Supercrowding: Weakly masking a target expands the range of crowding

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Crowding is impairment of peripheral object identification by nearby objects. Critical spacing (the minimum target-flanker distance that does not produce crowding) scales with target eccentricity and is consistently reported as roughly equal to or less than 50% of target eccentricity (0.5*e*). This study demonstrates that crowding occurs far beyond the typical critical spacing when the target is weakly masked by a surrounding contour or backwards pattern mask. A target was presented at a peripheral location on every trial and participants reported its orientation. Flankers appeared at target-flanker distances of 0.3–0.7*e,* or were absent. The target was presented with or without a mask. When flankers were absent, the masks only mildly impaired performance. When flankers were present but the mask was absent, target identification was nearly perfect at wide target-flanker distances (0.5*e*–0.7*e*). However, when flankers were present and the target was masked, performance dropped significantly, even when target-flanker distances far exceeded the typical crowding range. This phenomenon ("supercrowding") shares critical features with standard crowding: flankers similar to the target impair performance more than dissimilar flankers, and the characteristic anisotropic profile of crowding is preserved. Supercrowding may reflect a general interaction between crowding and other forms of masking.

Keywords: crowding, masking, object recognition, spatial vision

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Introduction

Crowding

An obvious limit to human vision is that it gets much worse in the peripheral regions of the visual field. For instance, text can be seen in the periphery, but reading usually requires eye movements to bring the text into the fovea. One source of this limitation is acuity, which is much worse for peripheral retina than in the fovea. A second important source of this limitation is crowding, which is not explained by mere limitations of acuity. Crowding is the impairment in the recognition of a target object in the presence of nearby flankers, despite the fact that the same target object can be identified at the same position in the absence of the distracting flankers (Bouma, 1970, 1973; recently reviewed by Pelli, Palomares, & Majaj, 2004 and Levi, 2008). Crowding imposes important limitations on real-world vision, including reading rate (Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007). The properties of crowding may provide important clues as to how the visual system performs object identification.

An illustration of crowding is given in Figure 1. Fixating on the upper cross, the letters on either side of fixation are easily named. Fixating on the lower cross, letters of the same size and at the same distance are difficult to identify. Under crowding conditions such as these, object identification is difficult, even though the basic features can be detected quite well. For instance, fixating on the bottom cross in Figure 1, you may observe that the middle letter (the "target") of the word is obscured

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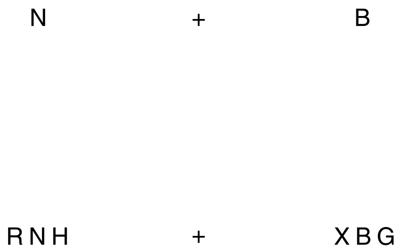

Figure 1. Fixating on the top cross, the letters to the left and right of the figure are easily identified by observers with normal vision. Fixating on the bottom cross, the central letters at the same spacing are difficult to identify. Nevertheless, it is trivial to verify that a letter is present in the central, target region of these configurations.

by the nearby letters (the "flankers"). However, you probably have no difficulty saying that a letter is present there, and you may also be able to perceive some properties (e.g., line segments) of the target letter. Thus, crowding does not significantly affect signal detection (Andriessen & Bouma, 1976; Levi, Klein, & Hariharan, 2002), neither does it reduce the apparent contrast between the target and flankers (Pelli et al., 2004).

Two key traits of crowding are its dependence on similarity between the target and flankers, and the wide distances over which crowding occurs. Flankers that are more similar in color, depth, shape, and spatial frequency to the target produce stronger crowding (Chung, Levi, & Legge, 2001; Kooi, Toet, Tripathy, & Levi, 1994). Crowding of a target in any given location can occur over an extremely large portion of the visual field compared with other interference effects. The range of crowding scales with eccentricity (e): as the target is moved farther into the periphery, the maximum target-flanker spacing that produces a crowding effect increases proportionally. The minimum distance between target and flanker items that relieves crowding is known as the critical spacing, and it has a characteristic stability across many studies, at around $0.5e$ (Bouma, 1970). The recent review by Pelli et al. (2004) found a multitude of studies that conform to this limit.

In addition to the fact that crowding affects neither signal detectability nor apparent contrast, other evidence also suggests that crowding affects a "late" (post-feature-detection) stage of visual analysis. For instance, crowded features that cannot be identified nevertheless influence average or textural estimates (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). Further, crowded features can induce orientation aftereffects (He, Cavanagh, & Intriligator, 1996). These properties suggest that crowding occurs after the analysis of basic features.

"Feature integration" processes, or those processes that "bind" disparate features into a unified representation of an object (Neisser, 1967; Treisman & Gelade, 1980), are viable candidates for the mechanisms that produce crowding. Several researchers have suggested that crowding occurs due to arbitrary pooling or averaging of signals within spatial regions that are fixed in spatial extent and location—that is, they are limited in their ability to focus on smaller regions when flanking distractors fall within the fixed large spatial regions of pooling (Parkes et al., 2001; Pelli et al., 2004). These theories envision feature integration fields that combine the outputs of feature detectors from large regions of the visual field. Others identify visual selective attention as the limiting feature integration process that results in crowding (Chakravarthi & Cavanagh, 2007; Intriligator & Cavanagh, 2001), pointing to similar spatial and temporal limits between crowding and attention.

The relationship between crowding and other forms of masking

Crowding can be viewed as a member of a broad class of interference phenomena generally referred to as "masking" effects. Much confusion seems to surround how various masking effects are interrelated. However, studies suggest distinctions between the properties of crowding and other, similar impairments due to interference between multiple visually presented elements. Unlike metacontrast masking (Averbach & Coriell, 1961) and overlay, or backwards pattern masking (Kahneman, 1968), for instance, crowding manifests primarily as impairment in identifying stimulus characteristics, not signal detection (Pelli et al., 2004). Unlike object substitution masking, crowding occurs even with full attention to the target (Enns & Di Lollo, 1997). Unlike most other forms of masking (such as metacontrast masking, overlay masking, and backwards pattern masking), crowding occurs when masking stimuli are spatially distant from the target stimulus, as noted earlier.

Surround suppression (Hubel & Wiesel, 1968), in particular, bears many similarities to crowding (summarized by Petrov, Popple, & McKee, 2007), including a peripheral locus, eccentricity scaling, size independence, radial-tangential anisotropy, and tuning to orientation and spatial frequency of the target (Petrov, Carandini, & McKee, 2005; Petrov & McKee, 2006). However, Petrov et al. (2007) suggest that crowding and surround suppression are distinct. In crowding, a flanker farther from the fixation than a target has a more debilitating effect than a flanker placed the same distance from the target, but nearer fixation. Petrov and McKee demonstrated that this "inward-outward anisotropy" is not observed under conditions that produce surround suppression. Further, crowding may also depend more on similarity in contrast polarity between targets and flankers (Chakravarthi & Cavanagh, 2007; Kooi et al., 1994) than surround suppression does (Petrov & McKee, 2006).

Although the distinctions among different forms of masking are still blurry at times, much effort has gone into cataloguing and differentiating types of masking, while relatively little effort has examined how these forms of masking interact. In fact, qualitative distinctions among different forms of masking can make them appear unrelated, perhaps leading to the assumption that they should combine additively in their effects on performance. When undertaken, efforts that have employed more than a single mask have exposed key properties of masking. For instance, in metacontrast masking studies, if the primary mask is also masked, recovery from masking is sometimes observed (Breitmeyer, Rudd, & Dunn, 1981). However, masking the mask does not always relieve the latter's effect. Petrov et al. (2005) showed that an overlay mask on a surround reduced surround suppression, but a surround mask acting on an overlay mask did not relieve overlay masking effects, implying that overlay masking precedes surround suppression. While such efforts have shown intriguing properties using 'nested' masks, surprisingly little work has examined how different types of masks interact when both are aimed at interfering with a common target. Here, we report a surprisingly over-additive interaction between crowding flankers and (presumably) lower-level masking effects.

A 'supercrowding' effect

We probed the interactions between masking and crowding in a preliminary study. In this study, we asked observers to identify the orientation of a T-shaped target. The target was either presented in isolation, or surrounded by a box, or by flanking distractor Ts, or by both. We found that, in the absence of flanking distractors, surrounding the target with a box reduced performance slightly but significantly. However, the addition of the flanking items to such a display produced dramatic interference with target identification, even when the flankers alone did not crowd the target, This preliminary observation led us to assume that the surrounding contour has a weak masking effect that interacted strongly with crowding flankers. Most intriguingly, the combined effect of the contour (henceforth referred to as the *mask*) and crowding was not only overadditive within the typical range of crowding, but it also expanded the critical spacing of crowding, greatly exceeding the robust 0.5*e* limit observed in many prior studies.

The experiments reported here establish this effect and clarify its relationship to typical crowding. Experiments 1A and 1B established this effect with a white frame contour mask. The polarity of the surround and the target are different in this experiment, reducing the possibility that this effect is due to combination of multiple crowding factors (Kooi et al., 1994). We show that this weak mask greatly impairs performance at target-flanker distances of (at least) 0.7*e*. Experiment 2 confirms that "supercrowding" isn't simply what occurs when a target is perceptually weakened while flanking distractors are not. Previous research (Kooi et al., 1994) has shown that lowered target contrast relative to flanker contrast enhances the effect of crowding flankers, but we found that this could not explain the supercrowding effect—without the weak mask, crowding was nearly absent when high-contrast flankers appeared at 0.5*e*–0.7*e* away from a low-contrast target.

This finding is intriguing—but is it a novel form of masking, or does it bear similarity to typical crowding? In Experiments 3 and 4, we examine two properties that this phenomenon should exhibit if it shares a common basis with crowding. First, crowding depends on the similarity of the target to the flanking objects (Kooi et al., 1994). In Experiment 3, we show that the identity of the flankers is still important for supercrowding measured at a target-flanker distance of 0.6*e*—supercrowding was stronger for flankers more similar to the target than for less similar flankers. This implies that the effect is like crowding, in that the features of the flankers matter in producing the effect. Secondly, crowding exhibits radial-tangential anisotropy, in which flankers oriented radially with respect to the target and fixation are more effective than those with a tangential orientation (Toet & Levi, 1992). Crowding also shows a distinctive inward-outward anisotropic profile, with radial flankers placed farther from fixation having a more profound effect on performance than those closer to fixation (Banks, Larson, & Prinzmetal, 1979; Bouma, 1973; Petrov et al., 2007). In Experiment 4, we show that the anisotropic characteristics of crowding are preserved for a weakly masked target at target-flanker distances of 0.6*e*. Thus, the decrement in performance at such target-flanker distances may be closely related to "traditional" crowding.

Finally, Experiment 5 asks whether the supercrowding effect occurs between crowding and backward pattern masking, another lower-level masking phenomena, or whether it is restricted to the kind of masking employed by Experiments 1A, 1B, 2, 3, and 4. Using a weak backward pattern mask, we found strong interactions between the mask and crowding flankers, similar to those shown with a surrounding contour mask.

Experiment 1A

Experiment 1A was conducted following several preliminary studies that yielded surprising effects, as mentioned above, to explore the interaction between crowding and other forms of masking. We observed that the most profound effects occurred when neither the mask nor the flankers were particularly deleterious to performance. Thus, for our crowding manipulation, we included conditions that placed flankers far outside the typical range of crowding. For our masking manipulation, we chose a weak surround contour mask that onset and offset simultaneously with the target and flankers. To minimize crowding and masking due to the contour itself, the contour color was white, opposite in contrast polarity to the target, which was black on a gray background. Opposite polarity metacontrast masks (Becker & Anstis, 2004) and crowding flankers (Kooi et al., 1994) are known to be relatively ineffective at impairing performance. Two example displays are depicted in Figure 2. The surrounding contour mask impaired performance slightly for some subjects when the target was presented with no flankers. Experiments 1A and 1B demonstrates that a weak masking contour strongly interacts with crowding flankers that are placed well outside of the typically reported range of crowding.

Methods

Participants

Participants were six volunteers, including three of the authors. In all experiments, participants were experienced psychophysical observers with normal or corrected-to-normal vision.

Stimuli

Stimuli were presented on a 17″ monitor from a distance of 57 cm, with the observer's head position affixed by a chin rest. Participants were tested individually in a room with low lighting. The experiments were programmed with Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) implemented in MATLAB (http://www.mathworks.com).

Targets and flankers were black (1.7 cd/m^2) T-shaped items that appeared on a gray (43.0 cd/m^2) background. T segments subtended approximately 1.25°. The width of the T's segments was approximately 0.10°. Targets always appeared at a distance of 11.8° directly below the center of a black fixation square, which appeared centered near the top of the display. On masked trials, a white (158.0 cd/m^2) square frame was presented, centered on the target image. The square frame subtended 3.3° on each side, and the width of its edges was 0.033°. When flankers appeared, they were positioned at the four cardinal positions around the target (see Figure 2). The flankers were T-shaped elements, whose orientations were randomly selected (left, right, up, or down).

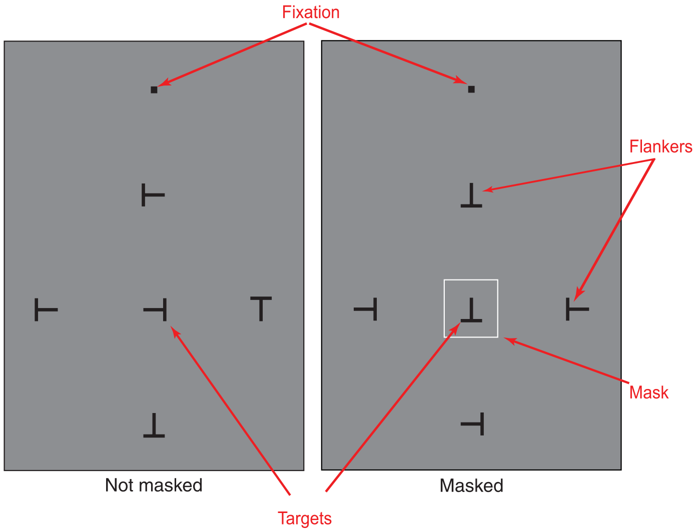

Figure 2. Basic paradigm for Experiments 1A, 1B, 2, 3, and 4. Participants fixated on a black dot, and triggered the trial by pressing the spacebar. After a fixed delay, all stimuli (targets, flankers, and, when applicable, masks) onset for 107 ms and disappear simultaneously. The task was to identify the central T's orientation. In addition to mask presence/absence, target-flanker distances were manipulated (flanking distractors also did not appear on some trials).

Procedure

Conditions were defined by masking condition (masked or not masked) and target-flanker distances: 0.3*e*, 0.5*e*, 0.7*e*, or not flanked (i.e., target-flanker distance equal to infinity). Before the main experiment, observers practiced at least 40 trials in each masking condition, with no flankers present. Observers then completed 40 trials in each condition, which were randomly intermixed, for a total of 320 trials. Trials were divided into blocks of 40 trials, with a break in between blocks.

Each trial began with the observer fixating the white fixation marker. The observer triggered the start of the trial by depressing the space bar, at which time the fixation marker turned black. The fixation marker remained on throughout the trial. After a 1000 ms delay, the targets, all flankers, and the mask (if present) appeared simultaneously for 106.7 ms, as described above. All target, flanker, and mask stimuli onset and offset simultaneously. Participants made an unspeeded judgment identifying the orientation of the T-shaped target, and responded by pressing the corresponding arrow key. Errors were signaled by a short beep. After the response was received, the fixation marker turned white again to signal that the next trial could begin.

Results

Figure 3 shows individual subjects' data and their average. When the target appeared without the mask, flankers only had a substantial effect at target-flanker spacing of 0.3*e*. However, when the target was weakly masked by the surrounding contour, flankers at 0.3*e*, 0.5*e*, and even 0.7*e* all had a very strong effect, greatly impairing performance compared to the no-flanker condition. A series of simple planned comparisons were conducted on averaged accuracy data to demonstrate the

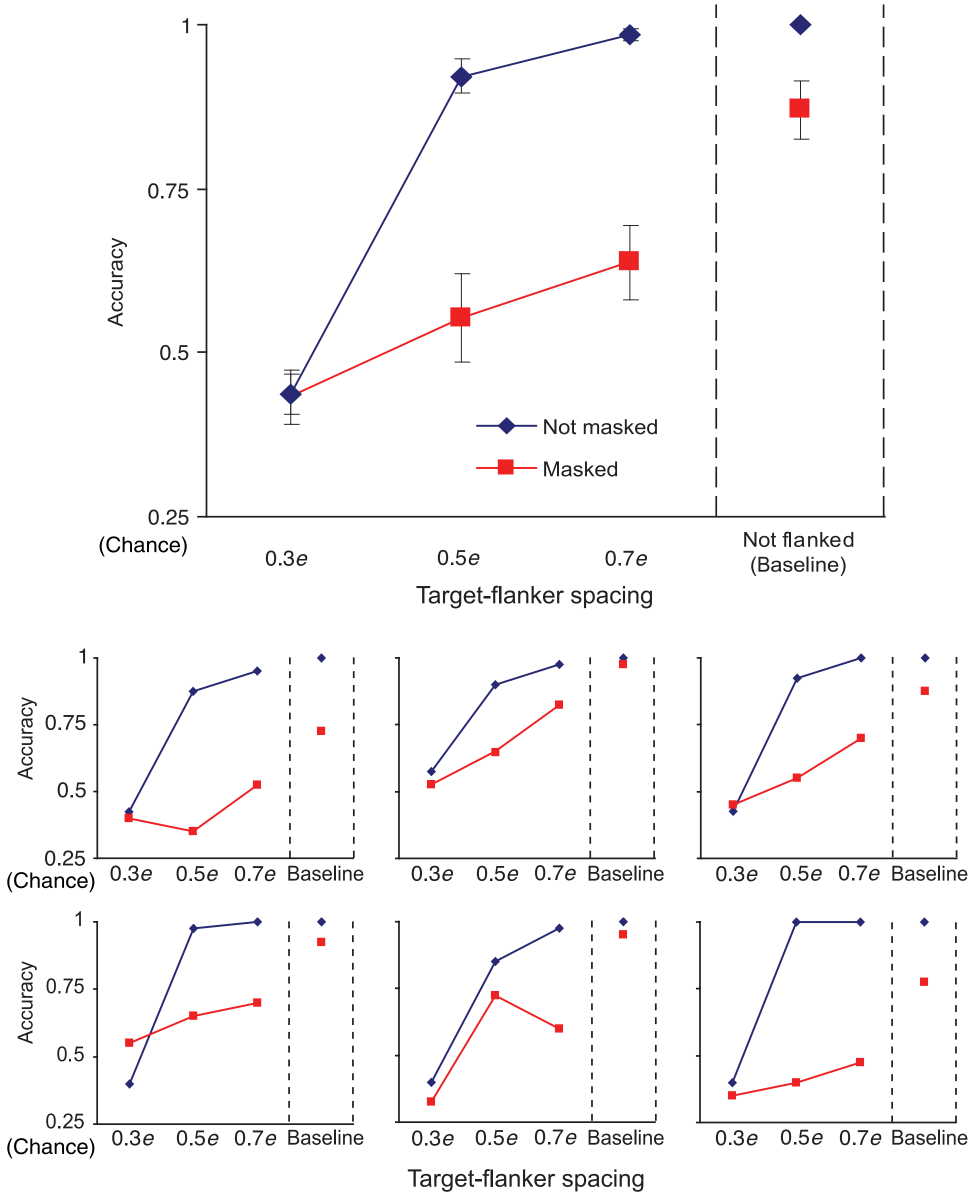

Figure 3. Accuracy results of Experiment 1A ($N = 6$). *Top*: average data for 6 subjects. Error bars represent standard error of the mean. *Bottom*: Results for 6 individual subjects. All subjects showed the supercrowding effect (compare baseline performance to performance with flankers at target-flanker distance of 0.7*e*).

effect of simultaneously appearing masks and widely spaced crowding flankers compared to the effects of each in isolation.

First, when targets were not flanked by the four T-shaped distractors, a significant effect of the masking contour was observed, reducing accuracy from 100% to 87.1%, on average ($t(5) = 3.15$, $p < .05$). Secondly, when the target was not masked, flankers appearing at a distance of 0.7*e* had a statistically insignificant effect, reducing performance on average from 100% to 98.3% ($t(5) = 2.00$, $p = .10$). If crowding ceased to affect at 0.7*e*, then adding a mask on a display with flankers at 0.7*e* should lead to the same level of performance as adding a mask alone. Furthermore, if the closed contour of the mask served to reduce target-flanker grouping, then the presence of the mask might even alleviate crowding from the flankers. Our results showed, however, that performance dramatically declined in that condition (63.8%), compared with when the mask was presented alone (87.1%, $t(5) = 7.43$, $p < .001$), or when the flankers were presented without masking (98.3%, $t(5) = 6.62$, $p < .001$). Considering only the effect of masking and the effect of adding flankers at 0.7*e*, a two-way ANOVA confirms a strong interaction ($F(1, 5) = 42.25$, $p < .001$), such that the crowding flankers at 0.7*e* were much more effective in the presence of a mask than in its absence.

A small but significant effect of crowding flankers was observed for target-flanker distances that were at or beyond 0.5*e,* in the absence of the mask, reducing performance from 98.3% at 0.7e to 92.1% at 0.5*e* ($t(5) = 3.48$, $p < .05$). For targets that were not masked, a strong crowding effect was observed only at the closest spacing that we tested, 0.3*e,* which resulted in 43.8% accuracy (all comparison to other unmasked data points, $p < .001$).

Masked targets showed strong crowding effects at all target-flanker spacing tested. Although the effect of altering this spacing was much less pronounced than in the unmasked condition, performance at the three target-flanker distances showed a significant linear trend ($F(1, 5) = 39.36$, $p < .005$), confirming an overall increased effectiveness of the flankers at crowding the target as target-flanker spacing was reduced. Performance at the closest spacing, 0.3*e,* however, was statistically indistinguishable between the masked and unmasked conditions ($t(5) < 1$).

Discussion

This experiment demonstrates an overadditive effect of a masking contour and crowding flankers. We term the combined effects of masking and crowding flankers "supercrowding," because flankers far outside the typically effective crowding range greatly impair performance. Even though the mask itself had only a moderate effect on performance, it revealed extremely long-range interactions between the target and flanking stimuli that are otherwise undetectable. This suggests that long-range interactions between targets and flankers may be latent in standard crowding conditions at target-flanker spacings far greater than 0.5*e,* despite their negligible impact on performance at those spacings.

For all subjects performance at the closest target-flanker spacing tested (0.3*e*) was roughly equivalent between the masked and unmasked conditions, suggesting that performance at tight target-flanker spacing is dominated by "standard" crowding.

Experiment 1B

In Experiment 1A, the supercrowding effect was dependent on a closed-contour square-shaped surround mask. Does the supercrowding effect depend on shared visual features between the mask and the target? In Experiment 1A, the surrounding contour was composed of opposite-polarity (white) lines, but it did share straight edge segment features with the target. In Experiment 1B, we employed a white circular mask contour for masked trials, to test the possibility that supercrowding depends on shared features between the mask and the target.

Methods

All methods were identical to Experiment 1A, except where noted.

Participants

Participants were six volunteers, including three of the authors.

Stimuli and procedure

All stimuli and procedures were identical to Experiment 1A, except that the mask was a white circular contour frame (Figure 4A). This circular mask had a diameter of 3.3° and was centered on the target.

Results

Figure 4B shows accuracy averaged over subjects for each condition. In the absence of flankers, the mask reduced performance from 99.6% to 91.7%, $t(5) = 3.03$, $p = .03$. When the target was not masked, flankers appearing at 0.7*e* from the target did not significantly impact performance, reducing it from 99.6% to 98.8%, $t(5) = 1.58$, $p = .18$. The supercrowding effect was again observed when the mask was present and the flankers were placed at 0.7*e* from the target. Accuracy was 71.7% in this condition, significantly lower than both the unmasked condition with flankers at 0.7*e* ($t(5) = 3.94$, $p = .01$), and significantly lower than the masked, but not flanked condition ($t(5) = 3.42$, $p = .02$). Considering only the effect of masking and the effect of adding flankers at 0.7*e,* a two-way ANOVA confirms an interaction ($F(1, 5) = 10.5$, $p = .023$), such that the crowding flankers at 0.7*e* were much more effective in the presence of a mask than in its absence.

For the other flanker-target distances, we assessed crowding in each condition by comparing performance to corresponding (masked or unmasked) condition with no flankers. For the unmasked conditions, significant crowding was observed at a target-flanker spacing of 0.3*e* (53.3%, $t(5) = 9.87$, $p < .001$), but not at 0.5*e* (86.3%, $t(5) = 1.79$, $p = .13$). For the masked condition, significant crowding was observed at both 0.3*e* (42.9%; $t(5) = 9.1$, $p < .001$) and 0.5*e* (56.3%; $t(5) = 15.0$, $p < .001$).

Discussion

Experiment 1B replicates the supercrowding demonstrated in Experiment 1A, but with a circular contour

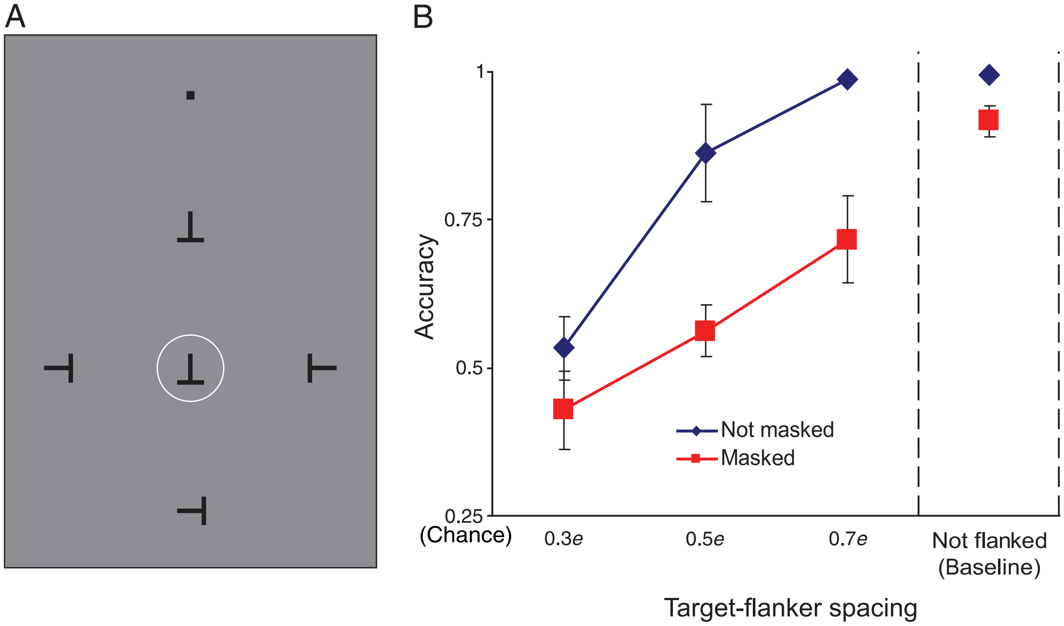

Figure 4. (A) Depiction of the modified, circular mask used in Experiment 1B. (B) Accuracy results of Experiment 1B ($N = 6$). Error bars represent standard error of the mean.

mask. Common features between the target and mask are evidently not required to produce supercrowding, since the black, straight-line segments of the target were not present in the white, circular mask.

Experiment 2

Is this phenomenon simply due to a "weakening" of the stimulus by means of masking? In other words, is the expansion of the critical spacing between targets and flanking distractors due to an effective reduction in stimulus contrast, or is it unique to the combination of masking and flanking stimuli? In Experiment 1A, only the target was masked, meaning that an effective reduction in target contrast would result in a low-contrast target flanked by high-contrast flankers. Indeed, such a situation is known to produce somewhat stronger crowding than when target and flanker contrast are identical (Kooi et al., 1994), although interactions well beyond half the target's eccentricity have not been reported.

In this experiment, we directly manipulated the contrast of the target. First, we equated performance at identifying the T in isolation to the average performance at identifying the T when it was masked, but not flanked by distractors, as in Experiment 1A. This individually tailored contrast was used for target contrast in the main experiment.

Methods

Participants

Five observers volunteered for Experiment 2, including three authors.

Stimuli

In terms of spatial layout, timing, and flanker contrast, stimuli were identical to those used in Experiment 1A. However, target contrast was reduced (according to the procedure described below), and no masks were used in this experiment.

Procedure

First, observers identified the orientation of T-shaped targets appearing (with no flanking stimuli or masks) at randomly varied contrasts at the same target location in the periphery used in Experiment 1A. We varied target contrast, initially, so as to determine the contrast at which identification performance was at 85% accuracy, which matched average performance at identifying the masked target (with no flankers) in Experiment 1A. This contrast was used in the next stage for each subject. The luminance values chosen for each subject ranged from 33.0 cd/m^2 to 34.6 cd/m^2, corresponding to Weber contrasts of between -3.33 and -0.20.

In the primary experiment, the high-contrast flankers were identical to those used in Experiment 1A, and the low-contrast target always appeared. Flankers either did not appear, or they appeared at 0.3*e*, 0.5*e*, or 0.7*e*. Participants completed a total of 160 trials (40 trials per condition, randomly intermixed), with a break every 40 trials. Otherwise, all aspects of this experiment were identical to Experiment 1A.

Results

Average accuracy is shown in Figure 5. Overall, our contrast manipulation was successful in reducing accuracy for identifying the orientation of the target in isolation to 83%, on average. In contrast to Experiment 1A, there was almost no effect of adding the high-contrast flanking elements at target-flanker distances of 0.7*e*, which produced an average performance of 79%. The 4% reduction was statistically insignificant ($t(4) = 1.02$, $p = .37$). We conducted a mixed interaction test (with flankers as a within-subjects effect (including only 0.7*e* and unflanked) and masked or lowered contrast as a between-groups factor (although 3 subjects participated in both Experiments 1A and 2), and found that the 24% supercrowding effect was significantly larger than the 4% reduction observed due to lowered contrast in Experiment 2 ($F(1,9) = 15.2$, $p = .004$). Flankers placed at target-flanker distances of 0.5*e* (leading to an average of 70.0% accurate responses) did not significantly impair performance compared with flankers at 0.7*e* ($t(4) = 1.54$, $p = .20$), but performance in this condition was significantly worse than the unflanked condition ($t(4) = 2.85$, $p < .05$). Performance with flankers at 0.3*e* produced effective crowding, as expected (down to 43.5%, $p < .01$ compared with all other conditions).

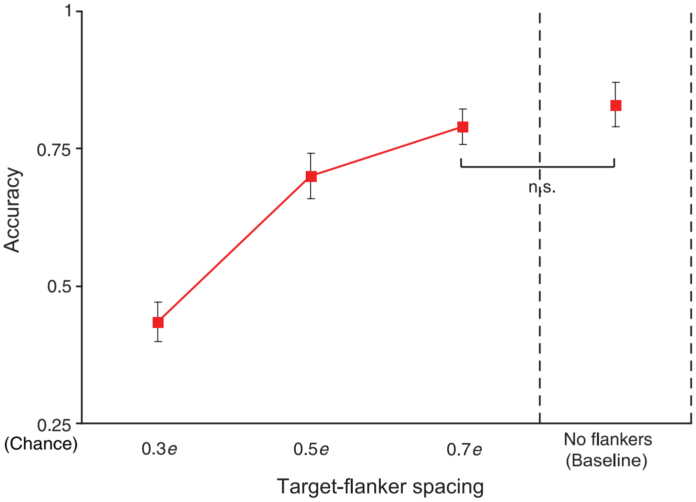

Figure 5. Results of Experiment 2 ($N = 5$). Of note is that, compared to the baseline condition, flankers have virtually no effect at target-flanker spacings of 0.7*e* with low-contrast targets, whereas they had a strong effect in Experiment 1A, when the high-contrast target was weakly masked. Error bars represent between-subjects standard error.

Discussion

As with the unmasked target stimuli of Experiment 1A, low-contrast targets saw no significant crowding by flankers placed at 0.7*e* from the target, and weak crowding at 0.5*e* from the target. This is despite the strong reduction in accuracy due to reducing the contrast of the target. While flanking low-contrast target stimuli with high-contrast flanker stimuli may, indeed, increase the magnitude of crowding (Kooi et al., 1994), the difference between Experiments 1A and 2 demonstrates the unusual potency of the weak mask in producing profound crowding effects.

Experiment 3

The terminology we have used to describe the novel interaction between masking and crowding reported here has implied that supercrowding is related to crowding. However, it could be an entirely distinct phenomenon. In Experiments 3 and 4 we test some basic properties that would be expected if supercrowding is related to crowding. The results imply that supercrowding has similar basic properties to crowding.

In Experiment 3, we evaluate the dependency of supercrowding on similarity between the target and flanking stimuli, a well-established feature of crowding (e.g., Kooi et al., 1994). Towards this end, we held target identity constant (a black T) and varied the identities of the flanking stimuli. Flanking stimuli were black Ts, white Ts, filled black squares, and filled white squares (see Figure 6A). We presented the flankers at a fixed distance from the target: 0.6*e*, a distance at which crowding is typically reported to have almost no effect. If the supercrowding effect shares properties with standard crowding, then the black Ts should be most effective at reducing performance, while the white squares should be least effective. If, on the other hand, the supercrowding effect depends on the amount of irrelevant visual stimulation or energy appearing on the screen (as it might if the effect is due to some sort of enhanced masking), then the squares might be more effective than the Ts at limiting performance.

Methods

Participants

Six observers (including three authors) volunteered for this experiment.

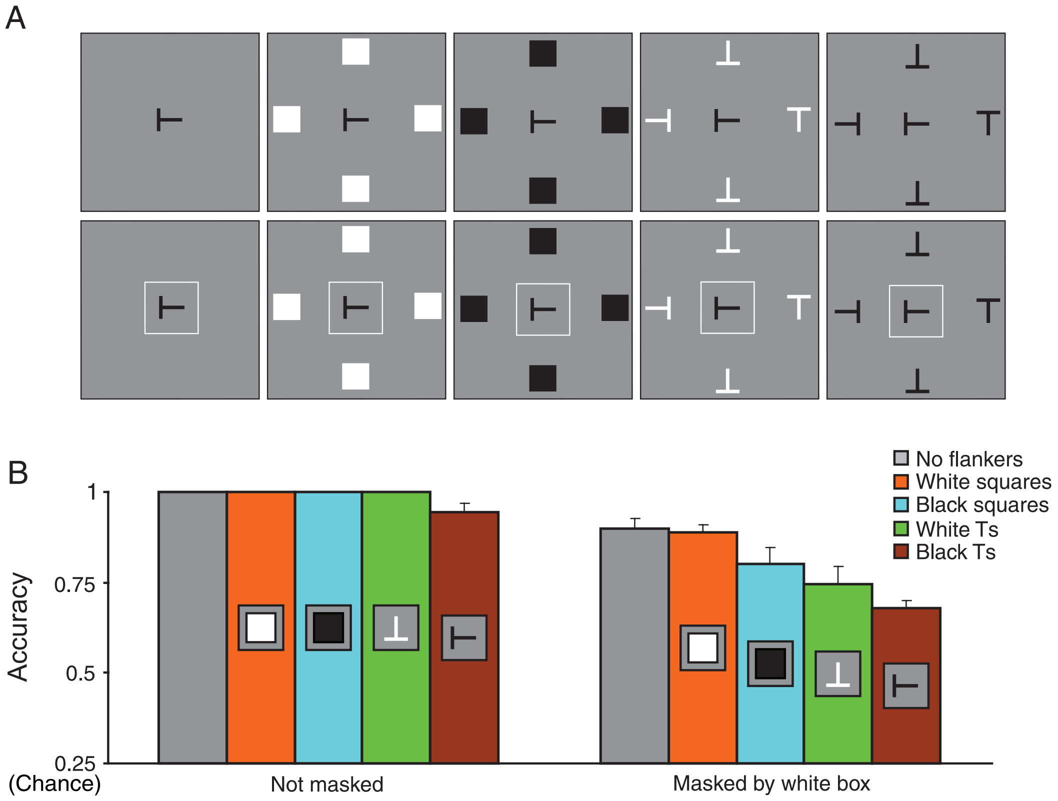

Figure 6. (A) The different flanker conditions of Experiment 3. (B) Average accuracy results of Experiment 3 ($N = 6$). Superimposed on each bar is an image of the type of flanker (if any) used in that condition. Error bars represent standard error of the mean.

Stimuli

The target and mask stimuli were all identical to those used in Experiment 1A, as were the trial timing parameters. The masking condition (masked or not masked by the white contour box) was crossed with five different flanker conditions: black T, white T, filled black square, filled white square, and no flankers (see Figure 6A). When flankers were present, they always appeared at a target-flanker distance equal to $0.6e$. The black and white filled squares were the same luminance and had the same extent as the corresponding flanker T shapes.

Procedure

Observers were given practice identifying the target's orientation with no flanking distractors (at least 40 trials masked and 40 trials without the mask) before the main experiment. A total of 400 trials (40 trials per experimental condition, intermixed randomly) were collected across 10 blocks of the main experiment. Trial procedure was exactly the same as in Experiment 1A.

Results

Average results are displayed in Figure 6B. When the target was not masked, there was a very small effect of the flankers, and accuracy was 100% in all conditions except when the flankers were black Ts. In this case, performance averaged 94.5%. The difference between this condition and all other unmasked conditions was marginally significant ($t(5) = 2.48$, $p = .056$).

The effect of masking the target was to reduce accuracy to an average of 90.0%, significantly lower than the unmasked condition ($t(5) = 4.30$, $p < .01$). Similar to Experiment 1A, the effect of the contour mask and the black T flanking distractors was much greater than either effect in isolation: accuracy was reduced to 67.9%, on average. This observation was confirmed with a two-way ANOVA with the two masking conditions and two flanker conditions (no flanker or black T flankers) as factors: a significant interaction was observed ($F(1, 5) = 45.46$, $p < .001$).

When the target was masked, the different flanker forms had different effects depending on the similarity of the target to the flankers. The black T flankers were the most effective at producing interference, yielding 67.9% accuracy. The white Ts were the next most effective, resulting in 74.5% accuracy. The black squares resulted in 80% accuracy, and finally, the white squares resulted in 88.8% accuracy. A 2 × 2 ANOVA with flanker color (black or white) and flanker shape (square or T) was performed to examine the effect of flanker similarity under masked conditions. Results showed that black flankers were more debilitating than white flankers

(74.0% vs. 81.7%; $F(1, 5) = 54.8$, $p < .001$), and that T-shaped flankers were more debilitating than square-shaped flankers ($F(1, 5) = 52.1$, $p < .001$). These two factors did not interact ($F < 1$). Post-hoc tests showed that the black Ts were significantly more potent flankers than black or white squares (both $p < .005$), and were marginally more potent than white Ts ($t(5) = 2.39$, $p = .062$). All flankers except the white squares led to significantly worse performance than performance without any flankers when the target was masked (all $p < .005$). White squares did not produce a significant impact on performance compared to the masked condition with no flankers ($t < 1$).

Discussion

This experiment replicated the interaction between widely spaced flanking distractors and weak masks, confirming their strong overadditivity. Furthermore, similarity of the flanking distractors was a strong determinant of performance, suggesting that supercrowding is characteristically similar to crowding. More similar flankers produced more effective supercrowding.

Experiment 4

Previous research has shown that crowding has a strong inward-outward anisotropic profile, such that the more distant flanker has a more profound effect on performance than a more proximal flanker situated at the same distance from the target. Crowding also exhibits a radial-tangential anisotropic profile, in that flankers situated radially with respect to fixation and the target are generally more effective than tangentially arrayed flankers (i.e., those flanking the sides of the target). Inward-outward anisotropy has been proposed by Petrov et al. (2007) as a definitive property of crowding that distinguishes it from some other forms of masking, particularly the one that bears the greatest similarity to crowding: surround suppression.

In Experiment 4, we asked whether the supercrowding effect shows a similar anisotropic profile. Similar to Experiment 3, we fixed target-flanker distance at 0.6*e*, and varied the number and positions of flankers. Flankers either did not appear at all, appeared at all four cardinal positions, or a single flanker appeared in one of those four positions around the target. If supercrowding shares properties with standard crowding, then the outermost flanker should be most harmful to performance.

Methods

Participants

Four observers (including two authors) volunteered for this study.

Stimuli

Targets, flanking distractors, the mask, and the fixation mark were all identical to those used in Experiment 1A. As in Experiment 3, when flankers appeared, they always appeared at a target-flanker distance equal to 0.6*e*. The target was always masked by the white contour box. Six conditions were defined by the presence and positions of the flanking distractors. Flankers were either not present, present in all four cardinal positions (as before), or present in a single position (outside, inside, left, or right of the target with respect to fixation).

Procedure

Trial timing and procedures were the same as Experiment 1A. Participants completed 240 trials divided into six blocks, with a total of 40 trials from each condition. Conditions were randomly intermixed throughout.

Results

Average accuracy results are depicted in Figure 7. Accuracy with no flankers was high, averaging 94.0%, while accuracy with all four flanking distractors was lowest, averaging 60.1%. Planned comparisons were conducted to examine the effect of the outermost flanker compared to the innermost (inward-outward anisotropy), and to examine the effects of radial flankers to tangential flankers (radial-tangential anisotropy). All subjects did worse when only the outermost flanker appeared (62.5% accuracy) than when only the innermost flanker appeared

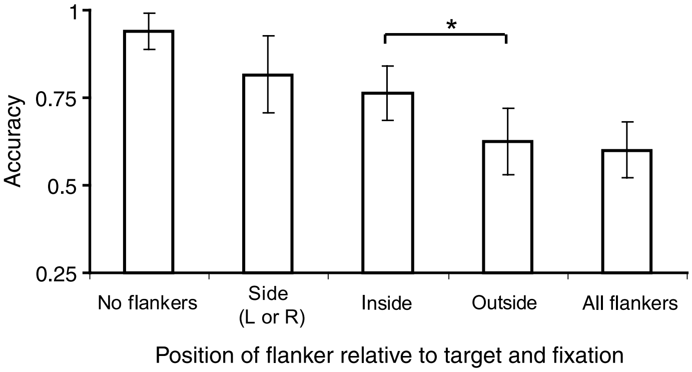

Figure 7. Results of Experiment 4 ($N = 4$). All trials were masked with the white box, and flankers (when present) were positioned at a distance of 0.6*e*. In this experiment, either no flankers appeared, all flankers appeared, or only one flanker appeared. When one flanker appeared, it appeared to the left or right of the target (averaged and reported as "side"), or it appeared between fixation and the target ("inside"), or it appeared on the other side of the target from fixation ("outside"). The critical comparison of the accuracy when the flanker appeared in the inside or outside position shows that the outermost flanker was more debilitating, as in standard crowding (* indicates $p < .05$).

(76.2% accuracy; *t*(3) = 3.29, *p* = .046), confirming inward-outward anisotropy. The averaged accuracy of flankers presented to the sides of the target (81.5%) was compared to the averaged accuracy of the innermost and outermost flankers (69.3%), revealing a significantly greater impairment due to radial flankers compared to tangential flankers and confirming radial-tangential anisotropy (*t*(3) = 4.16, *p* = .025). Inspection of the data and Figure 7 implies that the radial-tangential anisotropy was driven by the large effect of the outermost flanker, and that the outermost flanker was about as effective as all flankers appearing.

To confirm the anisotropy of typical crowding under the basic parameters of our study, we also tested four observers (two of whom were participants in this experiment) under standard crowding conditions (no mask) with flankers on both sides and one flanker either near fixation or an equal distance from the target, but farther from fixation. Target-flanker spacing was chosen by hand based on pilot data, in order to produce a moderate degree of crowding (i.e., overall accuracy approximately 62.5%). For one subject, this was approximately 0.16e, while for the other three participants it was approximately 0.24*e*. Results verified inward-outward anisotropy of standard crowding: all participants performed worse when the flanker farther from fixation was present (50.0%) than when the flanker nearest fixation was present (76.2%; *t*(3) = 4.84, *p* = .017).

Discussion

This experiment demonstrated that supercrowding has a strong anisotropic profile: like standard crowding, the farthest flanking distractor from fixation has the most effect. In fact, this effect was profound, impairing performance by itself almost as much as having all 4 flanking distractors present.

Experiment 5

We have implied that the supercrowding effect is due to weak masking of the target. However, the experiments presented so far always "masked" the target by the same means, enclosing it in a closed white contour. It is possible that something unique about the common region cue impairs performance in the presence of flankers. For example, it may define a surface onto which flanker identities are "tagged," leading to the illusory appearance of flanker features in the target region. In this experiment, we asked whether supercrowding occurs due to another lower-level masking effect, or if it is specific to the type of surrounding contour mask that we employed in the previous experiments.

In Experiment 5, a backward pattern mask was used to weakly mask the target. The procedure was similar in all respects to Experiment 1A, except that instead of a white contour, on masked trials the presentation of the target and flankers was followed by a pattern mask at the target position. The particular mask used and the delay between the onset of the target and the onset of the mask (SOA) was chosen such that the mask was ineffective on its own.

Methods

Participants

Participants were four volunteers, including two authors.

Stimuli

Experiment 5 trials are illustrated by Figure 8. Target and flanker stimuli were identical to those used in Experiment 1A. However, the target and flankers appeared for a total of only 26.7 ms. On unmasked trials, nothing else occurred and a response was solicited as before. On masked trials, the offset of the target was followed by a pattern mask was presented for 53.3 ms. SOA between the target display and the mask was chosen prior to the experiment and separately for each participant, such that the backward pattern mask was ineffective on its own. For three participants, the SOA was 53.3 ms for masked trials, while for the remaining participant the SOA was 26.7 ms. The pattern mask was simply the union of all four possible target T orientations. As in Experiment 1A, flankers were either not present, or appeared at a target-flanker spacing of 0.3*e*, 0.5*e*, or 0.7*e*.

Procedure

SOA was determined by a pilot study, and was chosen as it was the minimum temporal difference that produced

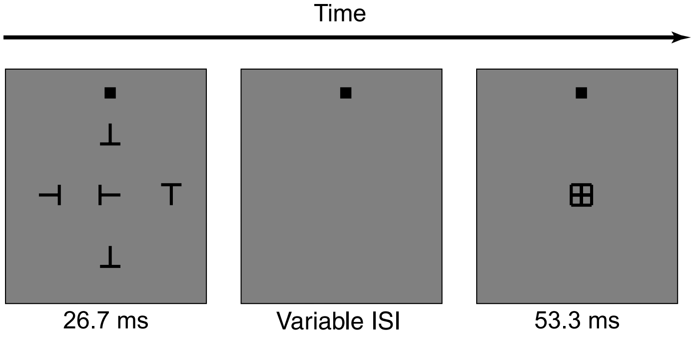

Figure 8. Trial procedure for Experiment 5. SOA was chosen prior to the experiment, and separately for each participant, such that the backwards pattern mask was ineffective in the absence of flanking distractors. SOA was 53.3 ms for 3 subjects and 26.7 ms for 1 subject.

little masking effect (better than 90% accuracy). Eventually we selected 53.3 ms as the SOA in the main experiment for all but one participant, who showed little masking with an SOA of 26.7 ms (when the mask immediately replaced the target). The procedure was identical to Experiment 1A, except as noted above. There were two masking conditions (masked or not masked) crossed with 4 flanker conditions (flanker spacings of 0.3*e*, 0.5*e*, 0.7*e*, and unflanked). 40 trials were collected per condition, for a total of 320 trials (with conditions randomly intermixed). The main experiment was preceded by a short practice session, in which the target appeared with no flankers and was either masked or not masked (at least 40 trials of each).

Results

Averaged accuracy for the four participants is shown in Figure 9. Considering only the unmasked trials, the effect of flankers appearing at target-flanker distances of 0.7*e* and 0.5*e* was to reduce performance to 95.0% and 81.9%, respectively, although neither was significantly different from the unflanked target accuracy of 98.8% (0.7*e* vs. unflanked: $t(3) = 1.27$, $p = .30$; 0.5*e* vs. unflanked: $t(3) = 1.82$, $p = .17$).

The backward pattern mask was weak in all four participants: when no flankers were present, the pattern mask reduced performance from 98.7% to 93.1% ($t(3) = 1.71$, $p = .19$). However, the combination of the backward pattern mask and the flanking distractors produced a profound impairment. Flankers at 0.7*e* target-flanker spacing led to average accuracy of 44.1% (compared to unflanked: $t(3) = 7.85$, $p < .005$) in the presence of a backward pattern mask. An ANOVA comparing only masked and unmasked performance with either no flankers or flankers at target-flanker distances equal to 0.7*e* shows a strong interaction ($F(1, 3) = 175.7$, $p < .001$): the mask and flankers in unison produced profoundly worse performance than either in isolation.

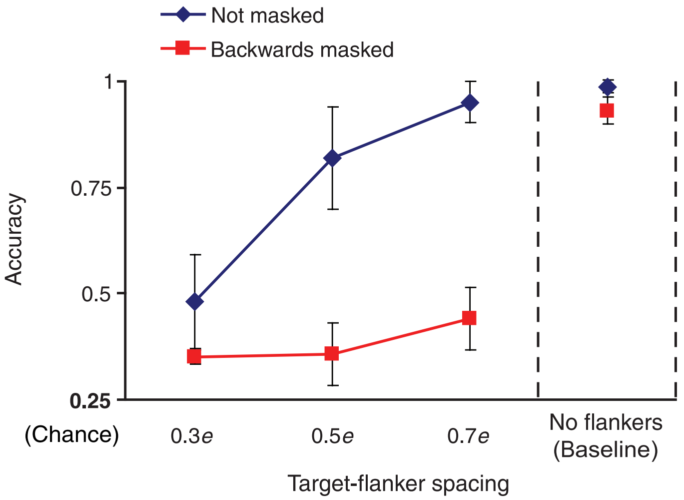

Figure 9. Averaged accuracy results of Experiment 5 ($N = 4$). Error bars represent standard error of the mean.

When the target was masked and flankers were presented at a target-flanker distance of 0.5e or 0.3e average accuracy was 35.8% and 35.0%, respectively. The decline in performance with decreasing target-flanker spacing was not significant, (0.5*e* vs. 0.7*e*, $t(3) = 1.66$, $p = .20$; 0.3*e* vs. 0.5*e*, $t < 1$), although this may be due to a floor effect and small sample size.

Discussion

A weak backwards pattern mask produced profound impairments with widely spaced flankers. Although the mask itself had only a small effect on its own, and widely spaced flankers by themselves had little effect, their combination devastated performance. Thus, the supercrowding combination of a mask and flanking distractors is not restricted to the type of masking stimuli used in Experiments 1A, 1B, 2, 3, and 4.

General discussion

This paper reports a novel phenomenon that we have termed “supercrowding,” because it exhibits many similarities to crowding, but reveals target-flanker interactions over much larger regions of the visual field than previously reported. Supercrowding depends on simultaneously masking the target and crowding the target with flankers. The phenomenon is evident even though either the masks or the flankers, alone, are weak sources of interference. Their combination powerfully disrupts performance. In this paper, we have emphasized the shared characteristics of this effect to “traditional” crowding by our focus on the effect of target-flanker similarity, inward-outward anisotropy, and radial-tangential anisotropy. However, we do not wish to rule out the possibility that supercrowding reflects a qualitatively distinct phenomenon from crowding. Some of our observations hint at qualitative differences. For instance, the relationship between target-flanker spacing and the release from crowding is different depending on whether the weak mask is absent (traditional crowding) or present (supercrowding). When the mask was absent, performance improved progressively as the target-flanker distance increased and reached asymptote when the spacing was 0.5*e*. When the mask was present, performance also improved as the target-flanker distance increased. However, performance was far below asymptote (the *no-flanker* condition) even at 0.7*e,* suggesting that the primary limiting factor may not be target-flanker distance. The size of the computer monitor limited our ability to test target-flanker distances much larger than 0.7*e*. At this point, we do not know whether supercrowding could be eliminated at a particular target-flanker distance (e.g., 1.0*e*), or whether it would be strong as long as the flankers were within the field of view.

As mentioned in the Introduction, the prevailing theories of crowding place the onus of the crowding effect on processes related to feature integration and pooling. The critical crowding distance of 0.5*e* is a widely replicated finding in traditional crowding studies, and this limit is so firmly established that it's sometimes referred to as Bouma's bound (e.g., Pelli et al., 2004) or Bouma's law (e.g., Pelli et al., 2007). The finding of supercrowding is at least superficially inconsistent with Bouma's law. However, the implications of our study go far beyond the specification of a particular value—0.5*e,* 0.7*e,* or some other value—as the critical spacing for feature pooling. Instead, the interaction between local masking and long-distance crowding suggests that the limitations of feature integrators do not simply reflect a fixed (physiological) limit in how widely these integrators sample. These integrators may sample a relatively narrow region (e.g., 0.5*e*) in the absence of local masking, but a much wider region (e.g., 0.7*e* and beyond) in the presence of local masking. Furthermore, existing theories would not have predicted a difference between weakly masking a target and lowering its contrast. Although lowering the target's contrast makes it more susceptible to crowding (Kooi et al., 1994), it produced nothing like the very large extent over which the flanking distractors impaired performance under supercrowding conditions.

How can the very large extent of supercrowding be explained? At this point, we can only speculate.

Focusing on the feature integration account of crowding (although a similar argument could be contrived for selective attention), suppose that object identification relies on the action of feature integrators that vary in size and position. To identify an object, the relevant feature integrators with integration fields that overlap the target location are selected for analysis. Their combined output is examined to determine the object's most probable identity. In traditional crowding, the number of possible integrators that may inform a decision about object identity is limited, because many integration fields that overlap with the target location also overlap the flanking distractor locations. Flanking distractors far outside the range at which crowding is observed may actually cause perceptual decisions to be made with input from many fewer integration fields, but this is undetected because there are enough smaller integration fields to compensate. Thus, in traditional crowding, critical spacing is defined as the target-flanker distance at which the identification process can pool enough target- (but not flanker-) related signals for accurate judgment. In contrast, weakening the target (e.g., lowering its contrast or masking it) impairs identification by reducing the signal strength of detection units that serve as inputs to the target feature integrators, not by limiting the maximum size of the integrators employed. Thus, more integrators may be needed, some of which have larger integration fields, making performance more susceptible to distant flankers.

So far, this explanation only covers traditional crowding. Why does a weak mask produce such a large range of interference compared with simply lowering contrast? Now suppose that in addition to varying in their sizes and positions in the visual field, integrators also vary in their feature selectivity and the grain of their temporal resolution. In terms of feature selectivity, for example, some integrators may combine information about contours independently of their colors, while others integrate information about contours of one particular color. Thus, some integrators would treat "white" and "black" contours as equivalent, while others would integrate contours of only one color. In terms of temporal selectivity, there may be variance in the amount of time over which integrators can effectively sample. Some integrators may be fast, providing two signals that can differentiate forms occurring in quick succession, while others are slow, providing signals that effectively average over two quickly presented stimuli.

Under this explanatory framework, the key difference between masking and lowering contrast is that a weak mask adds additional "noise," whereas lowering contrast only weakens the "signal." The feature integrators that used to exclusively overlap with the target's position now also receive information from the mask. To differentiate the target from the mask, only a subset of these feature integrators can be relied upon, such as those that only pool signals that detect features in the target's color (but not the mask's) or those which can limit integration to fine temporal periods corresponding to the presentation time of the target (but not the backward mask's). Such selective pooling would dramatically reduce the number of useful feature integrators. To compensate for the loss of local integrators, the identification system must rely on other useful integrators whose sampling range may be much wider, and hence overlapping with distant flankers'. In the absence of distant flankers, there may be enough local and long-range integrators whose features match the only the target's and not the mask's (the "*mask-only*" condition). In the absence of the mask, there may be enough (non-feature-selective/temporally coarse) local integrators for identification to succeed (the "*flanker-only*" condition at large target-flanker distances). The presence of both the mask and the flankers handicap the two compensatory mechanisms. The remaining useful feature integrators may simply not be enough for adequate identification, producing supercrowding.

Conclusion

Supercrowding reveals strong interactions between masking and crowding, which implies that the relationship between crowding and other forms of masking is not a simple additive one. The signature finding of this study is the extremely long range interactions between a target and flankers, which far exceed the typically observed range of interactions in crowding. We have shown that supercrowding is revealed by at least two types of masking, and that it is sensitive to factors that affect traditional crowding. Future research should test whether other kinds of local masking can yield supercrowding, and it should characterize local and non-local feature integration mechanisms.

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References

Andriessen, J. J., & Bouma, H. (1976). Eccentric vision: Adverse interactions between line segments. *Vision Research, 16,* 71–78. [PubMed]

Averbach, E., & Coriell, A. S. (1961). Short-term memory in vision. *Bell Systems Technical Journal, 40,* 309–328.

Banks, W. P., Larson, D. W., & Prinzmetal, W. (1979). Asymmetry of visual interference. *Perception & Psychophysics, 25,* 447–456. [PubMed]

Becker, M. W., & Anstis, S. (2004). Metacontrast masking is specific to luminance polarity. *Vision Research, 44,* 2537–2543. [PubMed]

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226,* 177–178. [PubMed]

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13,* 767–782. [PubMed]

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433–436. [PubMed]

Breitmeyer, B. G., Rudd, M., & Dunn, K. (1981). Metacontrast investigations of sustained-transient channel inhibitory interactions. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 770–779. [PubMed]

Chakravarthi, R., & Cavanagh, P. (2007). Temporal properties of the polarity advantage effect in crowding. *Journal of Vision, 7*(2):11, 1–13, http://journalofvision.org/7/2/11/, doi:10.1167/7.2.11. [PubMed] [Article]

Chung, S. T., Levi, D. M., & Legge, G. E. (2001). Spatial-frequency and contrast properties of crowding. *Vision Research, 41,* 1833–1850. [PubMed]

Enns, J. T., & Di Lollo, V. (1997). Object substitution: A new form of visual masking in unattended visual locations. *Psychological Science, 8,* 135–139.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383,* 334–337. [PubMed]

Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *The Journal of Physiology, 195,* 215–243. [PubMed] [Article]

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43,* 171–216. [PubMed]

Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. *Psychological Bulletin, 70,* 404–425. [PubMed]

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

Levi, D. M. (2008). Crowding—An essential bottleneck for object recognition: A mini-review. *Vision Research, 48,* 635–654. [PubMed]

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

Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience, 4,* 739–744. [PubMed]

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442. [PubMed]

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

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision, 7*(2):20, 1–36, http://journalofvision.org/7/2/20/, doi:10.1167/7.2.20. [PubMed] [Article]

Petrov, Y., Carandini, M., & McKee, S. (2005). Two distinct mechanisms of suppression in human vision. *Journal of Neuroscience, 25,* 8704–8707. [PubMed] [Article]

Petrov, Y., & McKee, S. P. (2006). The effect of spatial configuration on surround suppression of contrast sensitivity. *Journal of Vision, 6*(3):4, 224–238, http://journalofvision.org/6/3/4/, doi:10.1167/6.3.4. [PubMed] [Article]

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

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97–136. [PubMed]

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