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Crowding and surround suppression: Not to be confused

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Abstract

Crowding and surround suppression share many similarities, which suggests the possibility of a common mechanism. Despite decades of research, there has been little effort to compare the two phenomena in a consistent fashion. A recent study by D. M. Levi, S. Hariharan, and S. A. Klein (2002) argues that the two are unrelated because crowding effects can be much stronger than suppression effects. Here we report experiments in which the same Gabor target was used both for orientation identification (crowding) and contrast detection (suppression) tasks. In agreement with early crowding studies (e. g., H. Bouma, 1973) we found, that an outward mask is much more effective than an inward mask for the orientation identification task. Notably, no such anisotropy was observed for the contrast detection task, commonly used to measure surround suppression. The anisotropic masking, which defines crowding, is observed only at fine scales (roughly within an octave of the acuity limit), whereas surround suppression is observed at all scales. Our results demonstrate that surround suppression and crowding are indeed two distinct phenomena. We used this characteristic anisotropy to show that a popular crowding paradigm in which target contrast is varied to measure crowding is confounding it with surround suppression. Surround suppression apparently dominates at low contrasts, which would explain some of the reported similarities between the two phenomena.

Keywords

crowding; surround suppression; anisotropy

Introduction

Crowding and surround suppression have been active research topics for more than four decades, originating with the pioneering work of Bouma (1970, 1973), Hubel and Wiesel (1965, 1968), and Stuart and Burian (1962). Curiously, the research on the two phenomena had run largely in parallel with very little overlap until recently. Crowding was the realm of psychologists, surround suppression of neuroscientists.

Usually, different approaches are used when studying the two phenomena psychophysically: an identification task for crowding and a detection or discrimination task for surround suppression. This also reflects the predominant view on the mechanisms of the two phenomena: confusion for crowding and inhibition for surround suppression. Thus, Pelli, Palomares, and

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Majaj (2004) observed that in masking (including surround suppression) the signal disappears, whereas in crowding it remains visible but becomes ambiguous.

However, the recent psychophysical studies of surround suppression (Petrov, Carandini, & McKee, 2005; Petrov & McKee, 2006; Snowden & Hammett, 1998) revealed that in many aspects the two phenomena are surprisingly similar. Table 1 summarizes their common properties.

Although the degree of similarity between crowding and surround suppression is very impressive, two aspects of surround suppression and crowding do not match.

Kooi, Toet, Tripathy, and Levi (1994) reported that crowding was strongly reduced when mask contrast polarity was opposite to that of the target, whereas Petrov and McKee (2006) demonstrated that surround suppression does not depend on the phase of the surround grating. However, the stimuli in the two studies were very different. Kooi et al. used black or white “T”s on a gray background as target and mask, and thus one could argue that it was the average luminance mismatch between target and mask (instead of contrast polarity) that reduced crowding.

Kooi et al. (1994) also showed that 9 arcmin of horizontal disparity between target and mask significantly reduced crowding for intermediate target–mask separations, but Petrov and McKee (2006) did not find any significant effect of disparity on surround suppression. We note, though, that stimulus duration for the disparity experiment in Kooi et al. study was increased from 150 to 600 ms “to give observers enough time to develop a good depth percept”. This suggests that the longer duration in the crowding study was necessary to elicit a significant disparity effect. Petrov and McKee carried out their surround suppression measurements at 150-ms stimulus duration, which might explain the difference.

A recent study by Levi, Hariharan, and Klein (2002) used the superior strength of crowding as an argument against identifying it with surround suppression. Target letters E or C composed of Gabor elements were used for the orientation identification task (crowding), whereas a single Gabor target was used for the contrast detection task (surround suppression). The difference in stimuli and the task may undermine an argument based solely on the effect strength.

A study by Pelli et al. (2004) argues for a distinction between crowding and “ordinary masking” but makes no distinction between overlay masking and surround suppression. Indeed, most of the masking properties picked for comparison with crowding in their study are overlay masking properties and do not apply to surround suppression (see Petrov et al., 2005). Pelli et al. also argue that in masking the signal disappears, whereas in crowding it remains visible but becomes ambiguous. However, the ambiguity can in fact result from a disappearance of small features of the target (caused by surround suppression), which are important for the identification purposes.

In summary, the available experimental evidence suggests that surround suppression and crowding share a common neurological mechanism. Up to now, no compelling arguments have been presented to refute this explanation. Studies comparing crowding and surround suppression used different stimuli and/or experimental conditions, which could render such comparisons inappropriate.

In the present study, we used common stimuli: Gabor targets and grating/plaid masks (similar to the study of He, Cavanagh, & Intrilligator, 1996) to compare crowding with surround suppression. For the crowding experiment, we used the paradigm introduced by Neri and Levi (2006), where the overall size of the stimulus (target and mask) varied in an adaptive fashion (by shrinking or by expanding it uniformly), until observers were unable to perform the task, which determined a threshold stimulus size. The importance of this approach will become clear later. The task was to identify the slant of the Gabor (left or right). For the surround suppression experiment, we used the contrast detection paradigm, in which observers had to detect a low-contrast target.

In his less cited work, Bouma (1973) noticed that it is much easier to recognize the initial letter of a word when the word was presented to the left of fixation, and the final letter when the word was presented to the right of fixation; in short, the outermost letter was most easily identified. This inward–outward anisotropy of crowding has been since confirmed on numerous occasions (e.g., Banks, Larson, & Prinzmetal, 1979; Bex, Dakin, & Simmers, 2003; Chastain, 1982; Krumhansl, 1977). In this study, to distinguish crowding from surround suppression, we explored the effect of mask position around the target. Using identical stimulus conditions, we found a spectacular anisotropy in our crowding experiment but no evidence of an anisotropy in our surround suppression experiment.

The early studies of crowding measured letter identification as a function of the distance separating the test letter from surrounding letters or features of equal contrast (Bouma, 1970; Flom, Wheymouth, & Kahneman, 1963; Kooi et al., 1994). Strasburger, Harvey, and Rentschler (1991), and many others since, have instead measured the contrast needed for the test letter to be identified at some criterion percentage correct; typically, the surrounding letters in these studies were of higher contrast than the test letter. Many of the results from this latter procedure undoubtedly depend to some degree on surround suppression, which may explain the considerable similarity between surround suppression and crowding. Using the inward–outward anisotropy as a hallmark of crowding, we argue that surround suppression, not crowding, is measured by the above procedure.

Methods

Apparatus

Stimuli were displayed on a gray background (42 cd/m^2) and viewed through Wheatstone stereoscope on a pair of linearized 17 in. Sony Trinitron G220 monitors. The stereoscope has been used to study stereoscopic properties of crowding, including disparity, but it was only used for convenience in the current study. All components of the binocular images were presented with zero disparity. The display was 1400 × 1050 pixels; viewing distance was 65 cm. A pixel subtended 1.2 arcmin. For contrast detection threshold measurements, the video signal was rendered with (nominal) 8-bit precision, but an additional factor of 4 increase in precision was attained using 2 × 2 block-pixel ordered dithering (for details, see Petrov & McKee, 2006).

Subjects

Five observers with normal or corrected-to-normal visual acuity were tested; four were experienced psychophysical observers. Observers were trained for a short time (2–5 min) to get acquainted with the stimuli and the task.

Psychometric procedure

We used a two-alternative forced-choice procedure (2AFC), in which the test target appeared at one of two peripheral locations, left and right of the fixation point at equal eccentric loci (9°). We used faint dark circle, 15% in contrast, 1 pixel (1.2 arcmin) wide, to identify each location where the target might appear in the contrast detection experiments (Experiments 2 and 3). This reduced the observer's uncertainty about the possible target locations, which was particularly important for targets presented without a surround mask (Petrov, Verghese, & McKee, 2006). In all experiments, the mask was presented at both locations in a mirrorsymmetrical fashion with respect to fixation. The fixation pattern comprised of two low-contrast concentric circles and a pair of nonius lines was displayed at the center of the screen and remained continuously visible throughout fixation and target presentation.

In a 2AFC task, the observer indicated with a button press which location contained the test target: a Gabor slanted left (Experiment 1), a Gabor (Experiment 2), and a letter “T” normal side up (Experiment 3). The targets shown in the opposite location were, respectively, a Gabor slanted right, a no target, and an upside-down letter “T”. Thus, the task was an orientation identification in Experiments 1 and 3 and a contrast detection in Experiment 2. Stimulus duration was 150 ms in all experiments.

We used a slightly modified version of Kontsevich and Tyler (1999) adaptive staircase algorithm (for details, see Petrov & McKee, 2006). Thresholds corresponded to 76% correct responses as estimated from the psychometric function. At least 150 trials per datum were done by each observer to bring the variability of the estimated thresholds below 10%.

Stimuli

The test target in Experiments 1 and 2 was a standard cosine-phase Gabor ($\sigma = \lambda/\sqrt{2}$) in which ~1.5 periods (1°) of the sinusoidal pattern were visible, as shown in Figures 1a and 1b. The Gabor period λ was the variable parameter of the adaptive algorithm in Experiment 1; its contrast was fixed at 45%. In Experiment 2, λ was fixed at 0.67°, whereas the target contrast was the variable parameter. The Gabor was slanted ±45° from the vertical in Experiment 1 and had a vertical orientation in Experiment 2.

The test target in Experiment 3 was the Sloan letter T, 38 arcmin in size, displayed either normal side up, or upside down, as shown in Figure 1c. It was always lighter than the background, but its contrast varied according to the adaptive algorithm.

The mask used in Experiment 1 was a plaid made of two transparently overlaid Gabor patches. The patches were exact replicas of the target, except that one was rotated by 90°. Contrast of both patches was 45%; the resulting plaid contrast was close to 90%. Four mask locations around the target defined with respect to the fixation point were tested, as shown in Figure 1. The separation between the mask and the target was fixed at 4λ and thus varied along with the target (and mask) period λ according to the adaptive algorithm.

The mask used in Experiment 2 was the half-annulus shown in Figure 1b, which had an inner radius 2λ (1.3°) and outer radius 8λ (5.3°). It contained a sinusoidal grating of the same phase, orientation, and spatial frequency as the target. The grating contrast was 20%. The parameters were chosen to maximize the effect of surround suppression. Also, to ensure that no overlay masking was present, a blank region (at the background luminance) approximately 1 period wide (0.67°) separated the target from the mask (Petrov et al., 2005). Two mask locations, inward and outward of the target, were tested in Experiment 2.

Finally, the mask used in Experiment 3 was in the form of a square lattice made of Φ-shaped elements, their orientations randomized, as shown in Figure 1c. The lattice period was 46 arcmin, which created 8 arcmin gaps in between the lattice elements. The same size gap separated the mask from the “T” target. The lattice elements were the same size and contrast polarity as the target, their contrast was fixed at 30%. The mask extended 10° vertically and 5° horizontally either inward or outward of the target.

Results and discussion

The experimental data are shown in Figures 2, 3, and 4. The suppression factor, defined as the ratio of the masked to unmasked thresholds, was used to measure the strength of both crowding and surround suppression. The unmasked λ thresholds in Experiment 1 varied among subjects from 4.6 to 6.4 arcmin. The contrast thresholds varied from 1% to 1.5% in Experiment 2 and from 3.9% to 4.5% in Experiment 3.

Experiment 1: Crowding

In this experiment the slant (left or right) of a single Gabor patch had to be identified. The plaid mask was shown in one of the four locations around the target: above, below, inward, and outward—all defined with respect to fixation (see Figure 1a). Contrast of both target and mask was kept constant, whereas the scale of the whole stimulus varied to determine the resolution threshold needed for identification (Neri & Levi, 2006).

The results for five observers are shown in Figure 2; the mask location is plotted along the *x* axis. Data for individual observers are shown in the first five columns, data averaged over the five observers are shown in the last column. Error bars (1 standard deviation) for individual data were calculated as described in the Methods section; error bars for the average data did not include variation among the subjects.

The outward mask produced the strongest crowding, surpassing the crowding effect for the other locations by a factor of 5, on average. Placing the mask in the remaining three locations produced, on average, a very weak effect. Note that the strong outward masking accounts for the radial–tangential anisotropy reported by Toet and Levi (1992).

Experiment 2: Surround suppression

In this experiment, observers were required to detect a Gabor target flanked by a half-annulus mask. The mask was shown either on the inside (In) or on the outside (Out) of the target with respect to the fixation, as shown in Figure 1b. Unlike the crowding experiment, the target contrast varied here whereas the stimulus size was fixed.

The results for five observers shown in Figure 3 indicate a fair amount of surround suppression but no significant effect of mask location, in sharp contrast with the results of the previous experiment. The average suppression strength produced by the half-annulus mask was close to that of a bow-tie-shaped mask (Petrov & McKee, 2006).

Discussion of Experiments 1 and 2

The mask in Experiment 2 was chosen to maximize the effect of surround suppression. It had a different shape and a larger spatial extent than mask in Experiment 1. The larger spatial extent as well as the mask's distinct shape could permit some figure/background mechanisms to operate between the mask and the target. It is conceivable that such mechanisms could make the surround suppression more symmetric. Also, in the crowding experiment, the task was orientation discrimination, whereas in the surround-suppression experiment, the task was contrast detection. Is the loss of the inward–outward asymmetry in Experiment 2 simply due to the different tasks and/or the different spatial configurations of the stimuli?

In an attempt to answer this question, we first modified Experiment 2 as follows. Both the stimulus and the task in the control experiment were identical to Experiment 1, except that the spatial frequency of the stimulus was fixed at 1.5 cpd (the same as in Experiment 2), whereas its contrast varied to determine the orientation identification threshold. The 1.5-cpd stimuli were used to keep the target–mask separation ($4\lambda = 2.7°$) large enough to avoid any significant crowding. Recall that in Experiment 1 the sizes of the target, plaid mask, and their separation were reduced together until the subject could no longer identify the orientation of the target.

Two subjects (SPM and JF) carried out the control experiment. No significant surround suppression was observed. This is in a stark contrast with strong crowding observed in Experiment 1 with the same mask. This also agrees with our preliminary studies, which showed that when the surround mask is of the same size as the target very little or no suppression is produced, even when the mask is positioned immediately next to the target. Note that even with the half-annulus mask, the effect of surround suppression in Experiment 2 was smaller than the effect of (inward) crowding in Experiment 1. Our results support Levi et al. (2002) in that surround suppression is weaker than crowding.

To determine what spatial scale induces the onset of crowding, SPM repeated the control experiment for 3 and 5 cpd stimuli. There was very little or no masking effect at 3 cpd, but at 5 cpd a significant crowding was observed. The effect was very similar to the crowding observed in Experiment 1, including strong inward–outward anisotropy. Of course, this was to be expected, given that at 5 cpd the control experiment was almost identical to Experiment 1. Thus, unlike surround suppression, crowding only occurs when the Gabor target is near the acuity limit; 5 cpd is about an octave larger than the resolution limit at 9° eccentricity.

Because the first control did not produce enough suppression, we modified Experiment 2 in a different way. The stimulus duration was reduced from 150 ms to ~36 ms (3 video frames at 85 Hz screen refresh rate). Because surround suppression increases dramatically at short durations (Petrov, Carandini, & McKee, 2006), we expected that a small mask would produce strong suppression in this case. The mask was a single Gabor patch shown at 45% contrast. Otherwise it matched the target Gabor in slant (45° to the right), spatial frequency (3 cpd), and phase (cos). The slant and the increased spatial frequency were chosen to match stimuli in Experiment 1 more closely (see Figure 1a). The separation between the mask and the target was 4λ, the same as in Experiment 1. Only the inward and outward mask positions were tested.

Two observers (YP and SPM) carried out the control experiment. The results shown by star symbols in Figure 3 demonstrate that the Gabor mask produced equally strong suppression at inward and outward locations. Thus, neither the extent of the mask nor its shape explains the no-effect of the mask location in Experiment 2.

Altogether, the results of the first two experiments and the control experiments provide a clear demonstration that crowding and surround suppression are distinct phenomena. The small plaid mask produced strong crowding but no surround suppression. The crowding was characterized by the strong inward–outward anisotropy, whereas surround suppression was isotropic for both small and large surrounds. The inward–outward anisotropy in the crowding experiment is in agreement with Bouma (1973) and later studies which also showed that the inward letter of a word is much harder to identify than the outward letter. Thus, the anisotropy is not an artifact of the stimulus we used here but a general (and rather intriguing) property of crowding. Our results also argue against defining crowding as a “letter only” phenomenon, as suggested by Pelli et al. (2004).

We note that this anisotropy is too large to be accounted for by cortical magnification. The outward mask, at threshold, was on the average 1° more peripheral than the inward mask in Experiment 1. Given that the whole stimulus was at 9° eccentricity, the 11% difference in the mask eccentricity is insufficient to explain the fivefold increase in crowding based on cortical topography alone. Besides, Petrov and McKee (2006) noted that the stronger radial effects cannot be explained by cortical magnification as data from primate and human retinotopy (Adams & Horton, 2003; Schira, Kontsevich, & Tyler, 2005; Tootell, Switkes, Silverman, &

Hamiltonet, 1988; Van Essen, Newsome, & Maunsell, 1984) suggest that a radial–tangential anisotropy determined by equal cortical distance would, if anything, be in the opposite direction. This is because, at least along the vertical meridian, in order to travel an equal visual distance radially and tangentially, one must travel farther on cortex in the radial direction due to overlap when crossing ocular dominance columns. Along the horizontal meridian, the arrangement of columns is more haphazard and there is no particular cortical anisotropy other than magnification. In summary, these crowding anisotropies are not easily explained by retinotopy or cortical magnification, at least in primary visual cortex.

The anisotropy clearly distinguishes crowding from surround suppression. We will next use this anisotropy as a litmus test to test whether a commonly used “crowding” paradigm is measuring crowding or surround suppression. In this paradigm, the experimenter determines the contrast required to identify a target in the presence of flanking targets. The contrast of the flanks is kept constant, and it is normally considerably higher than the contrast of the test target. We note that this contrast threshold paradigm has been extensively used in recent years. For example, most of the important crowding studies cited in Table 1 (Chung, Levi, & Legge, 2001;Levi et al., 2002;Pelli et al., 2004;Strasburger et al., 1991) used this paradigm.

Experiment 3: Litmus test for crowding

As a generic crowding stimulus, we used a modified design borrowed from Tripathy and Cavanagh (2002). The letter “T” served as a target; the task was to identify whether it was upside down or normal side up. The mask was a jumble of Φ shapes extending either inward or outward of the target, as seen in Figure 1c.

The results for five observers are shown in Figure 4. The strength of the interaction, which we term “Crowding factor” here, was measured the same way as that in Experiment 2, that is, as a ratio of masked to unmasked contrast thresholds. Not surprisingly, the interaction strength was significantly larger than in Experiment 2. Considering the broadband spatial content of the “T” target and the mask elements, the effective separation between target and mask was much smaller than that in Experiment 2. In striking contrast to Experiment 1, there was no trace of the inward–outward anisotropy in the results: the mask positioned inward of the “T” target hindered its identification to the same degree as the outward mask.

General discussion

Experiments 1 and 2 showed that surround suppression and crowding are distinct phenomena, and that the inward–outward anisotropy can be used as a litmus test for crowding. The importance of such a test becomes obvious when one considers that crowding and surround suppression are operating in a parallel and a very similar fashion. This makes it easy to confound the two, and Experiment 3 provided one such example. We employed an experimental paradigm commonly used to study crowding and discovered that the interaction tested by this paradigm did not pass the litmus test for crowding. Because it showed no sign of the inward–outward anisotropy, we are compelled to conclude that surround suppression and not crowding caused the elevation of the identification thresholds here. Because the tested paradigm is commonly used in crowding studies, this is an obvious concern. Most of the properties listed in Table 1 as pertaining to both crowding and surround suppression were obtained by using such a paradigm.

We suggest that the paradigm used in Experiment 1, or any other paradigm in which target and mask have a similar contrast, is a much better choice for a crowding study. We also argue that the inward–outward anisotropy should be considered a hallmark of crowding instead of eccentricity effects or target size effects as suggested by Pelli et al. (2004). Besides its importance as the unique attribute of crowding, the anisotropy might also provide a clue to the role and the mechanism of crowding and thus deserves more attention in future studies.

Conclusions

Our results demonstrate that identification of a Gabor target is much harder when a mask made of two orthogonally overlaid Gabors is positioned on the outside the target compared to other locations around the target. This inward–outward anisotropy does not exist for surround suppression measured as a reduction of contrast sensitivity for the target Gabor. We suggest the observed masking anisotropy as the hallmark of crowding and use it to provide compelling evidence that the popular crowding paradigm in which target contrast thresholds are measured is confounding crowding with surround suppression.

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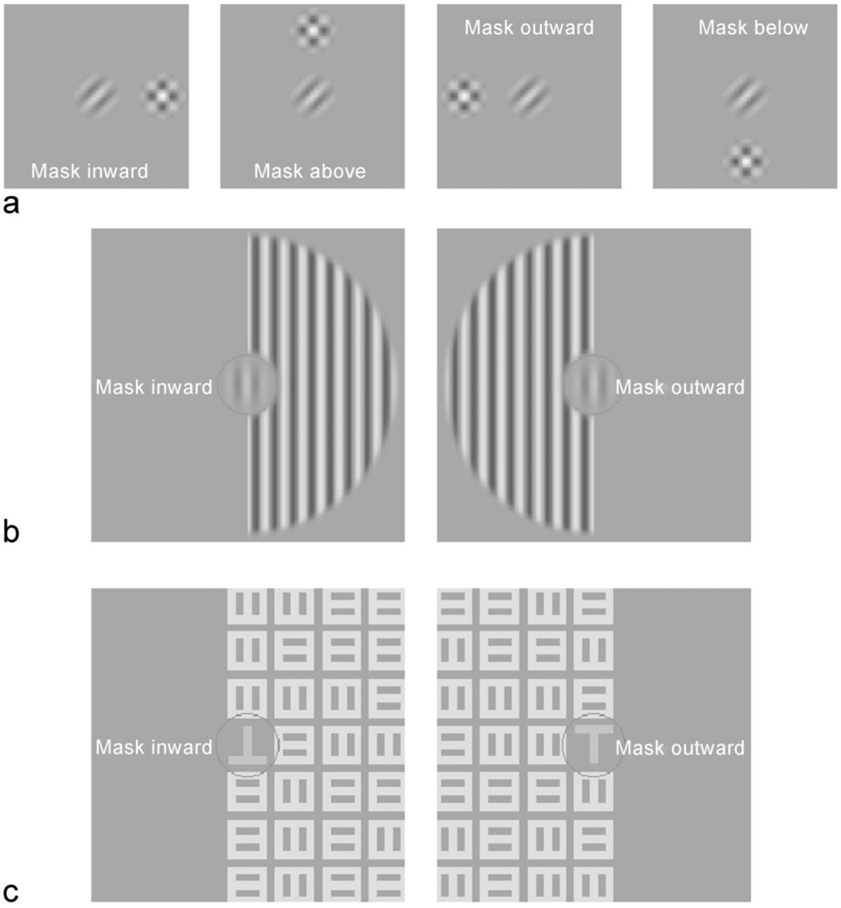

Figure 1.
An illustration of the stimuli used in this study. Fixation is assumed to the right of the figure. (a) Crowding by a mask positioned at four different locations around the target. A cosine-phase Gabor target with 45° orientation and a plaid mask made of two overlaid orthogonal Gabors are shown. (b) A vertical Gabor target surrounded by the half-annulus sine-grating mask. The inward and outward mask configurations are shown. (c) A T target upside down and normal side up and the half-surround Φ mask in inward and outward configuration are shown.

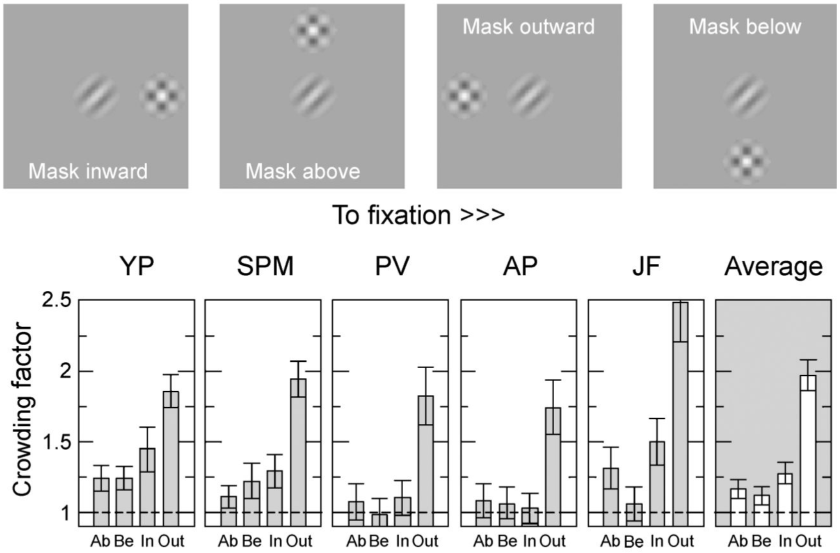

Figure 2.

Effect of mask location on crowding. Results for the following mask locations with respect to the target: above (Ab), below (Be), inward (In), and outward (Out). The dashed line indicates no effect (crowding factor = 1). Error bars show one standard deviation.

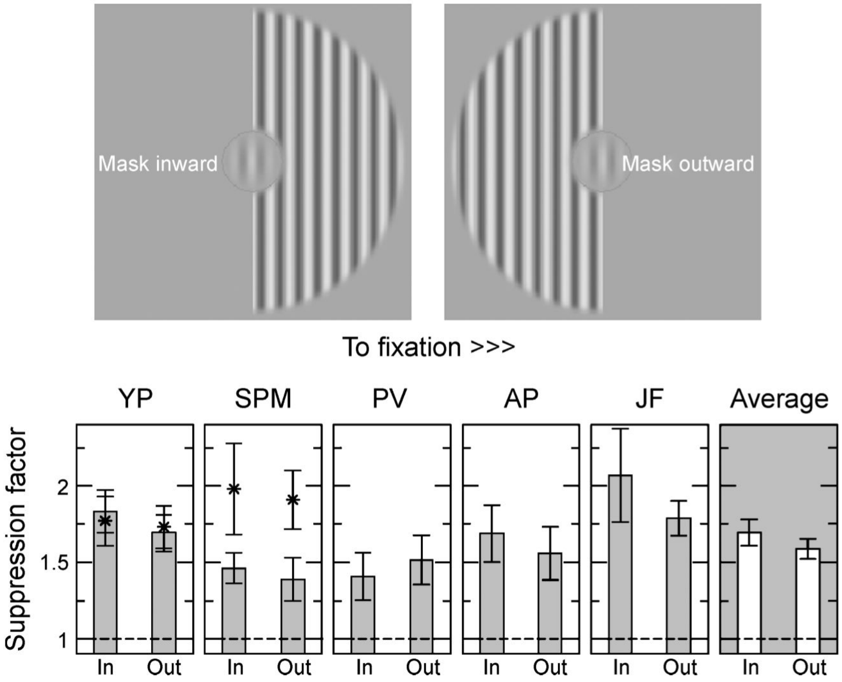

Figure 3.

Effect of mask location on surround suppression. Results for inward (In) and outward (Out) half-annulus masks are shown. The dashed line indicates no effect. Star symbols (for observers YP and SPM) show results of the control experiment, where a Gabor mask positioned at 4λ separation was used instead of the half-annulus (see discussion of the first two experiments for details).

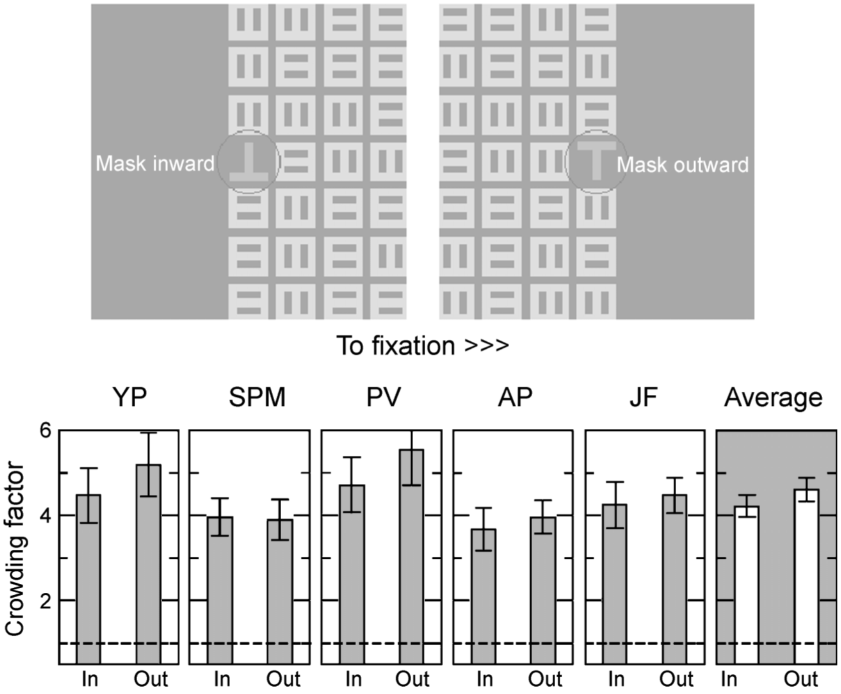

Figure 4.

Effect of mask location in the experiment where the orientation of letter “T” surrounded by a crowding mask had to be identified. Unlike Experiment 1, target contrast has been varied here to measure the identification thresholds.

Table 1

Common properties of crowding and surround suppression.

Property	Crowding	Surround suppression
Peripheral locus	Flom et al. (1963); Bouma (1970)	Andriessen and Bouma (1976); Snowden and Hammett (1998)
Radial–tangential anisotropy	Toet and Levi (1992)	Petrov and McKee (2006)
Orientation tuning	Levi et al. (2002)	Andriessen and Bouma (1976); Petrov et al. (2005)
Spatial frequency tuning	Chung et al. (2001)	Petrov et al. (2005)
Extent scales with eccentricity	Bouma (1970); Toet and Levi (1992)	Petrov and McKee (2006)
Extent does not depend on size	Strasburger et al. (1991); Tripathy and Cavanagh (2002)	Petrov and McKee (2006)
Saturates at high mask contrasts	Pelli et al. (2004)	Snowden and Hammett (1998); Petrov et al. (2005)