performance with crowded displays. Numerous studies have shown that attracting spatial attention to the target location, by presenting an abrupt onset cue next to the target location prior to its onset, improves performance in various tasks (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Cheal & Lyon, 1991; Eriksen & Hoffman, 1972; Eriksen & Rohrbaugh, 1970; Jonides, 1981; Lu & Dosher, 1998; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980; Remington, Johnston, & Yantis, 1992; Yeshurun & Carrasco, 1999). Can the deployment of spatial attention to the target location via attentional precues also diminish the effects of crowding? This question was examined recently by several studies, but the results were inconclusive (e.g., Felisberti, Solomon, & Morgan, 2005; Huckauf & Heller, 2002; Scolari, Kohnen, Barton, & Awh, 2007; Strasburger, 2005).

For instance, Huckauf and Heller (2002) compared letter identification with and without flanking letters. The target letter was presented either in isolation or with two flanking stimuli, one to each of its sides. They used as the attentional cue a gray rectangle of the same size as the target letter. The rectangle was presented at the target location before, simultaneously, or after the letters' display. They found that with both preceding and succeeding cues, the accuracy of target identification was better than without a cue, but the effect with the succeeding cue was smaller. The simultaneous cue probably masked the target, because identification in that condition was worse than in the no-cue condition. Huckauf and Heller (2002) concluded that these results indicate that a peripheral cue can improve target identification, partly by facilitating spatial

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selection of target location. However, cueing the target location did not eliminate crowding completely: performance was much higher for isolated than for flanked targets, regardless of cue condition, which led them to conclude that the cue did not prevent the flankers from interfering. The critical distance was not measured in their study.

In another study (Strasburger, 2005), spatial attention was manipulated by a peripheral ring cue that appeared at the target's location prior to its onset. In his study, contrast threshold of digit identification was measured at three eccentricities (1°, 2°, and 4°). The target was a digit presented in isolation or flanked by two other digits, one to each of its sides. Strasburger found lower thresholds in the cued than noncued condition at 1° of eccentricity; a smaller cueing effect at 2° of eccentricity; but no cueing effect at 4°. Although the critical distance in its typical form was not calculated, the comparison of thresholds found in the cued condition with those found in the no-flankers condition implies that the critical distance was smaller with the cue than without it at the nearest eccentricity and possibly also at 2° of eccentricity but not at 4°. Strasburger suggested that there were no attentional benefits at the farther eccentricities because the ring cue might have been too small and masked the target. Strasburger also found that the cue was not effective in reducing errors that involve reports of a flanker instead of the target and concluded, therefore, that the cue did not reduce the processing of the flankers.

Scolari et al. (2007) asked their observers to indicate the orientation of the letter T presented either in isolation or with two flanking stimuli—one above the letter and one below. These stimuli could appear at 8° of eccentricity, to the left or right of fixation, and a cue appeared at one of these possible locations prior to the stimuli onset. The critical distance was defined as the target–flankers distance at which accuracy achieved 90% of the asymptotic value, when plotting accuracy as a function of target–flankers distance. Higher asymptotic values were found for trials in which the cue appeared at the stimulus location than when it appeared at the other location. However, the critical distances of these two conditions did not differ significantly. Similar results were found when target eccentricity was 4°, and when performance with a peripheral cue was compared to that with a neutral cue (i.e., when both possible locations were cued). In contrast, when the target had a different color from the flankers, the critical distance was reduced. Scolari et al. (2007) concluded that attracting attention to the target location, via peripheral precues, facilitates target processing without affecting flankers' representation. Thus, precueing can enhance accuracy without showing a reduction in critical distance.

Felisberti et al. (2005) presented an array of five Gabor patches at an eccentricity of 3.8° to the upper left or lower right quadrants. The target could appear in one of the three middle positions within the array. In the cued condition, the exact location of the target was indicated in advance by a central cue—a line extending from the center of the screen to the target location. In the neutral condition, the exact location of the target was unknown as three lines extended from the center of the screen to three possible locations. They found lower orientation identification thresholds for the cued than neutral condition. Moreover, their cue reduced the critical distance: performance returned to baseline (i.e., performance without flankers) for the cued targets but not for uncued targets. However, the comparison of these findings with those of the abovementioned studies as well as the current study is intricate. The neutral condition in Felisberti et al.'s study included uncertainty regarding the target location within the array of stimuli (the target could appear in one of three possible locations), whereas in the other studies the target location within the stimuli array was always known (e.g., the target was always the central stimulus).

To summarize, all of these studies have found effects of precueing on overall performance—precueing attention to the target location improved accuracy or reduced thresholds (Felisberti et al., 2005; Huckauf & Heller, 2002; Scolari et al., 2007; Strasburger, 2005). The effect of precueing on the critical distance was less conclusive. Some of these studies found an attentional reduction of the critical distance, but only at near eccentricities (Felisberti et al., 2005; Strasburger, 2005) while others did not find such an effect or did not measure the critical distance (Huckauf & Heller, 2002; Scolari et al., 2007). One possible reason for the failure to find an attentional effect on the critical distance could be forward masking between the cue and the target (e.g., Huckauf & Heller, 2002; Strasburger, 2005). For instance, because the attentional cue in Scolari et al.'s study appeared at the exact same location as the target, forward masking may have prevented the emergence of an attentional reduction of the critical distance. Similarly, as suggested by Strasburger (2005), the lack of attentional effects in his study at higher eccentricities may be due to a too small ring cue that surrounded the target. The goal of this study was to reexamine the effects of peripheral precues on the critical distance and overall performance with crowded displays, at both near and far eccentricities, while avoiding forward masking effects.

To that end, we presented the target—the letter T—in various orientations either in isolation or with two flanking stimuli, one above and one below the target. The task was to indicate the orientation of the target. Target–flankers distance varied systematically to allow the assessment of the critical distance. Experiment 1 included various target eccentricities (3°, 5°, 9°); Experiments 2 and 3 included a single eccentricity (9°). Prior to the onset of the target display, we presented a cue (Figure 1). The cue either indicated the target location—cued condition—or did not indicate a location—neutral condition. To avoid masking effects, the peripheral cue was a small dot presented next to the target location (rather than at the same location), on the inner side of the target (i.e., closer

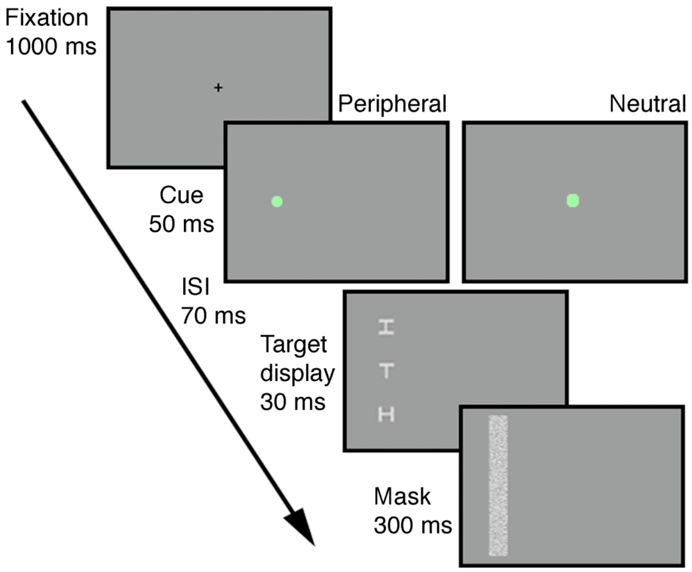

Figure 1. The sequence of events in Experiment 1.

to the fovea). This location was chosen because a higher interference was found with flankers placed at the outer (i.e., more peripheral) side of the target (Petrov & Popple, 2007). In light of previous studies, we expect to find an overall improved accuracy in the cued than the neutral condition. As for the critical distance, if the lack of attentional reduction of critical distance was indeed due to cue–target masking, such a reduction should emerge here.

Experiment 1

Methods

Observers

Fifteen students participated in the eccentricity condition of 3°, 15 students participated in the 5° condition, and 16 students participated in the 9° condition. All participants were students from the University of Haifa, with normal or corrected-to-normal vision, and all of them were naive to the purpose of the study. Six of these students participated in all eccentricity conditions; nine participated in two conditions and ten participated in a single condition.

Stimuli and apparatus

The stimuli were presented using PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993) on a 21-inch monitor of a PowerMac G4 computer. Similar to Scolari et al. (2007), 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. The gray target and flankers (20.7 cd/m^2) were presented on a darker background (17 cd/m^2), resulting in a contrast of 10%, and both subtended 1.05° × 1.05° of visual angle. There were nine possible distances between the flankers and the target, varying randomly from 1 to 9 in units of target width (e.g., Scolari et al., 2007). On 10% of the trials, the target appeared without flankers to provide a baseline. Target and flankers appeared to the left or right of fixation. There were three possible eccentricity conditions: 3°, 5°, or 9°. The peripheral cue was a green dot with a diameter of 0.35°, positioned at a nearer eccentricity, 1° closer to fixation than the target. The peripheral cue always indicated the correct target location. The neutral cue was a green disk, with a diameter of 0.55°, presented at the center of the screen. The fixation mark was a black (0.3 cd/m^2) cross (0.3° × 0.3°) presented at the center of the screen, and the mask was a 23.3° × 1.1° gray and white random dot rectangle.

Procedure

Each trial started with the fixation cross and after 1000 ms, the cue was presented for 50 ms. After an interstimulus interval (ISI) of 70 ms, the target and flankers appeared. The duration of the target and flankers' display was adjusted individually to ensure performance level of about 70% correct, and it ranged between 20 and 70 ms with a mode of 20 ms. The short time from cue onset to target offset 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. Each eccentricity condition was conducted in a separate session. For the participants who run in more than 1 eccentricity condition, the duration was adjusted independently for each condition and the order of eccentricity conditions was random. The other conditions (i.e., target–flankers distance and cue type) appeared equally often within each session but in a randomized order.

The observers had to report the orientation of the target. An auditory feedback followed their response. Each observer participated in about 300 practice trials and 960 experimental trials.

Results and discussion

Accuracy

A three-way, mixed design analysis of variance (ANOVA; within variables: cue type, target–flankers distance; between variable: eccentricity) was performed on the accuracy data, excluding the trials in which the target appeared without flankers. As expected, a significant main effect of cue type was found [$F(1, 43) = 34.81$, $p < 0.0001$] showing higher accuracy for cued than neutral trials. The main effect of target eccentricity was also

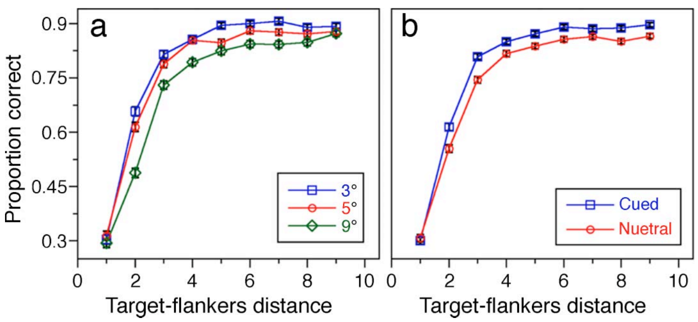

Figure 2. Averaged accuracy in Experiment 1 as a function of target–flankers distance (in units of target width). (a) Target eccentricity. (b) Cueing condition. Error bars correspond to one standard error.

significant [$F(2, 43) = 6.1$, $p < 0.005$]—accuracy decreased as target eccentricity increased. As in many previous studies of crowding (e.g., Bouma, 1970; Felisberti et al., 2005; Pelli et al., 2004; Poder, 2007; Scolari et al., 2007; Strasburger, 2005; Strasburger, Harvey, & Rentschler, 1991), a significant main effect was found for target–flankers distance [$F(8, 344) = 653.43$, $p < 0.0001$] demonstrating increased accuracy with increased target–flankers distance. A significant interaction was found between eccentricity and target–flanker distance [$F(16, 27) = 3.65$, $p < 0.0001$; Figure 2a]. This interaction emerged because except for the smallest target–flankers distance, the difference between the different eccentricities was more pronounced for smaller distances. At the smallest target–flankers distance, there was no difference between the different eccentricities—performance was close to guessing level at all eccentricities. The interaction between cue type and target–flanker distance was also significant [$F(8, 344) = 4.41$, $p < 0.0001$; Figure 2b]. This interaction emerged because unlike the other distances, there was no effect of cue type with the smallest target–flankers distance. At this distance, performance was close to guessing level for both cue types. No other effect reached statistical significance.

A two-way, mixed design ANOVA (within variable: cue type; between variable: eccentricity) performed on the trials with no flankers revealed a significant precueing effect [$F(1,43) = 4.92$, $p < 0.05$]: accuracy was higher in the cued than neutral condition. The two-way interaction was not significant indicating that this cueing effect did not vary significantly as a function of target eccentricity.

Critical distance

The critical distance analysis followed Scolari et al. (2007). The data from each observer were modeled individually using an exponential function to determine the critical distance. We employed the following equation:

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

where pc is proportion correct, a is the asymptote, s is the scaling factor, d is the target–flanker distance, and i is the x-intercept. The asymptotic value, scaling factor, and x-intercept were adjusted using 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–flanker distance at which accuracy achieved 90% of the asymptotic value, and it was calculated using the following equation:

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

The model fits the data well (mean $R^2 = 0.95$). Figure 3a demonstrates the outcomes of the fitting process of one exemplar participant. Two participants were removed from further analysis because their data did not reach asymptote level (i.e., the estimated critical distance was exceptionally large). A two-way mixed design ANOVA (within variable: cue type; between variable: eccentricity) was conducted on the critical distances calculated based on the individual data of each cueing condition at each eccentricity. As expected, this analysis revealed a significant effect of eccentricity [$F(2, 41) = 7$, $p < 0.005$]: The critical distance was larger as the target appeared at larger eccentricities. This finding suggests that the critical distance scales with target eccentricity and it was previously demonstrated by various studies (e.g., Bouma, 1970; Latham & Whitaker, 1996; Pelli et al., 2004; Strasburger, 2005; Toet & Levi, 1992). Most relevant for the goal of this study, the analysis also revealed a significant cueing effect [$F(1, 41) = 14.82$, $p < 0.0005$; Figure 4]: the critical distance for the cued condition was significantly smaller than for the neutral condition. There was no significant interaction between cue type and eccentricity [$F < 1$]. Indeed, planned comparisons confirmed that this cueing effect was significant at all

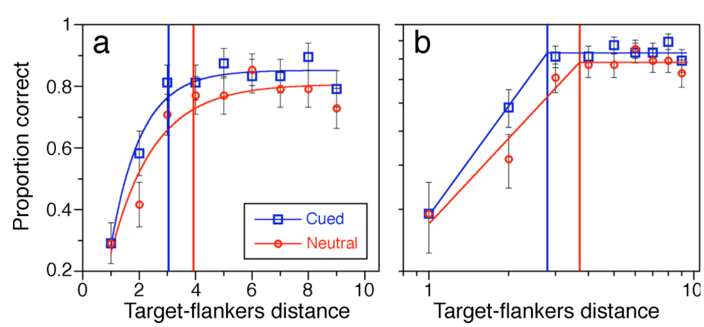

Figure 3. An example of the two methods employed for estimating the critical distance for one exemplar participant. (a) The "exponential method". (b) "Two-lines method". The vertical lines indicate the critical distance for cued and neutral conditions in both methods. Error bars correspond to one standard error.

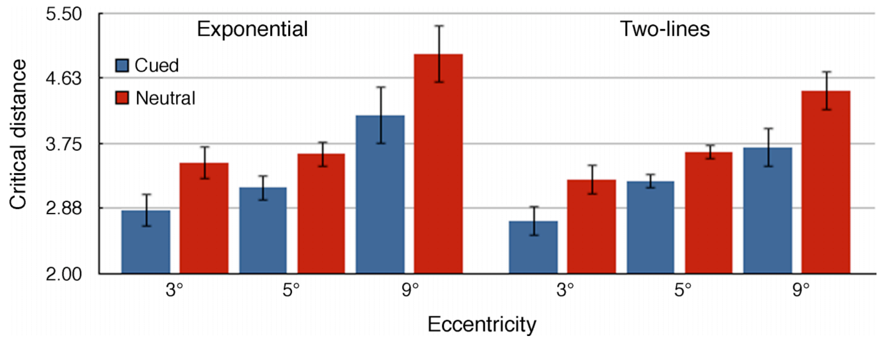

Figure 4. Mean critical distance values (in units of target width) as a function of cueing condition, estimated with each of the fitting methods for each target eccentricity in Experiment 1 (see text). Error bars correspond to one standard error.

eccentricities [3°: $t(14) = 2.82$, $p < 0.007$; 5°: $t(13) = 2.52$, $p < 0.02$; 9°: $t(14) = 2.07$, $p < 0.03$].

To ensure that the finding of a smaller critical distance in the cued than neutral condition does not depend on the specific method employed for the estimation of the critical distance, we also estimated this distance using a different method: Each individual plot of accuracy versus target–flankers distance, in each cueing condition at each eccentricity, was fitted with two straight lines on log–log coordinates (e.g., Hinkley, 1969). The first line has a positive slope, optimized by least-squares regression to fit the data, and the slope of the second line constrained to zero. The intersection of the two lines was defined as the critical distance (e.g., Chung, 2002; Chung, Levi, & Legge, 2001; Levi, Song, & Pelli, 2007). An example of this estimation process for one exemplar participant is demonstrated in Figure 3b. This model also fitted the data well (mean $R^2 = 0.97$). We then submitted these new estimations of the critical distance to the same statistical analysis and found the same pattern of results: the main effects of eccentricity and cue type were significant [cue type: $F(1, 41) = 21.97$, $p < 0.0001$; eccentricity: $F(2, 41) = 4.7$, $p < 0.02$; Figure 4], but their interaction was not [$F < 1$]. Planned comparisons confirmed again that the cueing effect was significant at all eccentricities [3°: $t(14) = 2.65$, $p < 0.01$; 5°: $t(13) = 3.6$, $p < 0.002$; 9°: $t(14) = 2.81$, $p < 0.008$]. Table 1 lists the averaged critical distance values that were estimated with both methods. We also compared the cueing effect on the critical distance with both methods of estimation and found that the effect did not vary significantly as a function of method [$F < 1$]. Hence, the finding that attention can reduce the spatial extent of crowding does not depend on the method used to estimate this extent.

As in previous studies (e.g., Felisberti et al., 2005; Huckauf & Heller, 2002; Scolari et al., 2007; Strasburger, 2005), the results of this experiment show that precueing the target location improves overall performance. This cueing effect did not vary as a function of eccentricity. Importantly, in this experiment we were able to show that precueing target location also decreased the critical distance. This decrement in the critical distance was found at all the eccentricities measured here and with both methods of estimations. Thus, unlike previous studies in which there was no attentional decrement of the critical distance (Scolari et al., 2007) or a decrement only at near eccentricities (Strasburger, 2005), in this study attracting transient attention to the target location improved performance and diminished the crowding effect at all eccentricities, as evident by the decrease in critical distance. These attentional effects emerged here, most likely, because we prevented forward masking effects between the cue and the target by presenting the cue at an adjacent location to the target, rather than at the same location. Specifically, the cue was presented at a location that was closer to fixation—a location known to inflict less interference (Petrov & Popple, 2007).

Experiment 2

In Experiment 1, a mask followed the target and flankers' display. One may wonder whether the effects

	3°		5°		9°	
	Exponential	Two lines	Exponential	Two lines	Exponential	Two lines
Cued	**2.85** (2.99°)	**2.71** (2.85°)	**3.15** (3.31°)	**3.24** (3.40°)	**4.13** (4.33°)	**3.70** (3.89°)
Neutral	**3.49** (3.66°)	**3.26** (3.42°)	**3.61** (3.79°)	**3.64** (3.82°)	**4.95** (5.2°)	**4.45** (4.67°)

Table 1. Averaged critical distance values (as estimated with each of the methods) in target width units (bold digits) and in degrees of visual angle (in parentheses), for cued and neutral conditions at 3°, 5°, and 9° of eccentricity in Experiment 1.

In target width units	In degrees of visual angle	
	Experiments 1 and 3	Experiment 2
1	1.05	0.9
2	2.1	1.8
3	3.2	2.7
4	4.2	3.6
5	5.3	4.5
6	6.3	5.4
7	7.4	6.3
8	8.4	7.2
9	9.5	8.1
10	–	9
11	–	9.9
12	–	10.8

Table 2. Target–flanker distances in Experiments 1–3 in target width unit and degrees of visual angle.

of attention found in this experiment depend on the presence of a backward mask. Smith (2000), for instance, suggested that precueing effects found for detection tasks reflect facilitation of information accrual rather than an improvement in overall sensitivity, and therefore, such effects should only be found when a backward mask interrupts information accrual before it reaches its maximal level. Although precueing effects were previously found even when masks were not present (e.g., Carrasco, Williams, & Yeshurun, 2002), to ensure that the attentional reduction of the critical distance is not merely due to the employment of a backward mask, in this experiment we measured the critical distance without a backward mask.

Apart from the lack of a mask, this experiment was similar to Experiment 1, but the target only appeared at 9° of eccentricity. In addition, to ensure that performance will reach asymptotic levels, larger target–flanker distances were added. If the attentional effects found before do not depend on the presence of a mask, they should be replicated even when a mask is not employed.

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, and five of them participated in Experiment 1.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure were identical to Experiment 1 except for the following: The size of the target and flankers was 0.9° × 0.9°, and there were twelve target–flanker distances—from 1 to 12 in units of target width (see Table 2). The target appeared at 9° of eccentricity only. No mask followed stimulus presentation. The duration of the target and flankers' display ranged between 20 and 70 ms, with a mode of 40.

Results and discussion

Accuracy

A two-way, repeated measures ANOVA (Cue type × target–flankers distance) was performed on the accuracy data, excluding the trials in which the target appeared without flankers. As in Experiment 1, both main effects were significant: accuracy was higher for cued than neutral trials [$F(1, 14) = 7.04$, $p < 0.02$] and accuracy increased with increasing target–flankers distance [$F(11, 154) = 146.46$, $p < 0.0001$]. The interaction was also significant [$F(11, 154) = 3.38$, $p < 0.0005$] due to the fact that the cueing effect was mainly present for the smaller target–flankers distances (Figure 5). Finally, there was no significant difference between averaged accuracy in the two cueing conditions of the trials with no flankers [$F < 1$].

Critical distance

As in Experiment 1, the exponential model fits the data well (mean $R^2 = 0.92$). Three participants were removed from further analysis because their data did not reach asymptote level. A one-way repeated measures ANOVA revealed a significant effect of cueing: [$F(1, 11) = 18.88$, $p < 0.002$; Figure 6]: the critical distance for the cued condition was significantly smaller than for the neutral condition (see the averaged critical distance values in Table 3), indicating a smaller critical distance when the target location was cued. A similar significant cueing effect on the critical distance emerged [$F(1, 11) = 6.85$, $p < 0.03$] when the critical distance was estimated for each participant using the two-lines method described above (mean $R^2 = 0.96$), and as in Experiment 1, this effect did

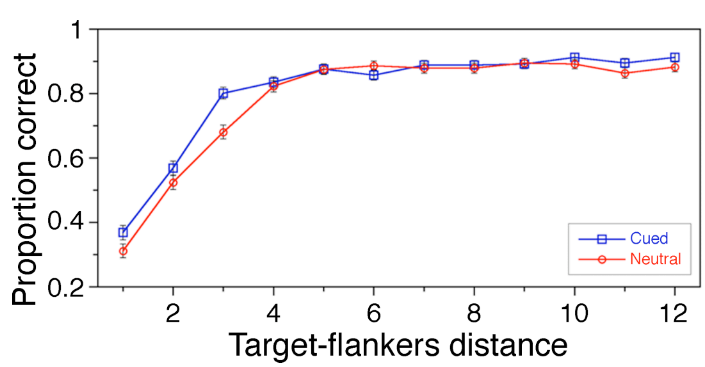

Figure 5. Averaged accuracy in Experiment 2 as a function of cueing condition and target–flankers distance (in units of target width). Error bars correspond to one standard error.

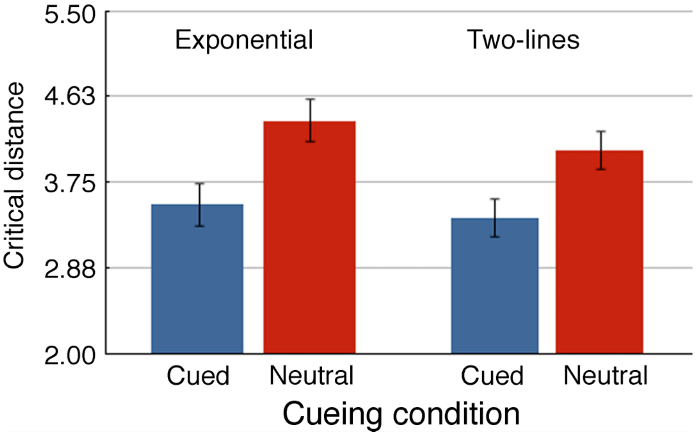

Figure 6. Mean critical distance (in units of target width) as a function of cueing condition and estimation method in Experiment 2. Error bars correspond to one standard error.

not significantly interacted with the factor of estimation method [$p = 0.16$].

The findings of this experiment show that even when a backward mask did not follow the target and flankers' display, a significant effect of attention emerged. Thus, the attentional decrement of the critical distance does not depend on the presence of a mask. Interestingly, the values of the critical distance obtained in this experiment are smaller than those obtained in Experiment 1 when a mask followed the target display ($p < 0.001$ for both estimation methods). This result replicates Vickery, Shim, Chakravarthi, Jiang, and Luedeman's (2009) finding that when the target is masked by a backward mask crowding occurs far beyond the typical critical distance. They suggested that this finding reflects strong interactions between masking and crowding, which implies nonadditive relationships.

Experiment 3

In the previous experiments of this study, the attentional cue indicated the target location with 100% validity. Such an informative cue might have encouraged the observers of these experiments to voluntarily attend the cued location. If so, the attentional effects found in Experiments 1 and 2 reflect some mixture of transient and sustained attentional effects. This is not highly likely because in all three experiments the timing between cue onset and the onset of the target and flankers' display was too short for voluntary allocation of sustained attention (e.g., Nakayama & Mackeben, 1989). Nevertheless, to test whether similar effects can be found under conditions that ensure the sole involvement of transient attention, the validity of the cue in this experiment was reduced to 50%.

Specifically, the target and flankers could appear in one of two possible locations to the left or right of fixation at 9° of eccentricity. On half of the trials—the *valid* trials—the attentional cue appeared next to the target location, and on the other half—the *invalid* trials—it appeared next to the other location. Thus, the attentional cue in this experiment is no longer informative, and the observers have no incentive to voluntarily attend the cued location. If transient attention can alleviate crowding effects, even when no voluntary mechanisms are involved, the attentional reduction of the critical distance in the valid trials should resemble those of the previous experiments of this study.

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. Eight of the observers also participated in Experiment 1, and two also participated in Experiment 2.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure were identical to Experiment 1 except for the following: The target appeared at 9° of eccentricity only. Instead of the neutral cue employed in the previous experiments, all of the trials included a peripheral cue. On half the trials—the valid trials—the cue appeared on the same side as the target, 1° closer to fixation (i.e., at 8° of eccentricity), as in Experiment 1. On the rest of the trials—the invalid trials—the cue appeared on the opposite side from the target in the corresponding eccentricity. The duration of the target and flankers' display ranged between 30 and 70 ms, with a mode of 40.

	Experiment 2		Experiment 3	
	Exponential	Two lines	Exponential	Two lines
Cued	**3.52** (3.17°)	**3.39** (3.05°)	**3.80** (3.99°)	**3.32** (3.49°)
Neutral (Experiment 2)/invalid (Experiment 3)	**4.38** (3.94°)	**4.08** (3.67°)	**4.63** (4.86°)	**4.15** (4.36°)

Table 3. Mean critical distances in target width units (bold digits) and degrees of visual angle (in parentheses), for the different cueing conditions in Experiments 2 and 3.

Results and discussion

Accuracy

A two-way, repeated measures ANOVA (cue validity × target–flankers distance) was performed on the accuracy data, excluding the trials in which the target appeared without flankers. Both main effects were significant. As in previous experiments, attracting attention in advance to the target location improved performance: overall accuracy was higher in the valid than invalid trials [$F(1, 15) = 12.29$, $p < 0.004$] and increasing target–flankers distance increased accuracy [$F(8, 120) = 341.34$, $p < 0.0001$]. The cue validity × target–flanker distance interaction was also significant [$F(8, 120) = 4.64$, $p < 0.0001$; Figure 7]; the cueing effect was largest at the smaller target–flankers distances, though not at the smallest distance at which performance was close to guessing level.

Similar to Experiment 1, the analysis of the trials in which the target appeared with no flankers indicated that accuracy was higher in the valid than invalid condition; however, this effect did not reach statistical significance [$F(1, 15) = 3.01$, $p = 0.1033$].

Critical distance

As before, both models fit the data well for both cueing conditions (exponential: mean $R^2 = 0.95$; two lines: mean $R^2 = 0.97$). One participant was removed from further analysis because her data did not reach asymptote level. The averaged critical distance values are listed in Table 3. We performed the same statistical analysis as in Experiment 2 on both estimations of the critical distance and found similar outcomes: the critical distance was smaller when a valid cue attracted attention to the target location than when an invalid cue attracted attention away from the target [exponential: $F(1,14) = 19.98$, $p < 0.0005$; two lines: $F(1,14) = 14.27$, $p < 0.002$; Figure 8]. Here too, this cueing effect did not interact significantly with the method of estimation [$F < 1$]. The fact that precueing the target location decreased the critical distance when the peripheral cue was not informative suggests that transient attention can diminish crowding effects even without voluntary allocation of attention.

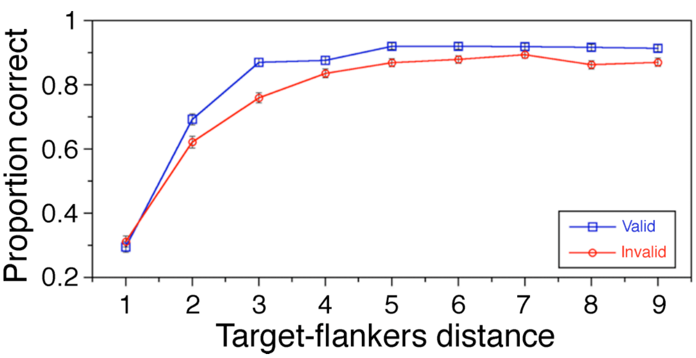

Figure 7. Averaged accuracy in Experiment 3 as a function of cue validity and target–flankers distance (in units of target width). Error bars correspond to one standard error.

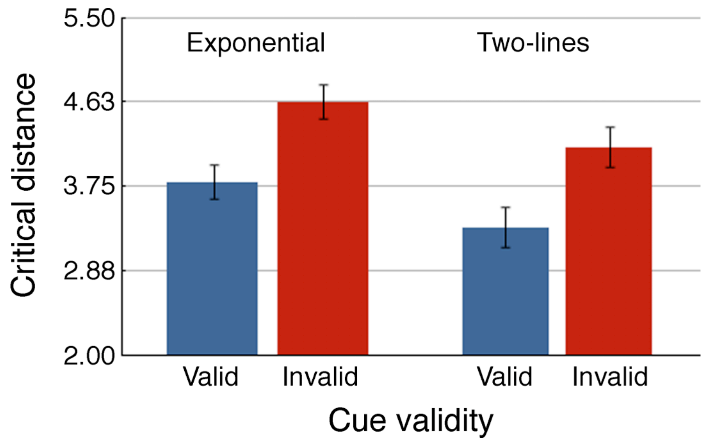

Figure 8. Mean critical distance (in units of target width) as a function of cue validity and estimation method in Experiment 3. Error bars correspond to one standard error.

General discussion

The present study examined the effects of attention on crowding. Orientation identification was measured with varying target–flanker distances with peripheral and neutral precues, at near and far eccentricities. The target–flankers display was either followed by a mask (Experiments 1 and 3) or not (Experiment 2), and the peripheral cue was either informative (Experiments 1 and 2) or not (Experiment 3). The results, across all experiments, show significant attentional increment of accuracy and significant attentional reduction of the critical distance at all eccentricities. These attentional effects were found regardless of the presence of a backward mask and whether the attentional cue was informative or not.

The finding that precueing target location improved overall accuracy is consistent with several previous crowding 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). Such an improvement suggests that attention enhances the processing at the attended location, possibly leading to a better representation of the target (e.g., Poder, 2006, 2007; Scolari et al., 2007).

However, previous studies that measured the critical distance while manipulating transient attention (Scolari et al., 2007; Strasburger, 2005) did not always find an attentional decrement of the critical distance. Specifically, Scolari et al. (2007) did not find any significant effect of attention on the critical distance, whereas Strasburger (2005) found an attentional decrement of the critical distance at near eccentricities (1° and possibly 2°) but not at 4° of eccentricity. In contrast, in this study directing attention to the target location reduced the critical distance at near (3°) and far (5° and 9°) eccentricities. It is possible that this attentional effect on the critical distance was not found in previous studies due to forward masking effects between the attentional cue and the target (e.g., Huckauf & Heller, 2002; Strasburger, 2005). In this study, to avoid such forward masking effects, the cue was located in adjacent location to that of the target, rather than the same location, and it was presented at a nearer eccentricity than the target, because it was shown that flankers presented on the inner side interfere less than flankers presented on the outer side (Petrov & Popple, 2007). Avoiding interference between the cue and the target allowed the emergence of a significant attentional effect on the critical distance. This account of the differences between the current and prior studies suggests that the attentional effect on the critical distance is more susceptible to forward masking than attentional effects on overall performance as prior studies found attentional effects on the latter but not on the former. This may be related to the finding that the spatial extent of crowding is significantly extended when the target is masked, but when flankers are absent, performance is only mildly impaired by the mask (Vickery et al., 2009). Furthermore, the higher "resistance" of attentional effects on overall performance is expected given that such effects most likely reflect the involvement of several attentional operations (e.g., gain enhancement, noise reduction, changes in decisional criterion, facilitation of processes, etc.), some of which may not be relevant for the attentional reduction of the critical distance. The assertion that more operations may be involved in the attentional effects on overall performance is supported by the fact that such effects can be found even when there is no crowding, that is when flankers are absent (e.g., Cameron, Tai, & Carrasco, 2002; Carrasco et al., 2000, 2002; Cheal & Gregory, 1997; Henderson & MacQuistan, 1993; Luck & Thomas, 1999; Müller & Rabbitt, 1989; Yeshurun & Carrasco, 1999). Another possible explanation for the emergence of an attentional effect on the critical distance is related to the fact that unlike Scolari et al. (2007), the fixation mark in the current experiments disappeared before the onset of the cue. MacKeben and Nakayama (1993) suggested that the disappearance of the fixation mark leads to a faster shift of covert attention (i.e., shifts of spatial attention in the absence of eye movements). Hence, the disappearance of the fixation mark in our study may have induced a more efficient allocation of attention to the target location increasing the ability of attentional process to affect the critical distance.

The fact that the attentional reduction of the critical distance was found even when a backward mask did not follow the target and flankers' display (Experiment 2), suggests that this reduction does not reflect a mere reduction in interference between the mask and the target, possibly by accelerating the processing of the target (Smith, 2000). In addition, the fact that precueing reduced the critical distance even when the attentional cue was not informative and therefore the observers had no incentive to voluntarily direct attention to the target location (Experiment 3) suggests that such an attentional reduction in critical distance does not depend on voluntary allocation of attention.

Several explanations were offered to account for the crowding phenomenon. One of the prominent explanations suggests that crowding is the outcome of faulty information "pooling" or integration of information over a relatively large area. Parkes, Lund, Angelucci, Solomon, and Morgan (2001), for instance, suggested that crowding occurs because, under crowded conditions, we do not have access to individual items but only to the pooled signal—the signal pooled over all items including the target and the flankers. Similarly, Pelli et al. (2004) suggested that crowding is due to "excessive feature integration". According to their view, crowding occurs at an intermediate level at which the output of single feature detectors is integrated within what Pelli et al. (2004) refer to as "integration fields". The size of these integration fields is small at the fovea and increases with eccentricity. When both the target and the flankers fall within the same integration field, their features are integrated together leading to a mistake in identification. Hence, crowding happens when the visual system uses inappropriately large integration fields, and the critical distance reflects the size of the integration field. According to this view, this intermediate stage of integration is preattentive—attention can only operate on its ambiguous product. That is, according to this view directing attention to the target location should not affect crowding. Our findings that precueing the target improved overall identification accuracy and reduced the critical distance do not support this latter claim. However, if the assumption that the stage of integration is preattentive is removed, the results of this study can be reconciled with the integration field view: The attentional reduction of the critical distance may reflect a reduction in the size of the integration fields at the attended location.

It was previously demonstrated that transient attention enhances the spatial resolution at the attended location (Yeshurun & Carrasco, 1998, 1999, 2000). Yeshurun and Carrasco (1998) suggested that attention might enhance spatial resolution by promoting the processing of information over a smaller area. The task of that study required the segmentation of a texture target from a background of orthogonal orientation. The advanced allocation of transient attention to the target location enhanced performance when this target appeared at the periphery, where the spatial resolution was too low due to the processing of information via spatial filters that are too big for the scale of the texture. However, when the target appeared at more central locations, in which the spatial resolution is too high due to the processing of information via spatial filters that are too small, attending the target location impaired performance. These findings are consistent with neurophysiological studies suggesting that attention contracts the cell's receptive field around the attended stimulus (see, e.g., Desimone & Duncan, 1995; Luck, Chelazzi, Hillyard, & Desimone, 1997; Moran & Desimone, 1985). Thus, the attentional reduction of the critical distance may reflect the processing of the target with smaller receptive fields, resulting in information integration over a smaller area. Note that the assertion that attention can affect intermediate levels of processing is consistent with a growing body of evidence suggesting that attention can affect neural activity as early as V1 (e.g., Brefczynski & DeYoe, 1999; Gandhi, Heeger, & Boynton, 1999; Ito & Gilbert, 1999; Kastner & Ungerleider, 2000; Martinez et al., 1999; Motter, 1993).

The attention resolution theory is another prominent explanation of crowding. It suggests that the extent of crowding is determined by the minimal selection region of attention (e.g., Chakravarthi & Cavanagh, 2007; He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002). When more than one item fall within the smallest possible selection region of attention, the items are selected as a group, and there is no access to the individual identity of one item. In this case, the identification of an individual item is not possible. Hence, according to this view, crowding reflects the limitation of the spatial resolution of attention. In the present study, however, precueing attention reduced the critical distance of crowding. If there is only one mechanism of attention, so that the selection mechanism attracted by the precue is the same mechanism that selects the item for final identification, our current results do not support the attention resolution theory because directing attention to the precued location reduced the extent of crowding. That is, crowding was not limited by the attentional selection. However, one can assume that these are different mechanisms (e.g., Jonides, 1981; Nakayama & Mackeben, 1989). For instance, Strasburger (2005) suggested that a voluntary mechanism of attention is imprecisely focused at the region of the target, and that this imprecision limits performance (i.e., results in crowding effects), while another attentional mechanism, triggered by transients like abrupt onset, can facilitate the processing of information within the focus of voluntary attention but does not affect the location of the attentional focus. Poder (2006, 2007) also suggested that at least two selection mechanisms are involved in the processing of crowded displays: a bottom-up salience-based mechanism that operates at relatively early stages of processing and a top-down mechanism operating at higher stages of processing. If we assume that the mechanism triggered by our peripheral cue is different than the selection mechanism described by the attention resolution theory (e.g., the former is transient attention presumably operating at an earlier stage, while the latter is a higher attentional mechanism, operating at a later stage), then our findings can also be reconciled with the attention resolution theory. Specifically, our findings suggest that the allocation of transient attention via the peripheral precue reduces the minimal selection region of the higher selection mechanism.

To summarize, our findings suggest that transient attention reduces the spatial extent of crowding. That is, the attentional reduction of the critical distance suggests that transient attention reduces the "confusion" area—the area over which the presence of flankers interferes with target identification. With some modifications, prominent accounts of crowding are in agreement with our findings.

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