

Focusing and orienting spatial attention differently modulate crowding in central and peripheral vision

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The allocation of attentional resources to a particular location or object in space involves two distinct processes: an orienting process and a focusing process. Indeed, it has been demonstrated that performance of different visual tasks can be improved when a cue, such as a dot, anticipates the position of the target (orienting), or when its dimensions (as in the case of a small square) inform about the size of the attentional window (focusing). Here, we examine the role of these two components of visuo-spatial attention (orienting and focusing) in modulating crowding in peripheral (Experiment 1 and Experiment 3a) and foveal (Experiment 2 and Experiment 3b) vision. The task required to discriminate the orientation of a target letter “T,” close to acuity threshold, presented with left and right “H” flankers, as a function of target-flanker distance. Three cue types have been used: a red dot, a small square, and a big square. In peripheral vision (Experiment 1 and Experiment 3a), we found a significant

improvement with the red dot and no advantage when a small square was used as a cue. In central vision (Experiment 2 and Experiment 3b), only the small square significantly improved participants’ performance, reducing the critical distance needed to recover target identification. Taken together, the results indicate a behavioral dissociation of orienting and focusing attention in their capability of modulating crowding. In particular, we confirmed that orientation of attention can modulate crowding in visual periphery, while we found that focal attention can modulate foveal crowding.

Introduction

Crowding refers to the impaired recognition or identification of a target when surrounded by other

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irrelevant stimuli (Stuart & Burian, 1962; Flom, Weymouth, & Kahneman, 1963a; Flom, Heath, & Takahashi, 1963b; see also Strasburger, Rentschler, & Jüttner, 2011, for a review). It has been reported to occur in a wide variety of tasks, such as letter recognition (e.g., Bouma, 1970; Toet & Levi, 1992), orientation discrimination (e.g., Andriessen & Bouma, 1976), and face recognition (e.g., Martelli, Majaj, & Pelli, 2005). Different models have been proposed in order to explain this phenomenon (see Tyler & Likova, 2007 for a perspective on crowding models), but according to one of the most accepted accounts, crowding can be explained in terms of the erroneous inclusion of features to be integrated within a spatial window, known as integration field (Wolford, 1975; Pelli, Palomares, & Majaj, 2004). Typically, when we identify a target, we have to combine information from several features within the integration field. Crowding occurs when the visual system operates over an improperly large region of the visual field which includes both target and flanker features. This results in an excessive feature integration that prevents target identification (e.g., Pelli et al., 2004; Solomon & Morgan, 2001). Crowding is a phenomenon described in detail, for which we have well-established diagnostic criteria (Pelli et al., 2004), and attempts have been made to account for the computation that occurs within the integration fields (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Nandy & Tjan, 2007; Balas, Nakano, & Rosenholtz, 2009; Freeman & Simoncelli, 2011; Freeman, Chakravarthi, & Pelli, 2012). According to the integration field account, the size of the integration fields can be measured by calculating the minimum target to flanker spacing needed to achieve target recognition, i.e., critical spacing or distance (e.g., Toet & Levi, 1992). The critical distance between the target and flanker scales with eccentricity, independently of target and flanker size, and the scaling is roughly proportional to half the target viewing eccentricity, although large individual differences in this proportionality have been reported (Bouma, 1970; Strasburger, Harvey, & Rentschler, 1991; but see also Pelli et al., 2004 for variations across studies). Thus, integration fields are small in the fovea, but larger in the periphery. As a result, the isolation of the target in the fovea is typically an effortless act in usual viewing conditions, whereas in the periphery, most often the integration fields include both the target and the flankers. Identification of objects between flankers, such as letters in words, and of multipart objects, such as faces, show this dependency on eccentricity and not size (Levi, Hariharan, & Klein, 2002; Pelli et al., 2004; Martelli et al., 2005; Rosen, Chakravarthi, & Pelli, 2014). By contrast, detection tasks, as well as one-feature judgements, are immune to crowding (Pelli et al., 2004).

Many studies that measure the identification of known targets, while presented always at the same retinal location, interpret crowding as the bottleneck of pattern perception (Levi, 2008; Pelli & Tillman, 2008; see also Strasburger, Rentschler, & Jüttner, 2011). Other authors, instead, have measured identification under location uncertainty and suggested that crowding is intimately linked to the construct of attention (He, Cavanagh, & Intriligator, 1996; Scolari, Kohlen, Barton, & Awh, 2007; Chanceaux & Grainger, 2013). Indeed, the attention-resolution account argues that crowding reflects the limitation of the spatial resolution of attention (e.g., He et al., 1996; He, Cavanagh, & Intriligator, 1997; Intriligator & Cavanagh, 2001). As a result, closely grouped targets and distractors can be said to lead to impaired target discrimination because the resolution of attention is insufficient to disambiguate the relevant and irrelevant elements in the scene (Scolari et al., 2007). According to this account, critical distance, and thus the integration field, reflects the finest region that attention can select, which determines the extent of crowding (e.g., He et al., 1996, 1997; Tripathy & Cavanagh, 2002; Chakravarthi & Cavanagh, 2007; Fang & He, 2008). Targets that are spaced more finely than the attention resolution capacity cannot be selected individually for further processing and recognition. Attention resolution is often substantially coarser than the smallest details resolvable by vision, i.e., acuity (Intriligator & Cavanagh, 2001). Clearly, the only distinction between the perceptual account and the attentional account of crowding consists in their different predictions on the role of bottom-up isolation and top-down selection processes.

Several studies have demonstrated that allocating spatial attention to a particular target location or object improves performance in several tasks (e.g., Eriksen & Rohrbaugh, 1970; Eriksen & Hoffman, 1972; Posner, 1980; Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Lu & Doshier, 1998; Yeshurun & Carrasco, 1999), by facilitating the discrimination of visual information or enhancing visual information processing (e.g., Desimone & Duncan, 1995; He et al., 1996, 1997). This effect is observable when the target signal is presented alone, but it is particularly pronounced when the identification of this signal is made more difficult by the presence of irrelevant distractors (e.g., Shiu & Pashler, 1994; Desimone & Duncan, 1995; Doshier & Lu, 2000). However, most of these studies, rather than a change of the critical distance, measured a threshold elevation effect and therefore did not disentangle low-level masking from midlevel crowding (Lu et al., 1998; Müller & Rabbitt, 1989; Desimone & Duncan, 1995; Doshier & Lu, 2000).

Some studies directly assess the spatial extent of crowding, demonstrating an attentional influence on

crowding or an attentional modulation of the critical distance (e.g., Wolford & Chambers, 1983; Van der Lubbe & Keuss, 2001; Huckauf & Heller, 2002; Felisberti & Zanker, 2005; Montaser-Kouhsari & Rajimehr, 2005; Strasburger, 2005; Pöder, 2007; Yeshurun & Rashal, 2010; Petrov & Meleshkevich, 2011; Strasburger & Malania, 2013; but see also Scolarì et al., 2007). In particular, valid cues decrease the critical distance whereas invalid cues increase it (Freeman & Pelli, 2007; Yeshurun & Rashal 2010; Grubb et al., 2013). These results suggest that under location uncertainty, observers are unable to use the smallest integration field available at a given eccentric location, and then correctly discriminate the target. Thus, attention may enable the selection of the smallest integration field available or enhance spatial resolution by overrepresenting the space in the attended area while simultaneously suppressing the space outside that area (Suzuki & Cavanagh, 1997; Intriligator & Cavanagh, 2001).

A further controversy in the literature concerns the difference between peripheral and foveal crowding. Most studies on this topic investigate the crowding phenomenon, and how it can be modulated by attention, while focusing only on the periphery of the visual field. As mentioned before, crowding is more pronounced in peripheral vision (Fine, 2004; Pelli et al., 2004), whereas the critical distances in fovea are typically small, covering only a few minutes of arc, close to the acuity threshold (Latham & Whitaker, 1996; Siderov, Waugh, & Bedell, 2013; Coates & Levi, 2014). Thus, given the limited extent of the integration fields in central vision, both crowding and attentional effects are less pronounced and harder to detect compared to those in peripheral locations. Accordingly, some studies reported that foveal crowding is absent (e.g., Strasburger, Harvey, & Rentschler, 1991; Hess, Dakin, & Kapoor, 2000; Liu & Arditi, 2000). Others instead have argued that foveal crowding can be hardly disentangled from overlap masking (e.g., Levi, Klein, & Hariharan, 2002; Levi, 2008; Pelli & Tillman, 2008). When measured foveally (e.g., Flom et al., 1963a; Westheimer & Hauske, 1975; Westheimer, Shimamura, & McKee, 1976; Butler & Westheimer, 1978; Levi, Klein, & Aitsebaomo, 1985; Chung, Levi, & Legge, 2001; Siderov et al., 2013; Lev, Yehezkel, & Polat, 2014) the extent of the critical distance varies from 4–6 min of arc (Flom et al., 1963a; Siderov et al., 2013) to 30 min of arc (Chung et al., 2001). The attentional effect seems to be less pronounced in the fovea relative to the periphery (Flom, 1991; Strasburger & Rentschler, 1995; Leat, Li, & Epp, 1999). However, measuring contrast threshold Strasburger (2005) has suggested that the focusing-in of attention becomes less precise as eccentricity increases. Critically, the size of

attentional modulation as a function of eccentricity is still a matter of debate.

Here we conjecture that differences across studies of attentional effect on foveal and peripheral crowding might also be related to the different processes involved in spatial attention. In particular, the allocation of attentional resources in space involves two distinct processes: an orientation process, which shifts the attentional resources to the relevant location for further processing (Posner, 1980); and a focusing process, which acts as a magnifying lens and allows us to concentrate our resources selectively on a limited space within the environment, while ignoring the rest of it (e.g., Castiello & Umiltà, 1990; Chun, Golomb, & Turk-Browne, 2011).

Previous studies (e.g., Castiello & Umiltà, 1990; Stoffer, 1991; Benso, Turatto, Mascetti, & Umiltà, 1998; Turatto et al., 2000) suggest that focusing and orienting are distinct and independent processes, characterized by independent mechanisms: One is automatic and exogenous, for short intervals, and the other is voluntary and endogenous, for longer intervals (Turatto et al., 2000). Some studies also demonstrate that focusing and orienting may operate differently depending on the visual conditions. Indeed, even if the control of the attentional focus can be deployed both in the center and in the periphery of the visual field (Henderson, 1991; Benso et al., 1998), peripheral focusing will typically arise at longer SOAs. It seems that in visual periphery orienting might be faster than focusing (Castiello & Umiltà, 1990), supporting the hypothesis of a low efficiency of focusing when it is deployed outside the fovea (Eriksen & St. James, 1986). Our previous results (Albonico, Malaspina, Bricolo, Martelli, & Daini, 2016) have found a behavioral dissociation between the orienting and focusing components of attention in central and peripheral view. In particular, by using single-letter detection and discrimination tasks with fixed target location (no side uncertainty), we demonstrated that although, a strong effect of the orientation component was evident in the periphery, this was not true for the focal component. Vice versa, in central vision, the effect of the focal component was clear. Therefore, it could be that previous studies have failed to find attentional effects on peripheral crowding, and especially on foveal crowding, because they did not take into account the specific role of focusing and orienting. In order to directly compare the effects of orienting and focusing attention at different retinal location the target position uncertainty should be minimized or equated. For this reason, we used a paradigm based on our previous study (Albonico et al., 2016), with no side uncertainty (i.e., the peripheral target always appears at the same location) and we investigated whether focusing and orienting differently modulate foveal and peripheral

crowding. In particular, we hypothesized that orienting would have a strong role in the periphery, while focusing would be more effective in reducing the critical distance only at central locations.

Experiment 1: Peripheral crowding

Yeshurun and Rashal (2010) have shown a clear attentional modulation of the crowding distance under location uncertainty, with a marked reduction obtained in the case of a valid eccentric cue relative to invalid or neutral cue conditions. Here we aim at replicating the attentional advantage while reducing the location-side uncertainty. Based on recent findings (Albonico et al., 2016), we predict the orienting component to dominate the peripheral attentional advantage. In this vein, we used different cue types to elicit the orienting and focusing attentional components: (a) similar to Yeshurun and Rashal (2010), a red dot, as the optimal cue for the orientation component (e.g., Posner, 1980; Castiello & Umiltà, 1990); (b) a small square just the size of the target stimulus as the optimal cue for the focal component (e.g., Maringelli & Umiltà, 1998; Turatto et al., 2000); and (c) a big square large enough to include the whole triplet in the largest spacing condition as a nonoptimal cue for the focal and orienting components (Maringelli & Umiltà, 1998; Turatto et al., 2000). In particular, the dot, acted as the optimal cue for the orienting processing because it directs and anchors attention to the precise target location, but does not convey any useful information about the target extension; indeed the dot, by attracting the attention on an area much smaller than the area covered by the target stimulus, does not induce a proper recalibration of the attentional window size. On the other hand, the small square encloses the target stimulus, and conveys information about the optimal field of integration to isolate the target from the distractors. The small square also informs about the position of the target stimulus, but does not allow the anchoring of attention to a specific point; rather it induces a recalibration of the attentional window to match target extension. For these reasons, we believe that the small square acted as an optimal cue for the focusing process. Lastly, a baseline condition in which the target appearance was not precued was also included. The presentation time of the cue was chosen on the basis of a previous study (Albonico et al., 2016) to enhance the attentional effects.

Materials and methods

Participants

Sixteen healthy volunteers (12 females, four male; mean age = 22.8 ± 2.0 SD, range = 19–26; 15 right-

handed and one left-handed) participated in Experiment 1. All participants had normal or corrected-to-normal vision, and none of them reported neurological, psychiatric, or other relevant medical problems.

All participants were unaware of the purpose of the experiment, and participation allowed the acquisition of course credits. Each participant was asked to sign an informed consent prior to being enrolled in the study, which was carried out according to the guidelines of the Ethical Committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli, and procedure

The stimuli and procedure were modelled on those of Toet and Levi (1992) and Albonico et al., (2016; see Figure 1). Participants were seated in front of a computer monitor (27 in., 600×340 mm) with a resolution of $1,920 \times 1,080$ pixels and a refresh rate of 120 Hz. A chin and forehead rest stabilized their head position and kept the viewing distance constant at 60 cm. Manual responses were collected by using a computer keyboard. The dominant hand was always used. Participants' eye movements were monitored by an SR Research EyeLink 1000 Eye-tracker controlled by SR Research Experiment Builder software (SR Research Ltd, Canada). Although viewing was binocular, only the right eye was tracked at a rate of 1,000 Hz. The Experiment Builder software was also used to control the presentation of the stimuli.

Stimuli were presented at 10° to the right of the fixation point (measured from fixation to the center of the target) along the horizontal meridian. In particular, this peripheral location was chosen because it was already used in previous studies on focusing (e.g., Castiello & Umiltà, 1990; Castiello & Umiltà, 1992; Albonico et al., 2016). Target stimuli consisted of a capital letter “T” (Sloan-like font, black) of 0.7° (height) \times 0.7° (width) of visual angle in size that could appear upright or rotated by 180° . Meanwhile, the flanker stimuli consisted both of a capital letter “H” (Sloan-like font, color black) of the same size, which could appear upright or rotated by 90° (the orientation of the two flanker stimuli was independent). The target size was selected so that accuracy in discriminating the orientation of the target presented alone was at least of 90% of correct responses. Indeed, the average performance (expressed as proportion of corrected responses) across observers for discriminating the orientation of an isolated target of the same size (0.7°) presented at the same 10° of eccentricity in the right visual field was 0.96 ± 0.06 . All stimuli had a stroke width of 5 pixels (corresponding to 0.14°). The center-to-center distance between the target and the flankers varied as a factor of the target size from 1 to 7.5 times that size (all factors,

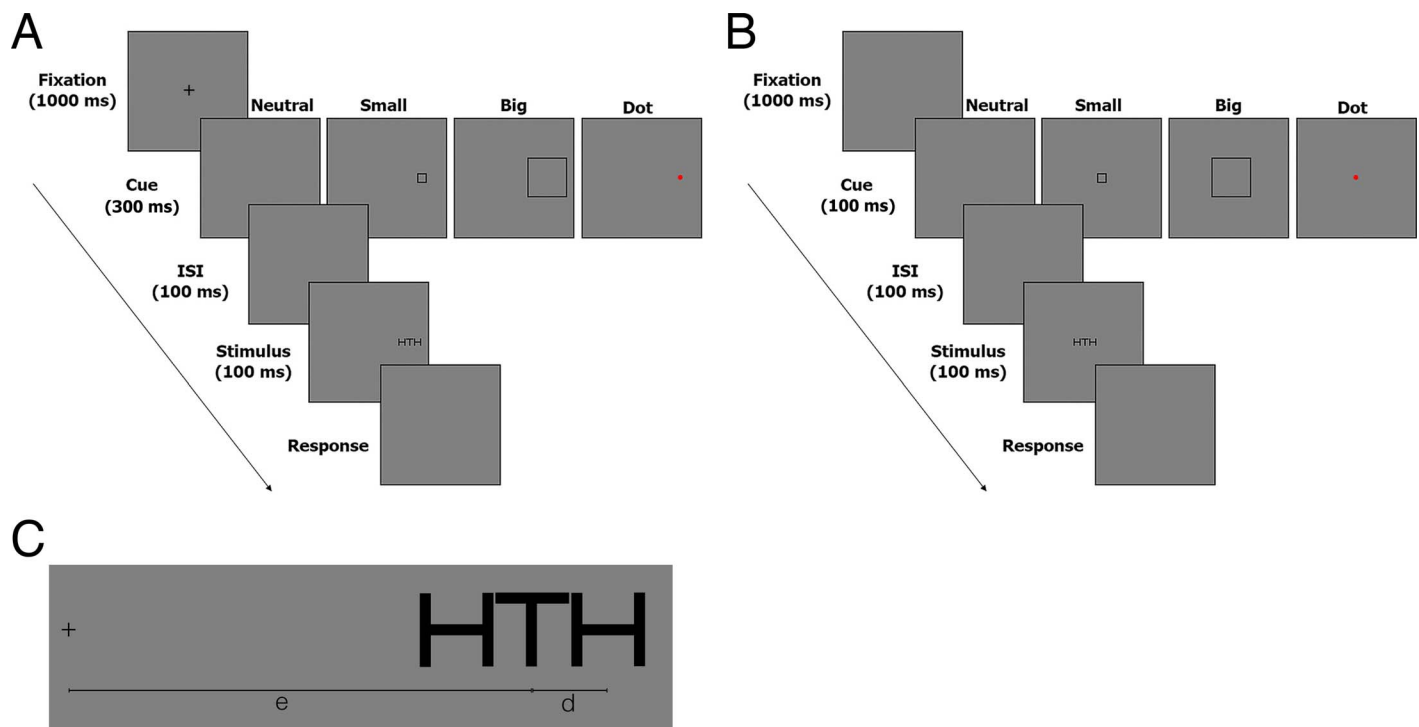


Figure 1. Example of a trial procedure in Experiment 1 (panel A) and Experiment 2 (panel B). The size of both the stimuli and the cues shown in the figure are not the actual sizes used in the experiment, but are adapted to better show the experimental procedure. Experiment 1 was run at 10° eccentricity, whereas Experiment 2 was run in foveal vision. Panel C shows an example of the stimuli used in periphery: Fixation point was shown at the center of the screen, while the target stimulus (here an upright T) was shown on gray background at 10° eccentricity e in the right visual field. Target stimulus was either shown singly or surrounded by a flanker left and right at distance d , measured from the center of the characters.

1, 1.2, 1.4, 1.7, 2.1, 2.5, 3, 3.6, 4.3, 5.2, 6.2, and 7.5, correspond to a distance of 0.7°, 0.84°, 0.98°, 1.19°, 1.47°, 1.75°, 2.10°, 2.52°, 3.01°, 3.64°, 4.34°, and 5.25°; please note that at a factor of 1 the flankers touched the target stimulus). These distances span Bouma's (1970) prediction on the crowding range at 10° of eccentricity. A further condition in which the target stimulus was presented without flankers was also included. If presented, the cue could either be a red dot presented at the target location (diameter of 0.28°), a small black square (0.84° × 0.84°, thickness of 2 pixels), a big black square (10.5° × 10.5°, thickness of 5 pixels), both squares surrounding the target, or it could be absent in 25% of the trials.

Each trial began with a fixation cross (0.6° × 0.6°) presented at the center of a gray screen (mean luminance 89.4 cd/m²), followed after 1,000 ms by one of the three possible cues or by the absence of any cue (baseline). The cue remained on the screen for 300 ms (SOA) after which a second blank gray screen appeared for 100 ms (ISI). After that, the triplet of letters was then presented for 100 ms (Figure 1A). Participants were asked to discriminate the orientation of the T target stimulus by pressing the corresponding buttons on the computer keyboard. Following the

participant's response, the next trial started. The fixation point remained on the screen for the entire duration of the trial to help participants maintain their fixation.

The experiment started with a three-point calibration, and the participant's eye movements were monitored to ensure proper fixation during the entire experimental session. In particular, trials in which the fixation was lost or fell outside a square of 1° centered on the fixation point were discarded and subsequently re-presented to participants in random order. Every participant completed 1,040 trials. Cue types and spacing between the target and the flankers were randomised across trials.

Prior to the main experiment, a practice session composed of 26 trials (equally divided among cue types and randomized relative to the target-flanker spacing) was administered to let the participants familiarize themselves with the task.

Statistical analyses

The proportion of correct responses was adopted as dependent measure and the critical manipulations were the cue types and the center-to-center distance between

the target and the flankers. Accuracy data were first submitted to two-way, repeated measures ANOVA with Cue (big square, small square, dot and absence of cue) and Target-Flankers Distance (of 0.7°, 0.84°, 0.98°, 1.19°, 1.47°, 1.75°, 2.10°, 2.52°, 3.01°, 3.64°, 4.34°, and 5.25°) as within-subject factors. The effect-size in the ANOVA was also measured by computing the eta squared (η^2) and significant differences were further explored by Bonferroni posthoc multiple comparisons (and corrected p values are reported).

The magnitude of crowding effect was also measured for each Cue condition as the log of the ratio between the proportion of correct responses in the smaller target-flanker distance and the condition of flankers' absence. A one-way, repeated-measures ANOVA was conducted on the log ratios, with Cue (big square, small square, dot, and absence of cue) as within-subject factor.

To determine the critical distance needed to reach the effect of crowding, accuracy data were then analysed using the Palamedes psychometric toolbox for Matlab (Prins & Kingdom, 2009). The model was chosen based on the foveal data distributions. The data from each observer at each cueing condition were fitted with the Weibull function:

$$PC = \gamma + (1 - \gamma - \lambda) \times \left(1 - e^{-\left(\frac{x}{\alpha}\right)^\beta}\right)$$

using a maximum-likelihood criterion, estimating for each participant the parameters α (threshold) and β (the slope parameter; see Strasburger, 2001 for calculating the slope from β), with the parameter γ set to 0.5 that corresponds to the guessing rate in a 2AFC task as our, and λ , the lapse rate value typically different from zero since human observers are prone to stimulus-independent errors (Wichmann & Hill, 2001), fixed at 0.02 as suggested in the model (Prins & Kingdom, 2009). The starting value of the free parameters was the same for all participants.

Following Yeshurun and Rashal (2010), an exponential and a clipped-line model were also applied to the data. The equations used were the same used by Yeshurun and Rashal (2010) and in particular we employed the following equation for the exponential fit:

$$PC = a \left(1 - e^{(-s(d-i))}\right)$$

where a is the asymptote, s is the scaling factor, d is the target-flanker distance, and i is the x intercept. The Levenberg-Marquardt algorithm, based on chi-square values, was used to fit a two-clipped function (two straight lines in log-log coordinates) to each set of data, with the slope of the first line set to zero; the equation employed was

$$PC = \min(p_{\text{ceil}}, (ae^{b\sigma}))x$$

where a is the break point at ceiling p_{ceil} . The critical distance was defined as ceiling break point.

While the peripheral data are similarly captured by a Weibull, an exponential and a clipped function (median R^2 0.70, 0.68, and 0.77, respectively), foveal data are not (Experiment 2). Median R^2 for the Weibull model applied to the foveal data is 0.62 (range 0.15–0.92). The exponential fit poorly captures the foveal data with a median R^2 of 0.51 (range 0.04–0.93) and a failure to model 18 distributions. Failures are not systematic for conditions or subjects. The clipped lines model performs better than the exponential ($R^2 = 0.48$; range 0.06–0.92) with no failures, but more poorly than the Weibull.

Thus, the Weibull model was chosen over the exponential or the clipped-line model based on the foveal data distributions. In particular, the Weibull function was favoured over other sigmoidal functions (i.e., the logistic function or the cumulative normal) because it has the ability to assume the characteristics of many different types of distributions.

The function was used to compute the critical distance, defined as the target-flanker distance required to achieve 90% accuracy. This criterion level of task performance was chosen in accordance with previous studies investigating the attentional influence on crowding (Yeshurun & Rashal, 2010; Scolarì et al., 2007; however please note that whereas we used a similar criterion, different psychometric function models were used in the two studies cited) and because a higher criterion will be more sensitive in detecting attentional effects in foveal vision where critical distances are typically very small. To analyze the critical-distance differences between cueing conditions, a one-way, repeated-measures analysis of variance (ANOVA) on critical distance was conducted, with Cue (big square, small square, dot, and absence of cue) as the within-subject factor. Planned comparisons were used to further investigate the difference between Cued conditions and the absence of cue, as well as to test the difference between the small square and dot conditions. Effect-sizes were also measured by computing the eta squared (η^2).

Results

Accuracy

The ANOVA on the accuracy data showed a significant effect of the *Target-Flankers distance*, $F(11, 165) = 37.06$, $p < 0.001$, $\eta^2 = 0.428$, showing increased accuracy with increased target-flankers distance, as widely showed in many previous studies on crowding (e.g., Strasburger et al., 1991; Strasburger, 2005; Pelli et al., 2004). The main effect of *Cue* on accuracy was also significant, $F(3, 45) = 9.48$, $p < 0.001$, $\eta^2 = 0.024$, and posthoc comparisons highlighted that the overall

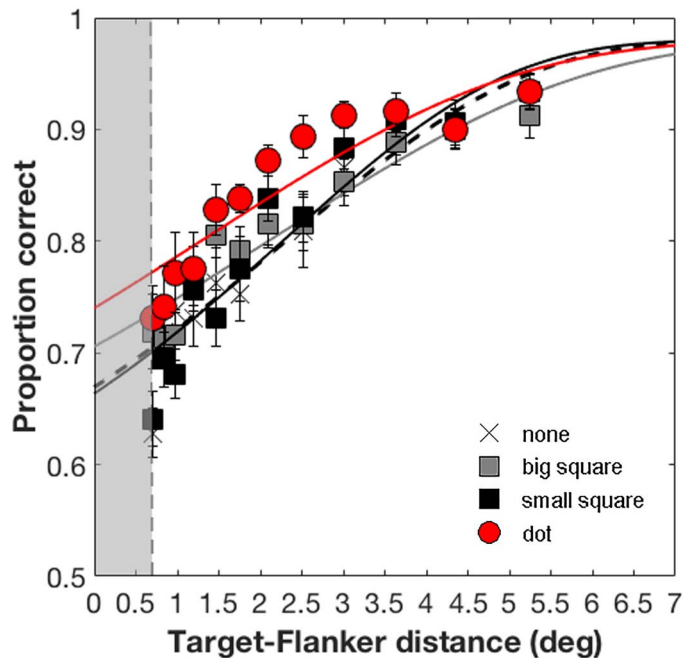


Figure 2. Results of Experiment 1. Proportion of correct responses as a function of target-flankers distance and cue type for 0.7° letter-T targets at 10° in the right visual field. Error bars = standard error of the mean (SEM) with a Weibull function fitted. Please note that functions do not reach the lower asymptote because the target-flanker distance cannot be made sufficiently small in this condition, i.e., it cannot exceed the minimum target-flanker distance of 0.7° (indicated as dashed line).

accuracy of the dot condition (proportion correct: 0.843) was significantly higher than the accuracy of the other three conditions (absence of cue: 0.797, $p = 0.009$; big square: 0.808, $p = 0.007$; small square: 0.798, $p = 0.001$), which, in turn, did not differ from each other (all p s > 0.05).

The interaction between *Cue* and the *Target-Flankers Distance* was not significant, $F(33, 495) = 1.20$, $p = 0.209$, $\eta^2 = 0.025$, showing that the effect of the dot was significant independent of the target-flankers distance (see Figure 2).

Analysis on the magnitude of the crowding effect revealed a significant effect of the *Cue*, $F(3, 42) = 3.14$, $p = 0.035$, $\eta^2 = 0.182$, and planned comparison highlighted that the extent of the crowding reduction was significantly larger in the dot condition relative to the no-cue condition, -0.125 and -0.192 , respectively, $F(1, 14) = 11.66$, $p = 0.004$, $d = 0.92$; but no difference was found between the dot and the small square cue condition, -0.125 and -0.175 , respectively, $F(1, 14) = 2.94$, $p = 0.108$, $d = 0.74$.

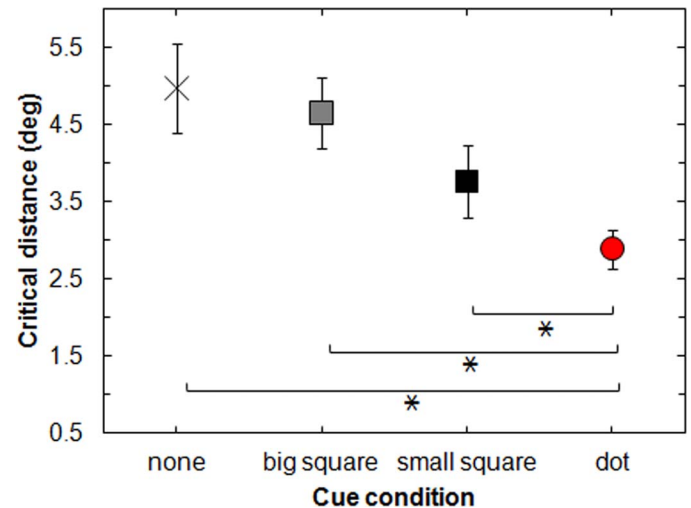


Figure 3. Results of Experiment 1. Critical distance (center-to-center defined as being at 90% correct) at 10° eccentricity by cue type. Error bars = standard error of the mean (SEM); * indicates $p < 0.05$.

Critical distance

The median explained variance and the goodness of fit of the Weibull function were $R^2 = 0.70$ with a transformed likelihood ratio = 127.4, respectively. Critical distance was extracted as the respective point at 90% correct on the Weibull fit (as explained in Methods) and an ANOVA was carried out on the obtained critical distance values. One participant was removed from further analysis because, since his data did not reach asymptote level, the estimated critical distance was exceptionally large for this participant (results are shown in Figure 3). The main effect of *Cue* on critical distance was significant, $F(3, 42) = 4.73$, $p = 0.006$, $\eta^2 = 0.252$. Planned comparisons showed that in peripheral vision only the dot significantly decreased the critical distance compared to the absence of a cue, 2.88° and 4.97°, respectively, $F(1, 14) = 6.31$, $p = 0.025$, $d = 0.93$; whereas neither the small square, 3.76°, $F(1, 14) = 2.24$, $p = 0.157$, $d = 0.53$, nor the big square, 4.66°, $F(1, 14) = 0.35$, $p = 0.56$, $d = 0.12$, were effective compared to the condition in which the target stimulus was presented without cue. Furthermore, planned comparisons also highlighted that the critical distance associated with the dot condition was significantly lower than the critical distance associated with the small, 3.76°, $F(1, 14) = 5.86$, $p = 0.03$, $d = 0.88$, and the big square, 4.66°, $F(1, 14) = 13.2$, $p = 0.003$, $d = 0.19$.

Comments

The results of Experiment 1 confirm and extend previous findings that peripheral crowding can be

reduced by orienting attention to the target even in the case of moderate location uncertainty (at least at 10° of eccentricity). In particular, Experiment 1 suggests that only the orientation component of spatial attention is effective in reducing the critical distance, whereas the focal component does not seem to affect peripheral crowding (at least at 10° of eccentricity). Note that, despite that the cues were of different sizes, visibility did not determine our pattern of results; indeed if this was the case, we would expect the small square cue (which size was $0.84^\circ \times 0.84^\circ$) to have a stronger effect compared to the dot cue (with a size of 0.28° diameter); by contrast, we found that the dot cue was more effective than the small squares and the other cues in reducing crowding.

Experiment 2: Foveal crowding

We have shown that triggering the orienting component of attention produces a reduction in the critical distance for peripheral targets even when presented at a known location (at least at 10° of eccentricity). On the other hand, we did not find an effect of focal attention. Given that previous findings (Albonico et al., 2016) indicate a strong advantage of focusing in foveal detection and discrimination tasks of isolated targets, we predict that focusing is active in reducing crowding in central vision. In this vein we might expect the small square to strongly modulate the foveal crowding range. Because central vision does not involve notable location uncertainty, we expected to observe no effect of the dot cue on critical distance. The conditions in Experiment 2 replicate Experiment 1 at a central retinal location.

Materials and methods

Participants

Sixteen new participants (10 females, six male; mean age = 24.7 ± 3.0 SD, range = 19–31; 14 right-handed and two left-handed) took part in Experiment 2. All participants had normal or corrected-to-normal vision, and none of them had neurological, psychiatric, or other relevant medical problems.

All participants were unaware of the purpose of the experiment, and participation allowed the acquisition of course credits. Each participant was asked to sign an informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the Ethical Committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli, and procedure

The apparatus and procedure were the same as in Experiment 1, adapted for foveal presentations (see Figure 1B); in particular, in this experiment the viewing distance was kept constant at 300 cm. Since the foveal crowding range is small, measurements with the letter triplets must be taken close to the acuity threshold (Latham & Whitaker, 1996; Siderov et al., 2013; Coates & Levi, 2014). Prior to the experiment we measured the isolated size of the T threshold for each participant by varying size in a 40-trial run using the improved QUEST staircase procedure, with a threshold criterion of 75% correct responses (Watson & Pelli, 1983). The adaptive QUEST procedure increased or decreased the T size according to the participant's accuracy. Averaged acuity across participants was $0.040^\circ \pm 0.008^\circ$ (2.4 ± 0.48 min of arc). Even though it is known that visual acuity can be affected by the type of font used, the average acuity we obtained is similar to the one reported in previous studies with Sloan font (Jacobs, 1979; Strasburger et al., 2011).

The target stimuli (Sloan-like font, center black) used in the experimental session were $0.05^\circ \times 0.05^\circ$ in size (3×3 min of arc). Orientation discrimination performance averaged (expressed as proportion of corrected responses) across participants obtained with isolated Ts of the selected size was 0.90 ± 0.07 . All stimuli had a stroke width of 1 pixel (0.006°). The distance between the target and the flankers (measured center-to-center) varied as a factor of the target size, from 1 to 2 times the size of the target stimulus (all factors, 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, and 2, corresponding to a target-to-flanker distance of 0.05° , 0.055° , 0.06° , 0.065° , 0.07° , 0.075° , 0.08° , 0.09° , and 0.1°). A further condition in which the target stimulus was presented without the flankers was also included. The cue could be represented by a red dot (diameter of 0.02°) or a small black square ($0.07^\circ \times 0.07^\circ$, thickness of 0.006°) or a big black square ($0.75^\circ \times 0.75^\circ$, thickness of 0.012°) or by no cue. Both target stimulus and cue were displayed always at the center of the screen on a gray background (mean luminance 89.4 cd/m²).

Each trial began with a blank gray screen followed after 1,000 ms by one of the three possible cues or by the absence of any cue (baseline). We chose not to display any fixation point to avoid giving an additional or confounding cue to participants. The cue remained on the screen for 100 ms (SOA) after which a second blank gray screen appeared for 100 ms (ISI). After that, the triplet of letters was then presented for 100 ms.

As in Experiment 1, participants were required to discriminate the orientation of the T target stimulus by pressing one button on the computer keyboard when it was upright and another when it was inverted. Following the participant's response, the next trial started. Every participant completed 800 trials; cue

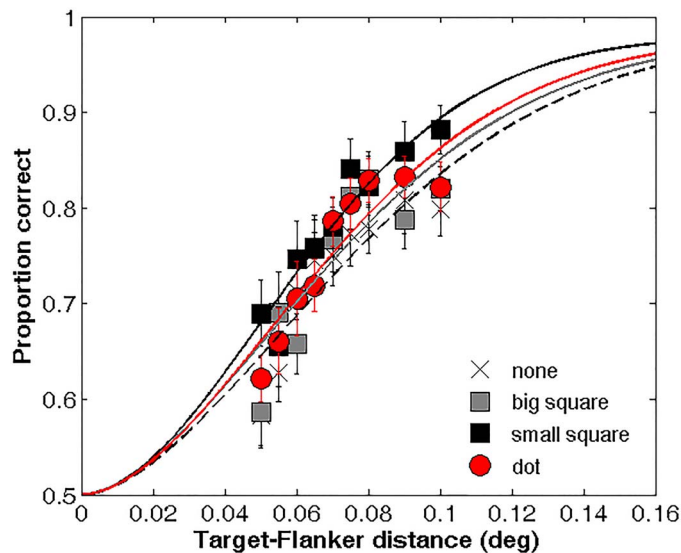


Figure 4. Results of Experiment 2. Proportion of correct responses as a function of target-flankers distance and cue type for foveal presentation of 0.05° letter-T targets. Error bars = standard error of the mean (SEM) with a Weibull function fitted.

types and spacing between the target and the flankers were randomised across trials.

Before the main experiment, a practice session composed of 25 trials (equally divided among cue types, and randomly selected for target-flankers spacing) was run to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

The proportion of correct responses was adopted as dependent measure and the critical manipulations were the cue types and the center-to-center spacing between the target and the flankers. The same statistical analyses as in Experiment 1 were also applied to the data of Experiment 2. As in Experiment 1 the data from each observer at each cueing condition were fitted with the Weibull function, using a maximum-likelihood criterion.

Results

Accuracy

The first analyses on the accuracy data showed a significant effect of the *Target-Flankers Distance*, $F(8, 120) = 55.26$, $p < 0.001$, $\eta^2 = 0.431$, demonstrating increased accuracy with increased target-flankers distance. The main effect of *Cue* was significant, $F(3, 45) = 5.80$, $p < 0.005$, $\eta^2 = 0.028$, and posthoc comparisons highlighted that only the mean accuracy associated

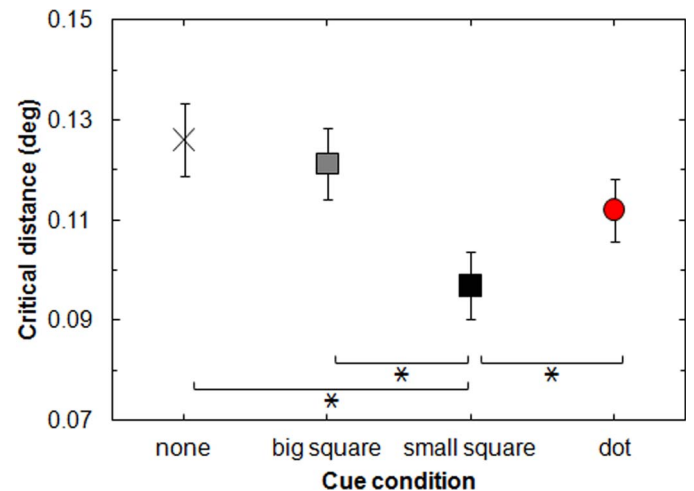


Figure 5. Results of Experiment 2. Critical distance (center-to-center defined as being at 90% correct) by cue type. Error bars = standard error of the mean (SEM); * indicates $p < 0.05$.

with the small square (proportion correct: 0.782) was significantly different from the mean accuracy of the absence of cue (0.731; $p = 0.005$), whereas neither the big square (0.746; $p = 1.00$) nor the dot (0.753; $p = 0.602$) conditions were.

The interaction between *Cue* and the *Target-Flankers Distance* was marginally significant, $F(24, 360) = 1.47$, $p = 0.07$, $\eta^2 = 0.031$, showing that the small square condition was the best condition in almost all target-flankers distances (see Figure 4).

The analysis on the magnitude of crowding effect revealed again a significant effect of the *Cue*, $F(3, 45) = 6.68$, $p = 0.001$, $\eta^2 = 0.308$: Both the small-square (-0.102) and the dot (-0.118) cueing condition showed significantly bigger effect than the no-cue condition (-0.183 ; $F(1, 15) = 19.79$, $p = 0.001$, $d = 0.98$ and $F(1, 15) = 8.62$, $p = 0.010$, $d = 0.88$; but they did not differ between each other, $F(1, 15) = 0.959$, $p = 0.343$, $d = 0.23$.

Critical distance

The median explained variance and the goodness of fit of the Weibull function were $R^2 = 0.62$ and transformed likelihood ratio = 81.4, respectively. Critical distances were extracted at 90% correct as explained in the methods to Experiment 1. The subsequent ANOVA on the critical distance data highlighted a significant main effect of *Cue*, $F(3, 45) = 5.09$, $p = 0.004$, $\eta^2 = 0.258$; see Figure 5). Planned comparisons showed that the critical distance associated with the small square was significantly smaller than the one associated with the absence of cue, 0.097° and 0.126° , respectively, $F(1, 15) = 9.39$, $p = 0.008$, $d = 0.78$; whereas the critical distance of the big square, 0.121° , $F(1, 15) = 0.274$, $p = 0.61$, $d = 0.11$, and of the

dot, 0.112° , $F(1, 15) = 2.50$, $p = 0.13$, $d = 0.37$, conditions were not significantly different from the absence of cue. Furthermore, planned comparisons also demonstrated that the small square condition was significantly different from both the dot, $F(1, 15) = 12.81$, $p = 0.003$, $d = 0.54$, and the big square condition, $F(1, 15) = 9.40$, $p = 0.008$, $d = 0.65$.

Comments

Therefore, taken together, the results of Experiment 2 suggest that the critical distance in foveal crowding can be modulated by focusing attention on the target spatial position.

Experiments 3a and 3b

Results from Experiment 1 and 2 demonstrate that focusing and orienting attention can differently affect crowding in peripheral and foveal vision. However, since we used a limited number of trials per data point, the goodness of fit (R^2 and transformed likelihood ratio) of our model in Experiment 1 and 2 were not “ideal.” This is important since our main conclusions are drawn from the critical-distance data, which are parameters estimated based on those fits. For this reason, to further confirm our results, we conducted two more experiments, one in peripheral vision at 10° eccentricity and one in foveal vision, with an increased number of trials per data point.

Materials and methods

Participants

Six participants (four females, two males; mean age = 23.2 ± 1.5 SD; range = 21–25; two left-handed) took part in Experiments 3a and 3b. All participants had normal or corrected-to-normal vision, and none of them had neurological, psychiatric, or other relevant medical problems.

Apparatus, stimuli, and procedure

The apparatus and procedure used for Experiment 3a and 3b were the same as in Experiment 1 and 2. In particular, Experiment 3a was modelled onto Experiment 1, but an additional target-flankers distance condition of 6.5° was added. Similarly, Experiment 3b was modelled onto Experiment 2, but a further target-flankers distance condition of 0.12° was added.

Every participant completed 2,240 trials in Experiment 3a (at 10° eccentricity) and 1,760 trials in Experiment 3b (foveal presentation).

Statistical analyses

The proportion of correct responses from each observer at each cueing condition was fitted with the Weibull function, using a maximum-likelihood criterion, and critical distances were extracted at 90%. Since only six subjects were tested, to analyze the critical-distance differences between cueing conditions, a nonparametric Friedman’s ANOVA on critical distance was conducted, with Cue (big square, small square, dot, and absence of cue) as the within-subject factor. In the case of a significant effect, Wilcoxon Signed-Ranks Tests were carried out to clarify the effect of the Cue.

Results

Experiment 3a

Figure 6 shows the individual fit for data in Experiment 3a; subject S006 was excluded because of a technical error during the experiment. First, the increase in the numbers of trials per data point resulted in better fits compared to Experiment 1, since in this case, the Weibull function fitted the data well (median $R^2 = 0.95$; median transformed likelihood ratio = 10.22).

The Friedman’s ANOVA on critical distance data (see also Table 1) revealed a significant effect of the Cue condition, $\chi^2(3) = 9.96$, $p = 0.019$, and subsequent paired Wilcoxon Signed-Ranks Tests showed that the critical distance associated with the dot (2.70°) was significant smaller of the critical distances of the small square (3.53° , $p = 0.043$), big square (3.86° , $p = 0.043$), and of the absence of cue (3.68° , $p = 0.043$).

Experiment 3b

Figure 7 shows the individual fit for the data in foveal vision. Again, as evident from the figure, the increase in the numbers of trials per data point resulted in better fits compared to Experiment 2. Indeed, in this case, the Weibull function fitted the data well (median $R^2 = 0.96$, median transformed likelihood ratio = 18.0).

The Friedman’s ANOVA on critical distance data (see also Table 1) revealed a significant effect of the Cue condition, $\chi^2(3) = 13.2$, $p = 0.04$, and subsequent paired Wilcoxon Signed-Ranks Tests showed that the critical distance associated with the small square (0.097°) was significant smaller of the critical distances of the dot (0.105° , $p = 0.028$), big square (0.112° , $p = 0.028$), and of the absence of cue (0.111° , $p = 0.028$). Furthermore, the critical distance of the dot condition (0.105°) was significantly reduced compared to the big square (0.112° , $p = 0.046$) and the absence of cue (0.111° , $p = 0.046$).

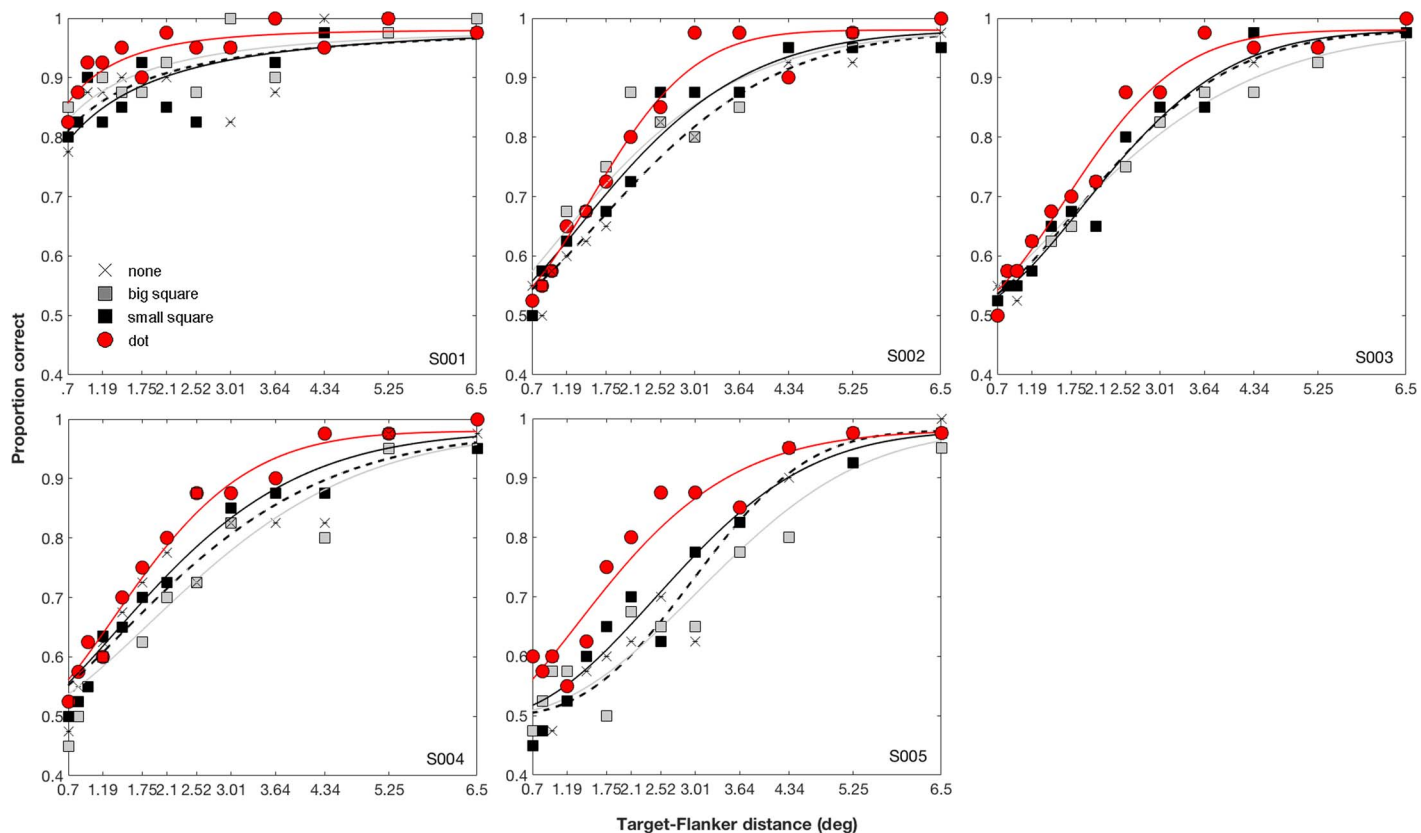


Figure 6. Results of Experiment 3a. Individual Weibull fits of the proportion of correct responses as a function of target-flankers distance and cue type for 0.7° letter-T targets at 10° in the right visual field.

Comments

Results from Experiments 3a and 3b confirm the evidence obtained in Experiment 1 and 2, showing that focusing and orienting attention can differently modulate the critical distance in foveal and peripheral crowding. In particular, Experiment 3a confirms that only orienting was effective in reducing the critical distance in peripheral vision (at 10° eccentricity). Experiment 3b showed that, even though both focusing and orienting reduced the critical distance in fovea compare to the absence of cue, the reduction associated with focusing was significantly larger than the effect of orienting.

Discussion

The aim of the present study was to investigate the differential role of focusing and orienting attentional processes in the modulation of crowding and the reduction of the critical distance in foveal and peripheral vision. We found that, equating for task difficulty by measuring the critical distance at the same accuracy level for all conditions and observers, crowding was differently modulated by focusing and orienting attention. Indeed, in the periphery (Experiment 1 and Experiment 3a, that were at 10°) only the

Subject	Gender	Age	Experiment 3a				Experiment 3b			
			None	Big square	Small square	Dot	None	Big square	Small square	Dot
S001	Female	22	1.90	1.57	2.05	1.05	0.110	0.109	0.104	0.112
S002	Female	24	4.07	3.69	3.64	2.80	0.110	0.116	0.095	0.107
S003	Male	25	3.81	4.36	3.74	3.08	0.109	0.113	0.099	0.102
S004	Female	21	4.39	4.68	3.92	3.11	0.111	0.110	0.100	0.102
S005	Female	23	4.25	4.99	4.32	3.45	0.107	0.109	0.095	0.104
S006	Male	24	-	-	-	-	0.117	0.116	0.093	0.106

Table 1. Critical distance (defined as the respective point at 90% correct on the Weibull fit) data for all six subjects that participated in Experiment 3a and 3b. Notes: Experiment 3a was conducted in peripheral vision at 10° eccentricity, whereas Experiment 3b, in foveal vision.

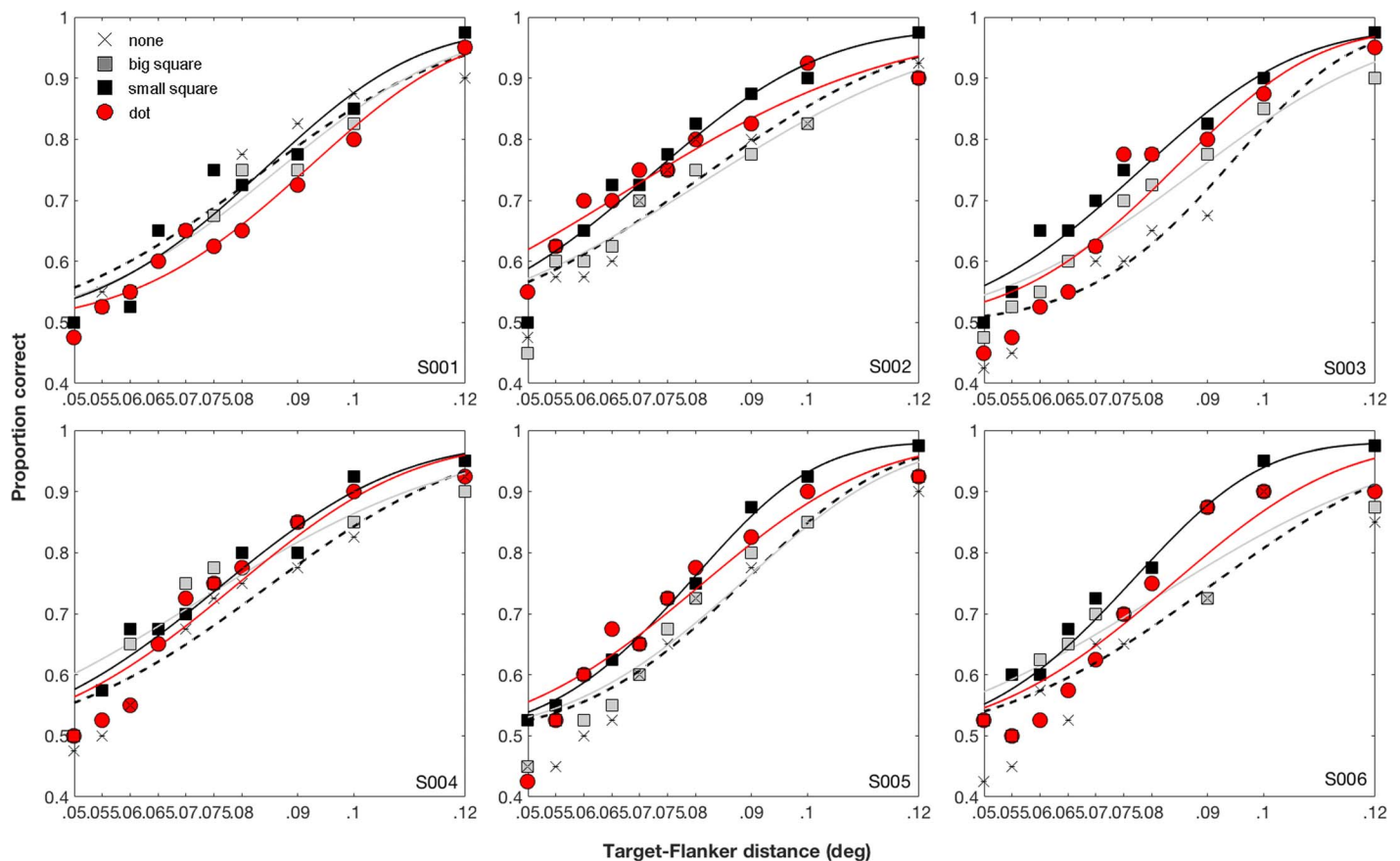


Figure 7. Results of Experiment 3b. Individual Weibull fits of proportion of correct responses as a function of target-flankers distance and cue type for foveal presentation of 0.05° letter-T targets.

dot cue (i.e., the optimal cue for the orienting process) was effective in reducing crowding compared to the absent cue condition, while the big square and the small square were not. On the other hand, foveal results (Experiment 2 and Experiment 3b) show a reduction of the critical distance when the small square was used as a cue (i.e., the optimal cue for the focusing process). In Experiment 2 the large square and the dot did not modulate the crowding range relative to the absent cue condition, whereas in Experiment 3b the dot did reduce the critical distance compared to the large square and the absence of cue, but still this effect was smaller compared to the one associated with the small square.

Bouma's rule states that the critical distance between the target and flanker below which crowding is eliminated is roughly proportional to half the target viewing eccentricity (Bouma, 1970). In the condition of the absence of cue, our data led to a Bouma's factor (calculated as the slope b of the median critical distances in foveal and peripheral vision) of 0.35 (Experiment 1 and 2) and of 0.40 (Experiment 3a and 3b). Precueing the target letter diminished crowding and the critical distances, though. Previous studies have already demonstrated that directing attention to the target location can reduce the critical distance (e.g.,

Van der Lubbe & Keuss, 2001; Heller, 2002; Felisberti & Zanker, 2005; Huckauf & Strasburger, 2005; Pöder, 2007; Yeshurun & Rashal, 2010), and, according to some accounts of crowding, this would suggest that attention could reduce the size of integration fields responsible for crowding. The reduction of the critical distance that we obtained in peripheral vision is similar to the one found in previous studies that have used similar eccentricity (9°), threshold criterion (i.e., 90% accuracy), and attentional cue (a dot); indeed, in our study the dot induced a reduction in the critical distance of 2.09° compared to the absence of cue (Experiment 1) and of 0.98° (Experiment 3a), while Yeshurun and Rashal (2010) in their experiment 2 reported a reduction of 0.77° and Grubb et al. (2013) reported a reduction of approximately 0.5° . Similarly, previous studies showed that in foveal vision for high contrast stimuli, crowding in normal observers extends over distances on the order of about 4–6 min arc (Flom et al., 1963a; Wolford & Chambers, 1984; Danilova & Bondarko, 2007; Siderov et al., 2013). Our results are in the same range, with critical distances of 7.6 (Experiment 2) and 6.7 (Experiment 3b) min of arc without cue. We also showed that critical distances in fovea can be reduced by attention: The small square induced a

reduction of 1.8 min of arc (Experiment 2) and of 0.9 min of arc (Experiment 3b). Taken together, our results from Experiment 1, 2, 3a, and 3b show initial evidence that foveal and peripheral crowding are modulated independently by the two components of spatial attention. In agreement with previous evidence (e.g., Castiello & Umiltà, 1990; Turatto et al., 2000; Albonico et al., 2016), our results show that whereas focusing dominates central vision (even though orienting can still affect performance in the fovea even if to a lesser extent than focusing), it does not modulate peripheral performance. Instead, peripheral processing can be enhanced by the orienting process.

Reducing spatial uncertainty by presenting the target stimulus at the same location might have hidden the effect of the orientation mechanism, particularly in foveal vision, and further studies would be needed to better disentangle the effect of eccentricity from the effect of location uncertainty. However, our results show that spatial attention could diminish crowding even in the absence of spatial uncertainty (side uncertainty). According to previous studies (Maringelli & Umiltà, 1998), equating spatial uncertainty in the fovea and the periphery enables direct comparison of the effects of orienting and focusing attention at a different retinal location. The dot mainly acts as the optimal cue for the orienting process, anchoring attention to the precise target location. On the other hand, the small square primarily induces a recalibration of the attentional window to match target extension. Our results indicate that orienting and focusing are dissociated. Strasburger (2005) found an eccentricity dependent modulation of the focussing component of attention. Similarly, in comparing the effect of a cue surrounding the target as a function of the cue size, Strasburger and Malania (2013) extended previous findings, showing an overall effect of cuing on threshold, independent of cue size, with no effect on source confusion (target and flankers confusability). Our results replicate and extend these findings. They indicate that “focusing-in” is active in the fovea and sluggish in the periphery, where, similar to Strasburger and Malania (2013), the square cue size doesn’t matter. Additionally, by comparing the effect of different cues, we found a qualitative difference: Focusing dominates in the fovea, while orienting in the periphery. This dissociation is a direct evidence of the multicomponential nature of attention in enhancing spatial resolution.

This dissociation could also be helpful in explaining the reported discrepancies in previous studies on the attentional modulation of the foveal crowding range. It has been suggested that foveal crowding could be less sensitive to the effect of attention compared to peripheral crowding (Flom, 1991; Strasburger & Rentschler, 1995; Leat et al., 1999), because of the

limitation of visual acuity. However, our data suggest that attention can modulate both foveal and peripheral crowding through the contribution of separate components. In particular, we propose that focusing would act in the fovea, reducing crowding by overrepresenting the space in the attended area and simultaneously suppressing the space outside of that area (Suzuki & Cavanagh, 1997; Intriligator & Cavanagh, 2001). This is consistent with previous studies, which show that attention can enhance the spatial resolution at the attended location by promoting the processing of information over a smaller area (Yeshurun & Carrasco, 1998, 1999, 2000). On the other hand, orienting would still improve peripheral identification by reducing the target residual position uncertainty and enabling the selection of the smallest integration field available at the target location (e.g., Pöder, 2006, 2007). Thus, it could be that previous studies have failed to find an attentional effect on foveal crowding because they did not take into account either the independence of these two distinct processes across the visual field or the different conditions in which they operate. Moreover, as a consequence of our results and interpretation, we speculate that the reason why crowding is more pronounced in peripheral vision could be the lack (or reduction) of focal attention.

It has to be mentioned that only a single eccentric location was tested in the present study; still, after comparing performance in the fovea and at 10° of eccentricity in the right visual field, our results support the notion that focusing and orienting are dissociable processes (e.g., Benso et al., 1998; Turatto et al., 2000; Albonico et al., 2016). However, it is possible that testing graded eccentric locations would lead to graded differences between focusing and orienting: In particular, the role of focusing may gradually decrease as we move away from the fovea, whereas the role of orienting would increase with increasing spatial uncertainty. A similar argument can be made for the cue timing manipulation since only one SOA interval for each viewing condition was used. In particular, some studies have showed that focusing in foveal vision is best revealed under exogenous conditions (e.g., Benso et al., 1998; Maringelli & Umiltà, 1998); thus, one might expect that longer SOAs would reduce the effect of focusing. Overall, despite this consideration, our results reliably demonstrate that orienting and focusing can have dissociable effects on foveal and peripheral crowding.

Recently, it has been shown that crowding represents a limit for reading in both normal and pathological individuals. Indeed, in normal individuals, the critical distance for crowding is equal to the critical distance for reading (Pelli & Tillman, 2008), and crowding affects the visual span (e.g., Legge et al., 2007), which predicts reading rate (e.g., Pelli et al., 2007). Further-

more, some studies demonstrate that both developmental and acquired dyslexia could be associated with a pathological crowding, which causes an abnormal integration of the letters presented simultaneously (Bouma & Legein, 1977; Atkinson, 1991; Spinelli, De Luca, Judica, & Zoccolotti, 2002; Crutch & Warrington, 2007, 2009; Martelli, Di Filippo, Zoccolotti, & Spinelli, 2009; Martelli, Arduino, & Daini, 2011). Some authors also suggested that the anomalous crowding found in some of these patients could be due to an alteration of attentional mechanisms (Saffran & Coslett, 1996; Mendez, Shapira, & Clark, 2007). This, in combination with our results, strengthens the hypothesis that the smallest range of crowding across the visual field may be modulated by spatial attention, and that the different components of spatial attention play different roles across the visual field. Further studies are needed to explore how much of the abnormal crowding found in diverse populations can be attributed to a sluggish attentional deficit.

Keywords: focal attention, orientation of attention, central vision, peripheral vision, crowding

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