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Spatial-frequency and contrast properties of crowding

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Abstract

Crowding, the difficulty in recognizing a letter flanked by other letters, has been explained as a lateral masking effect. The purpose of this study was to examine the spatial-frequency and contrast dependencies of crowding, and to compare them with the properties of pattern masking. In experiment 1, we measured contrast thresholds for identifying the middle letters in strings of three randomly chosen lower-case letters (trigrams), for a range of letter spacings. Letters were digitally filtered using a set of bandpass filters, with peak object spatial frequencies ranging from 0.63 to 10 c/letter. Bandwidth of the filters was 1 octave. Frequencies of the target and flanking letters were the same, or differed by up to 2 octaves. Contrast of the flanking letters was fixed at the maximum value. Testing was conducted at the fovea and 5° eccentricity. We found that crowding exhibits spatial-tuning functions like masking, but with generally broader bandwidths than those for masking. The spatial extent of crowding was found to be about 0.5 deg at the fovea and 2 deg at 5° eccentricity, independent of target letter frequency. In experiment 2, we measured the contrast thresholds for identifying the middle target letters in trigrams for a range of flanking letter contrasts at 5° eccentricity. At low flanker contrast, crowding does not show a facilitatory region, unlike pattern masking. At high flanker contrast, threshold rises with contrast with an exponent of 0.13–0.3, lower than corresponding exponents for pattern masking. In experiment 3, we varied the contrast ratio between the flanking letters and the target letters, and found that the magnitude of crowding increases monotonically with contrast ratio. This finding contradicts a prediction based on a grouping explanation for crowding. Our results are consistent with the postulation that crowding and masking may share the same first stage linear filtering process, and perhaps a *similar* second-stage process, with the additional property that the second-stage process in crowding pools information over a spatial extent that varies with eccentricity. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Crowding; Lateral masking; Pattern masking; Spatial-frequency specificity; Contrast specificity

1. Introduction

Our ability to identify a letter is better when it is presented alone, than when it is flanked by other letters in close proximity (e.g. Bouma, 1970; Townsend, Taylor, & Brown, 1971). This phenomenon is termed *crowding*. A closely related phenomenon, *contour interaction*, refers to the effect of proximal *contours* such as bars or edges on the resolution of a single letter (Flom, Weymouth, & Kahneman, 1963). In addition to letter identification, the presence of proximal features also adversely affects other spatial tasks such as two-bar resolution (Takahashi, 1967), Vernier discrimination (Westheimer & Hauske, 1975; Levi & Klein, 1985; Levi, Klein, & Aitsebaomo, 1985), stereopsis (Butler & Westheimer, 1978) and line orientation sensitivity (Westheimer, Shimamura, & McKee, 1976).

Previous studies have shown that even when targets are scaled in size, the spatial extent (Jacobs, 1979; Toet & Levi, 1992; Latham & Whitaker, 1996a) and intensity (Loomis, 1978; Jacobs, 1979) of the interaction are still greater in peripheral than central vision. This enhanced interaction has been suggested as a major factor accounting for slow and inefficient reading in peripheral vision, even when character size is not a limiting factor (Latham & Whitaker, 1996b; Chung, Mansfield, & Legge, 1998), and when oculomotor demands are mini-

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mized with rapid serial visual presentation (e.g. Rubin & Turano, 1994; Latham & Whitaker, 1996b; Chung et al., 1998). Evidence supporting crowding as a contributing factor to the reading deficits in the periphery comes from the observation that increased letter spacing improves word recognition performance in the periphery (Whittaker, Rohrkaste, & Higgins, 1989; Latham & Whitaker, 1996b).

Our interest in studying crowding stems from our desire to understand the reading deficits in peripheral vision — a problem facing millions of people who lose their central vision due to age-related macular degeneration. Despite the extensive work that has been done on the crowding effect, a fundamental question remains unanswered — what is the underlying mechanism of crowding? If crowding does indeed contribute to slow peripheral reading, then we need to understand how it occurs.

In this paper, *crowding* refers to the interfering effect on letter recognition of non-overlapping adjacent letters. Crowding is often used synonymously with the broader term *lateral masking* (Townsend et al., 1971; Wolford & Chambers, 1984; Mansfield, Legge, & Ortiz, 1998). *Lateral masking* refers to any effect on the detectability, discriminability or recognition of a target by non-overlapping spatially adjacent patterns. The use of the term 'masking' introduces a presumptive link to pattern masking in which the visibility of a target is affected by a spatially superimposed masker.

In addition to the traditional crowding studies using letters as targets and flankers, lateral masking has also been studied using Gabor patches as targets and flankers (Gabor-by-Gabor masking: Polat & Sagi (1993), Zenger & Sagi (1996); Wilkinson, Wilson, & Ellemberg (1997)), or using different types of stimuli as targets and flankers (e.g., noise patches masking letters, Gabors masking letters: Palomares, LaPutt, & Pelli (1999)). The use of the term 'lateral masking' to refer to crowding bears an underlying implication that crowding *is* a form of masking. However, to date, there is no direct evidence to support or disprove this conjecture.

In traditional crowding experiments, flanking letters are placed adjacent to target letters. There is evidence that traditional crowding is greatest when target and mask are similar in stimulus properties such as size, shape, orientation etc. (Andriessen & Bouma, 1976; Nazir, 1992; Kooi, Toet, Tripathy, & Levi, 1994), suggesting that crowding, like masking, might be spatial-frequency selective. Recent studies of Gabor-by-Gabor lateral masking show that detection thresholds of a target Gabor are raised in the presence of nearby flanking Gabors (e.g. Polat & Sagi, 1993; Zenger & Sagi, 1996). These studies also demonstrate spatial-frequency specificity, and suggest that masking of Gabors and gratings and crowding of letters might share a number of important properties (and possibly mechanisms).

As a way of approaching the mechanisms underlying crowding, we examined the spatial-frequency and contrast dependencies of crowding in order to determine if crowding and pattern masking share similar stimulus properties. There have been numerous studies of pattern masking in which the target and masker are spatially overlapping sinewave gratings (e.g. Legge, 1979; Legge & Foley, 1980; Swift & Smith, 1983). A strong advantage of using the spatial-frequency approach in studying visual masking is that the properties of the stimuli (contrast, spatial frequency, bandwidth, etc.) are easily controlled and specified, and the effects of these stimulus dimensions are now quite well understood. Therefore, in order to facilitate the investigation of the spatial properties of crowding, we used spatial-frequency limited letters and manipulated their properties in terms of spatial frequency and contrast.

2. General methods

2.1. Experimental set-up

The magnitude of crowding was quantified by measuring the elevation in contrast threshold for identifying the middle target letters in strings of three lower-case letters (trigrams), compared with those obtained for unflanked letters. Letters were presented on two optically superimposed Apple high-resolution monochrome monitors, each equipped with a video attenuator (Institute for Sensory Research, Syracuse, NY). Both monitors were γ-corrected for their luminance output, using VideoToolbox software (Pelli & Zhang, 1991), and were driven by an Apple Macintosh 8600/300 computer equipped with two separate graphics boards. We presented the target letter on one of the two monitors, and the flanking letters on the other monitor, so that we could independently control the contrast of the target and the flanking letters. The images of the two monitors were combined optically, using a front-surface mirror and a beam splitter of 50% transmittance and reflectance (Edmund Scientific, NJ). The mean luminance of the combined screen, as seen by the observer, was 55 cd/m^2. Before each session of data collection began, we checked the alignment of the monitors and the optical system, and adjusted them if necessary. Although our optical set-up was quite robust to slight head movement, a chin and head rest was used throughout the experiment.

2.2. Stimuli

Letters making up each trigram were chosen randomly from all 26 letters of the Times-Roman alphabet and each was digitally filtered with a set of nine raised cosine log filters, with peak object spatial frequencies ranging from 0.63 to 10 c/letter, in half-octave steps. To generate the band-pass filtered letters, we first created an image for each letter as a single white (color value of 1) letter on a black (color value of 0) background of 512×512 pixels, for a range of x-heights (16–100 pixels). We specified the spatial frequency of the letter with respect to the x-height. Each letter was positioned such that the letter-x counterpart would be centered on the background. The binary image was then Fourier transformed and multiplied with one of the nine raised cosine log filters, rendered in the frequency domain. Each filter has a bandwidth (full-width at half-height) of 1 octave and is radially symmetrical in the log-frequency domain. The equation of the filter is given by:

$$\text{Amplitude at radial frequency fr} = \frac{1.0 + \cos\left(\pi * \dfrac{\log(\text{fr}) - \log(\text{ctr})}{\log(\text{cut}) - \log(\text{ctr})}\right)}{2}$$

where ctr represents the spatial frequency corresponding to the peak amplitude of the filter (center frequency) and cut represents the frequency at which the amplitude of the filter drops to zero (cut-off frequency). An inverse Fourier transform was then performed on the product of the multiplication which resulted in the final filtered image, with color values falling within a range ± 127.5. The filtering procedures were performed using the HIPS software (Landy, Cohen, & Sperling, 1984). Fig. 1 shows a set of these filtered images of the letter ‘s’. Because of the difficulty in satisfactorily defining the contrast of filtered images (Peli, 1990; Alexander, Xie, & Derlacki, 1994), we adopted a ‘relative contrast’ definition. The contrast of a letter after filtering and, without rescaling, was assigned as having a relative contrast of 100%. This means that the actual contrast of letters containing high-frequency bands is low, because of the drop in the amplitude spectrum of letters.

2.3. Psychophysical procedures

In each block of trials, we tested between eight and ten different testing conditions. For each testing condition, the target letter frequency, flanking letter frequency, letter spacing and contrast of the flanking letters could be specified independently. We used a 3 down–1 up staircase psychophysical procedure to track the contrast threshold corresponding to a 79% observed correct probability on the psychometric function. Eight reversals were used in each staircase and the average of the last six reversals was taken as the threshold for that block of trials. Step sizes were 0.3 log units before the second reversal and subsequent step sizes were 0.1 log units. Within each block, the various testing conditions were tested in a random sequence. Each datum reported in the study represents the average of four to six independent measures of threshold for the same condition, collected on different days.

2.4. Observers

Two observers with normal vision, one of the authors and a paid observer unaware of the purpose of the study, participated in the experiments. Both had (corrected) acuity of 20/15 or better in both eyes. Observer SC was an experienced psychophysical observer while observer GR did not have prior experience in visual psychophysics. Consequently, GR was given an extensive period of training (approximately 20 h) until her performance on each condition stabilized. Data collected during the training phase are not included in this paper. The experimental protocols were approved by the IRB at Indiana University (Bloomington) and written informed consent was obtained from observer GR after the procedures of the experiment were explained, and before the commencement of training.

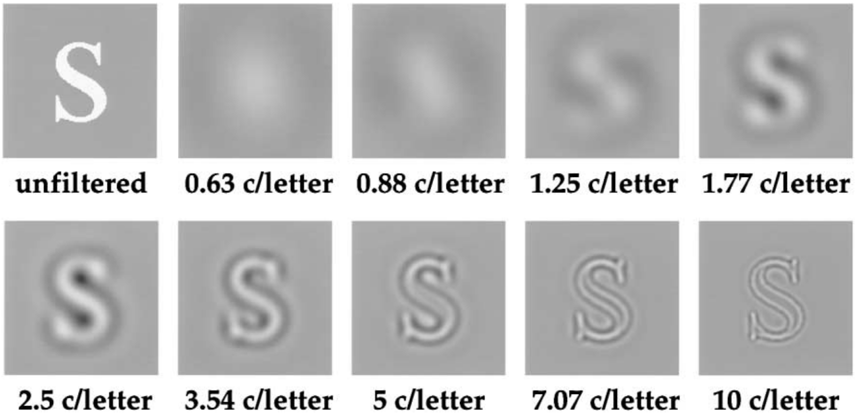

Fig. 1. Illustrations of the unfiltered letter ‘s’ and its spatially filtered versions. The spatial frequency given underneath each illustration represents the peak object frequency of the bandpass filter. All these letters share the same relative contrast of 1 (maximum contrast after filtering without rescaling).

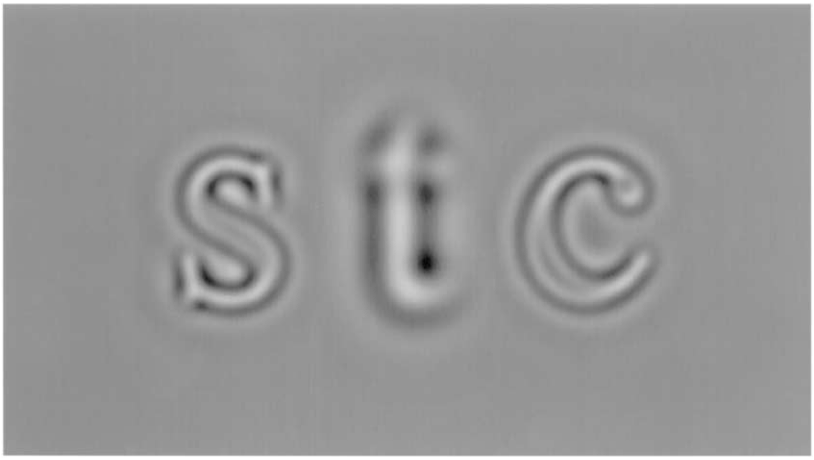

Fig. 2. A sample trigram stimulus. In this example, the target letter frequency of the middle letter 't' is 2.5 c/letter; whereas the letter frequency of the two flanking letters 's' and 'c' is 5 c/letter. The letter spacing is 1.25x (1.25 times the x-height).

3. Experiment 1: effect of frequency content of flanking letters and letter spacing

A key property of pattern masking is its spatial-frequency specificity. In general, the masker is most effective when its spatial frequency is close to that of the target. As a first step in comparing the spatial properties of crowding with masking, we tested whether or not crowding shows spatial-frequency specificity. For each target letter frequency, we measured the magnitude of crowding for a range of flanking letter frequencies. Because crowding diminishes with separation between the target and its flankers, we also examined how the magnitude of crowding changes with letter spacing.

3.1. Methods

Observers were tested monocularly at the fovea and 5° in the inferior visual field, with the non-viewing eye occluded. When testing at the 5° eccentricity, a small red dot was used as the fixation target. Viewing distances were 240 and 140 cm for foveal and 5° eccentricity testing, respectively.

Based on the knowledge that letter identification is mediated by spatial-frequency channels that peak at about 1–3 c/letter (Ginsburg, 1980; Parish & Sperling, 1991; Solomon & Pelli, 1994; Alexander et al., 1994; Majaj, Pelli, Kurshan, & Palomares, in press; Chung & Legge, 1997), we tested four target letter frequencies: 1.25, 1.77, 2.5 and 3.54 c/letter. For each target letter frequency, up to seven flanking letter frequencies were tested. These flanking letter frequencies were the same or differed by up to ± 2 octaves, in half-octave steps, from the target letter frequency. The contrast of the flanking letters was fixed at a nominal value of 100% (see Section 2). Once the flanking letters were combined with the image of the target letter through the beam splitter, the nominal contrast of the flanking letters became 50% (Michelson's contrast definition). For comparison, we also measured contrast thresholds for identifying *unflanked* target letters (contrast of flanking letters set to zero). Letter size was twice the single letter acuity-limit at each eccentricity (0.32 deg at the fovea and 1.1 deg at 5° eccentricity, for both observers) which was measured for each observer prior to the beginning of this part of the experiment. Spacing between letters refers to the distance between the centers of adjacent letters, and ranged from 0.5 to 3x the height of a lower-case letter 'x'. Some overlapping between the target and flanking letters occurred at spacings of 0.5 and 0.8x.

Trigrams were presented such that the middle letters were always centered on the background, which subtended $5.1 \times 3.8°$ at the fovea, and $8.7 \times 6.5°$ at 5° eccentricity. Each trigram was presented for 150 ms, after which the observer was required to choose from an array of 26 unfiltered lowercase letters the one that matched the target letter. An audio tone denoted each correct response. Fig. 2 shows a sample trigram.

3.2. Results

Threshold elevation plotted as a function of flanking letter frequency exhibits spatial-tuning functions, at least at small letter spacings (Fig. 3: foveal data; Fig. 4: 5° eccentricity data). The threshold elevation is substantial and peaks when the frequencies of the target and its flanking letters are similar, and diminishes as the difference between these frequencies increases. For larger letter spacings (twice x-height or greater), contrast threshold for identifying target letters is virtually unaffected by the presence of flanking letters. These properties of crowding with respect to letter spacing are *qualitatively* similar between the fovea and 5° eccentricity. To describe the spatial-tuning functions of threshold elevation at small letter spacings, we fitted each data-set, plotted on log–log axes, with a Gaussian function of the form:

$$\text{Threshold elevation} = 1 + \text{peak amplitude} \times e^{-((\text{sf} - \text{sf}_p)/\sigma)^2}$$

where peak amplitude is the elevation from the baseline (a value of 1) to reach the peak threshold elevation, sf is the center spatial frequency of the band-pass filter, sf_p is the spatial frequency at which peak threshold elevation occurs and σ is the S.D. of the Gaussian function.

To determine how the peak of the spatial-tuning functions relate to target letter frequency, we plotted in Fig. 5 the frequency at peak masking as a function of target letter frequency, for different letter spacings. Clearly, the spatial frequency at which peak masking occurs depends only on target letter frequency, but does not depend on letter spacing, nor retinal eccentricity. A power function (straight line on log–log axes) fitted to the data pooled across conditions yields a slope of 0.73 ± 0.06.

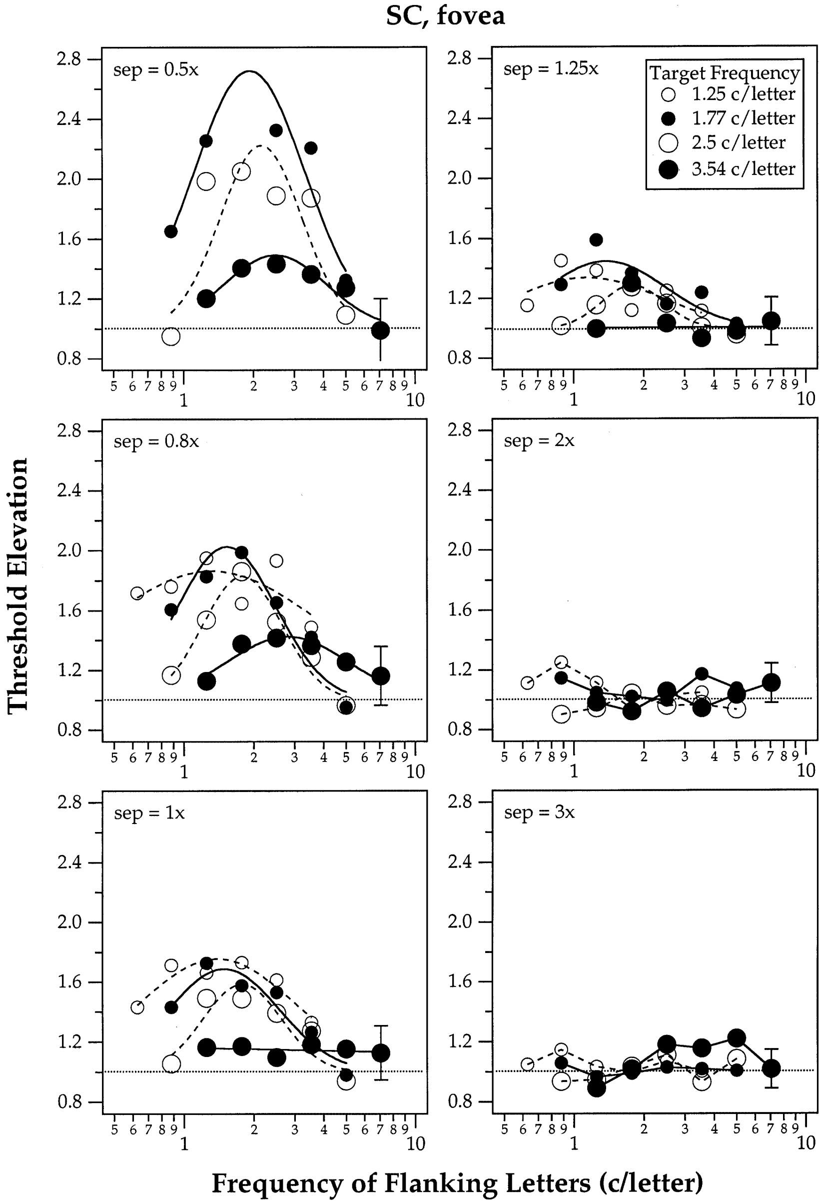

Fig. 3. Threshold elevation, defined as the contrast thresholds for identifying flanked letters normalized to those for unflanked letters, is plotted as a function of the spatial frequency of flanking letters (c/letter). Data shown were obtained from observers SC (a) and GR (b), for foveal viewing of the stimuli. Each panel includes threshold elevation measured for the 4 target letter frequencies (represented by symbols of different size and color), at the letter-separation specified in each panel. At the letter-separation of 0.5x for SC and 0.8x for GR, data for only three letter frequencies are shown, because we were unable to collect data for the target letter frequency that is not shown, due to the high baseline contrast thresholds for identifying the unflanked letters. To avoid clutter, only one error bar is shown in each panel. This error bar represents the average error across all the conditions shown in the respective panel. The fitted curve is a single Gaussian function (see text for details).

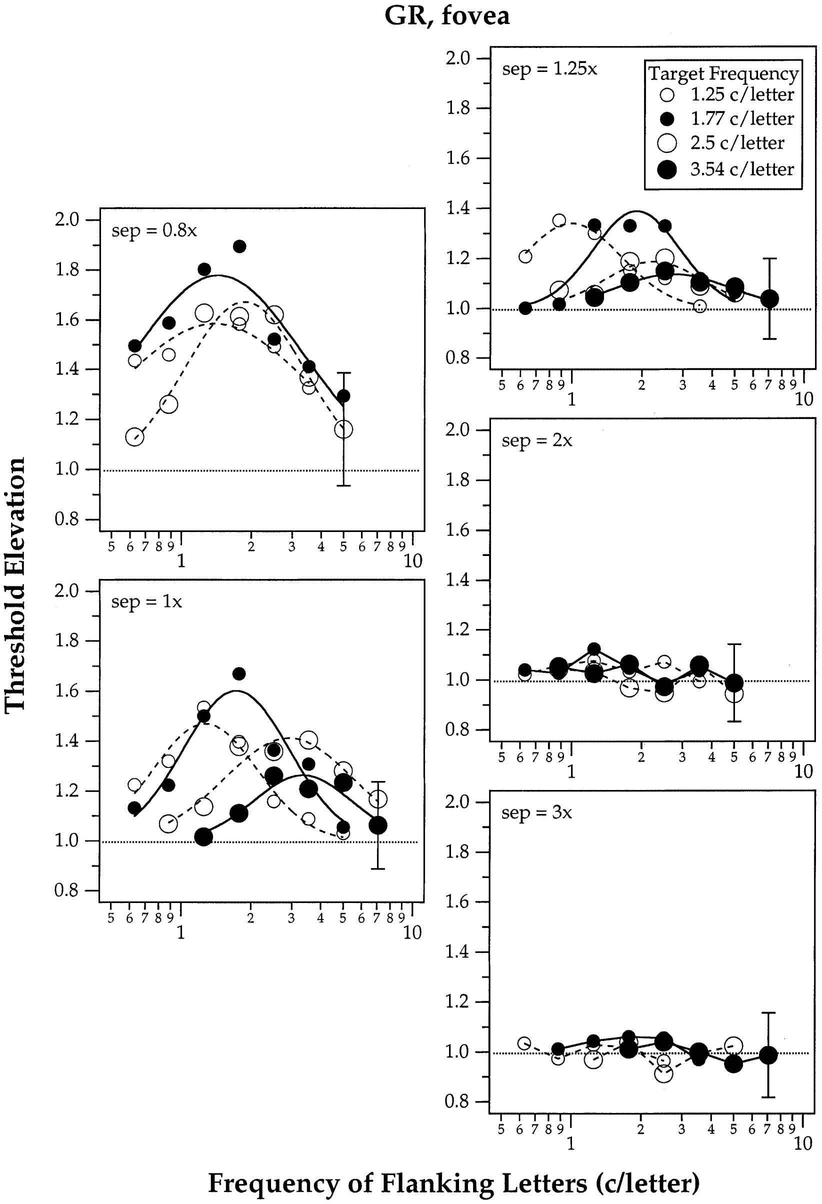

Fig. 3. (*Continued*)

To quantify the spatial-frequency specificity of crowding, we calculated the bandwidth (full-width at half-amplitude) of the spatial-tuning functions. Fig. 6 summarizes how the bandwidth of the spatial-tuning functions changes with target letter frequency, for the range of letter spacings. Consistent with the effects on the spatial frequency at peak masking, neither letter spacing nor retinal eccentricity have any systematic effect on the bandwidth of the masking function. However, even target letter frequency does not have much effect on the bandwidth of the masking functions (repeated measures ANOVA: $F_{(3,41)} = 2.93$; $P = 0.201$). Across all conditions, the bandwidths of masking functions average 2.72 ± 0.79 octaves. When analyzed separately for the two retinal eccentricities, the bandwidths are 2.77 ± 0.86 octaves at the fovea and 2.66 ± 0.56 octaves at 5° eccentricity.

Given that crowding shows spatial-frequency specificity, we expected that the lateral spread of the effect in space should be related to the spatial-frequency channel that mediates the task. Specifically, we predicted that the spatial extent of crowding should be a constant multiple of the period of the channel underlying identification of the target letter. Fig. 7 shows threshold elevation as a function of letter spacing, normalized to the spatial period associated with the peak frequency of the target letter. Only data collected with identical target and flanking letter frequencies were included in this analysis. Fig. 7 shows that the elevation in threshold becomes smaller with increased letter spacing, up to a certain letter spacing, and then threshold remains virtually unaffected by the presence of flanking letters at larger spacings. To quantify how the spatial extent of crowding varies with testing parameters, we fitted each plot of threshold elevation versus normalized letter spacing with two straight lines (on log–log coordinates) where the slope of the second line was constrained to zero. We define the intersection of the two lines as the *critical letter spacing*, i.e. the letter spacing beyond which crowding vanishes. Fig. 8 summarizes how the critical letter spacing changes with target letter frequency and eccentricity. According to our prediction, the critical letter spacing in multiples of spatial period should remain constant regardless of target letter frequency. Clearly, data in Fig. 8a are not consistent with this prediction. However, when expressed as angular subtense, the critical letter spacing becomes independent of target frequency, and is approximately 0.5 deg (1.56 times the x-height) at the fovea and 2 deg (1.82 times the x-height) at 5° eccentricity. This gives an E_2, the eccentricity at which the critical letter spacing doubles in size, of approximately 1.7 deg. The independence of the spatial extent of crowding on target frequency is inconsistent with a pure spatial-frequency basis of crowding. The implication of this finding will be addressed in the discussion.

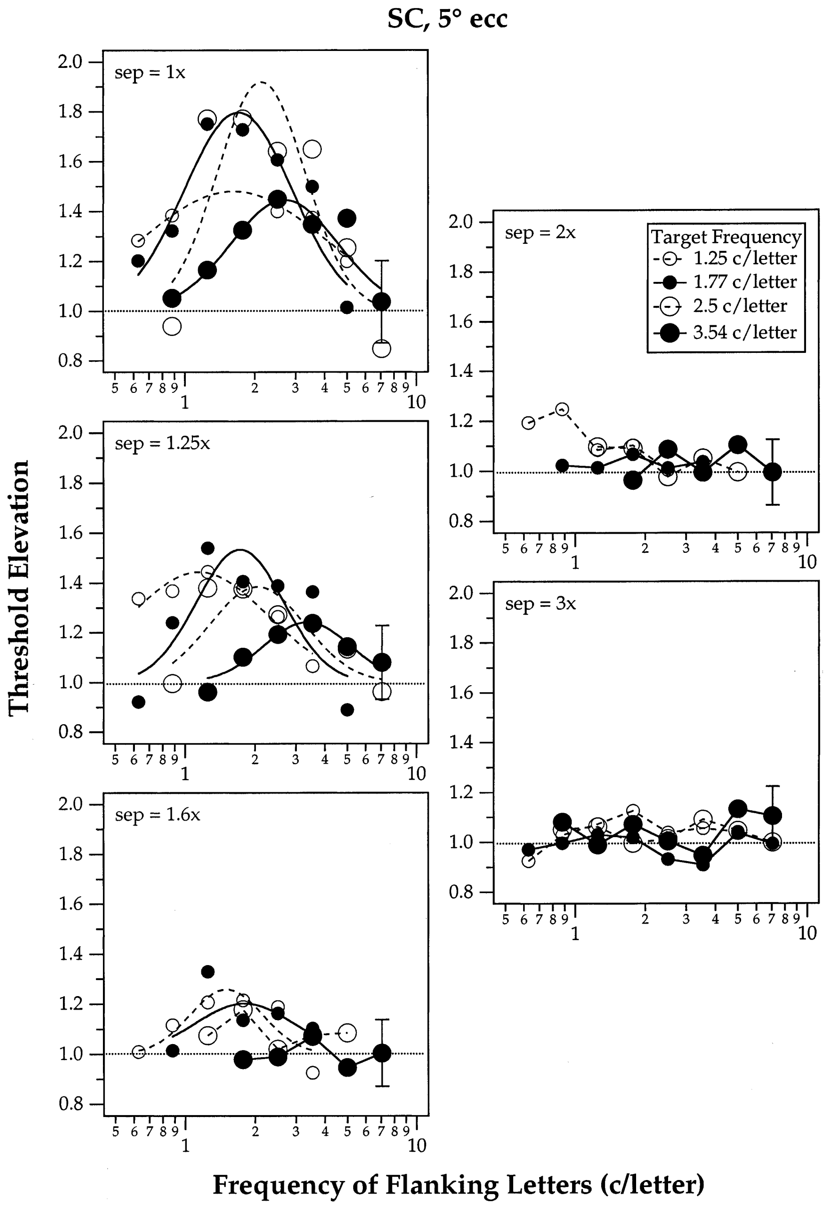

Fig. 4. Threshold elevation is plotted as a function of the spatial frequency of flanking letters (c/letter) for the same two observers SC (a) and GR (b), at 5° eccentricity. Details of the figure are as in Fig. 3.

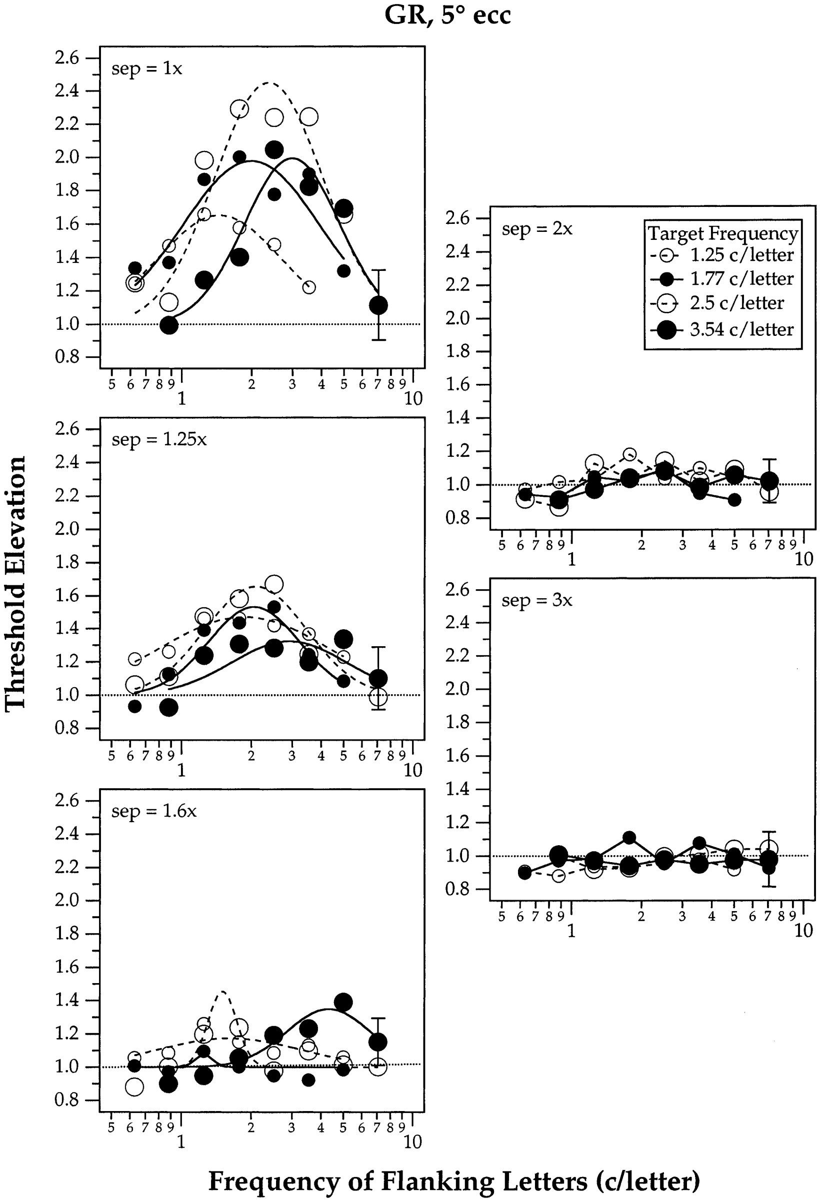

Fig. 4. (*Continued*)

4. Experiment 2: effect of contrast of flanking letters

A typical plot of threshold elevation versus masker contrast shows a ‘dipper’ effect where the masker facilitates the detection of the target at low masker contrast. At higher masker contrasts, target thresholds rise as a power function of masker contrast. This relationship is found in both sine-on-sine masking (e.g. Legge, 1979; Legge & Foley, 1980) and Gabor-by-Gabor lateral masking (Zenger & Sagi, 1996).

As our second comparison between the properties of crowding and that of masking, we examined the dependence of target thresholds on the contrast of the flanking letters. If crowding is indeed a form of masking, then we expect that crowding should show facilitation at low flanker contrast, and a power function at high flanker contrast.

4.1. Methods

Target letter frequencies were 1.25 and 2.5 c/letter. Because the facilitation effect in masking only occurs when the masker and target frequencies are essentially identical (Legge & Foley, 1980), we tested whether crowding shows facilitation by having flanking and target letters with the same spatial-frequency content. Spacing between adjacent letters in the trigrams was the same as the x-height. Testing was conducted at 5° eccentricity. Letter sizes were 2.2 deg (4x acuity). To accommodate the larger letter sizes, we changed the viewing distance to 70 cm. Accordingly, the background subtended 16.9 × 12.9°. Within any staircase, the physical contrast of the flanking letters was fixed. Ten flanking letter contrasts, ranging from 2.25 to 50%, were tested (50% was the contrast used in experiment 1).

4.2. Results

Threshold for identifying the middle letter in a trigram is unaffected by the presence of low-contrast flanking letters (Fig. 9). In other words, unlike masking, crowding does not show any facilitation effect. Above approximately 6% flanker contrast, contrast thresholds for target letters show a power-function increase, similar to masking. To estimate the exponent of the power function, we fitted each set of data with a two-line fit (on log–log axes), where the slope of the first line was constrained to zero. The slope of the second line is 0.30 for a 1.25 c/letter target and 0.13 for a 2.5 c/letter target. These exponents are much lower than most exponents reported for sine-on-sine masking studies (e.g. Legge & Foley, 1980; Legge, 1981), but are similar to exponents found in oblique masking studies (e.g. Wilson, McFarlane, & Phillips, 1983; Waugh, Levi, & Carney, 1983).

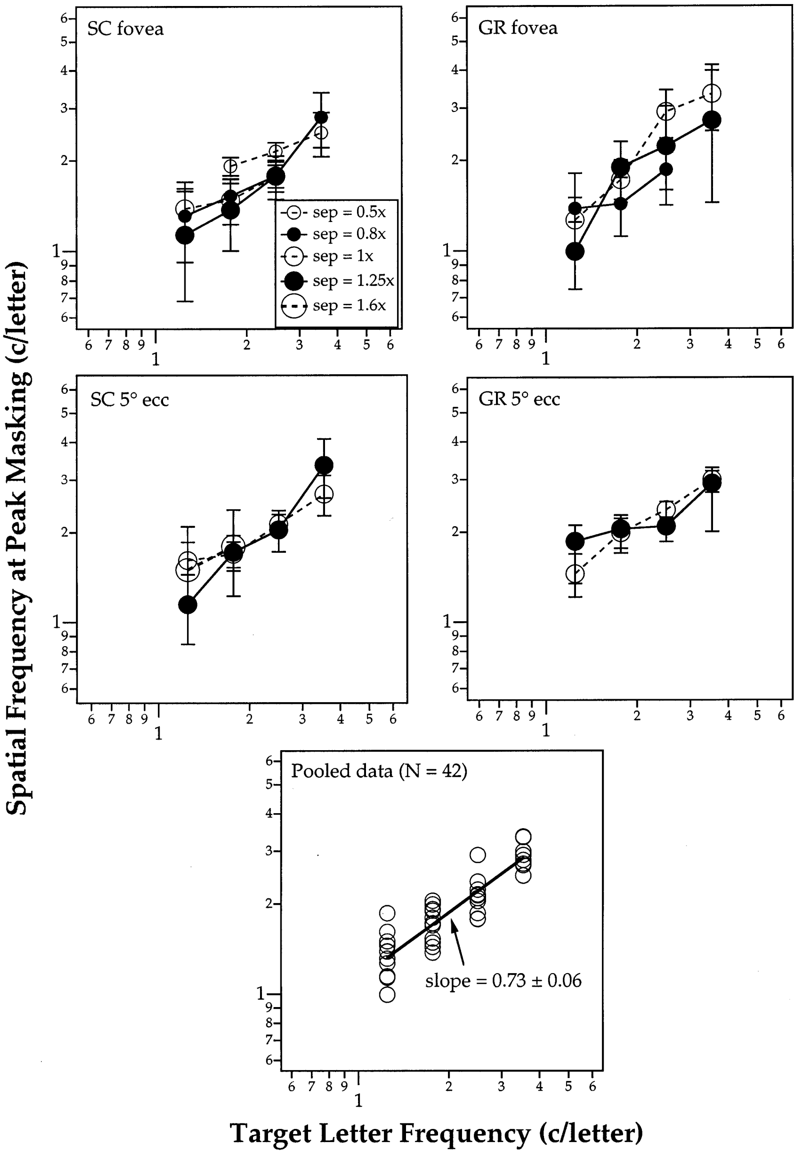

Fig. 5. Spatial frequency at peak masking (c/letter) as derived from Figs. 3 and 4 is plotted as a function of target letter frequency (c/letter), for both observers and both retinal locations (top and middle panels). Error bars represent ±1 S.E. of estimate of the peak masking spatial frequency. Data are shown for the various letter spacings (denoted by symbols of different colors and sizes). The bottom panel shows the data pooled across observers, retinal locations and letter spacings. The solid line in the bottom panel is a power function (straight line on log–log axes) fitted to the data. In general, peak masking occurs at a spatial frequency close to the target letter frequency, and does not depend on letter spacing.

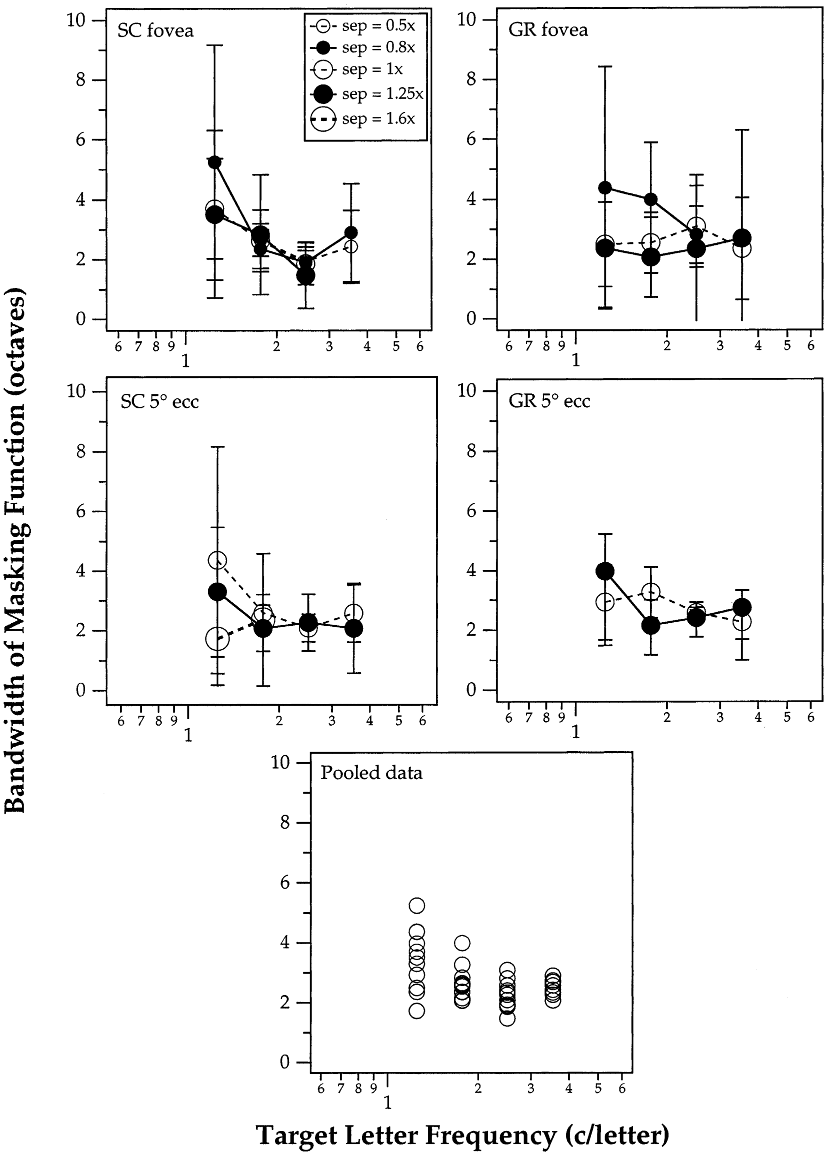

Fig. 6. Bandwidth of the spatial-tuning functions obtained from Figs. 3 and 4 (in octaves) is plotted as a function of target letter frequency (c/letter), for both observers and both retinal locations (top and middle panels). Error bars represent ± 1 S.E. of estimate of the bandwidth. Data are shown for the various letter spacings (denoted by symbols of different colors and sizes). The bottom panel shows the data pooled across observers, retinal locations and letter spacings.

5. Experiment 3: effect of contrast ratios between flanking and target letters

The monotonic increase in threshold contrast for flankers above 6% contrast is consistent with the properties of masking, but contradicts a competing hypothesis of crowding — the pattern-grouping hypothesis. There is evidence that crowding is greatest when target and mask are similar in stimulus properties such as target orientation, size, shape, contrast polarity, color and depth (Andriessen & Bouma, 1976; Nazir, 1992; Kooi et al., 1994). With respect to the stimulus property of contrast, the grouping hypothesis predicts that crowding should be maximal when the contrast of the target and its flanking letters are the same, and diminishes when the contrast of the flanking letter is either higher or lower than that of the target. To test this prediction, we yoked the contrast of the flanker and target together in fixed ratios in this experiment. According to the grouping-by-contrast hypothesis, we expected that maximal crowding should occur at a contrast ratio of 1, and less crowding should be observed for contrast ratios greater than or less than 1.

5.1. Methods

Target and flanking letter frequencies, letter sizes, letter spacing and testing eccentricity were all the same as experiment 2. The only difference is that in this experiment, the contrast of the flanking letters was yoked to that of the target letter in a fixed contrast ratio, for a given staircase. Four contrast ratios (0.25, 0.5, 1 and 1.5) were examined for a letter frequency of 1.25 c/letter. Two additional contrast ratios (2 and 2.5) were examined for a letter frequency of 2.5 c/letter.

5.2. Results

Fig. 10 shows that the increase in threshold elevation with contrast ratio also follows a power law relationship. The exponent of the power functions is 0.24, a value that falls well within the range found in experiment 2. The monotonic increase in threshold elevation with contrast ratio is consistent with crowding being a form of masking, and argues against the grouping-by-contrast hypothesis, which predicts that the threshold elevation should peak at a contrast ratio of 1.

6. Discussion

Our goal in this study was to compare several key spatial properties of crowding with those of pattern masking, in order to determine if crowding shares the same stimulus effects with pattern masking and, presumably some common underlying mechanisms.

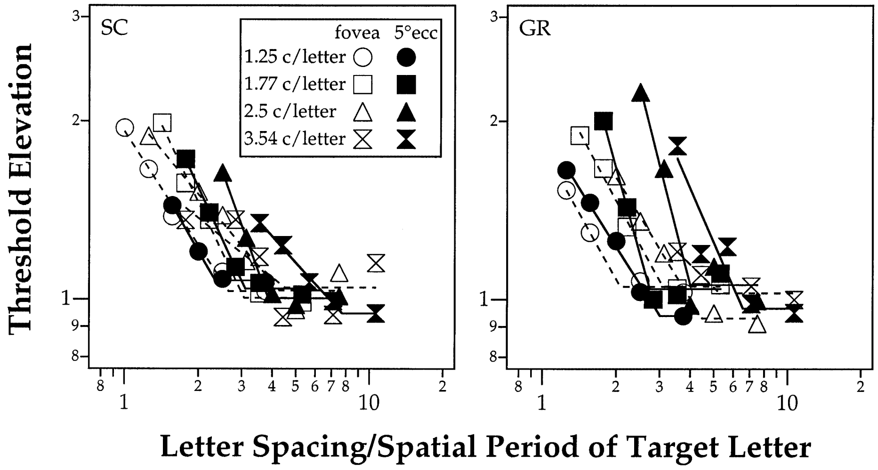

Fig. 7. Threshold elevation is plotted as a function of letter spacing, expressed as multiples of the spatial period associated with the peak frequency of the target letter, for observers SC (left) and GR (right), collected at the fovea (unfilled symbols) and 5° eccentricity (filled symbols). Data are only plotted for conditions in which the target and flanking letters were identical. Each data-set was fit with a two-line fit, as described in the text.

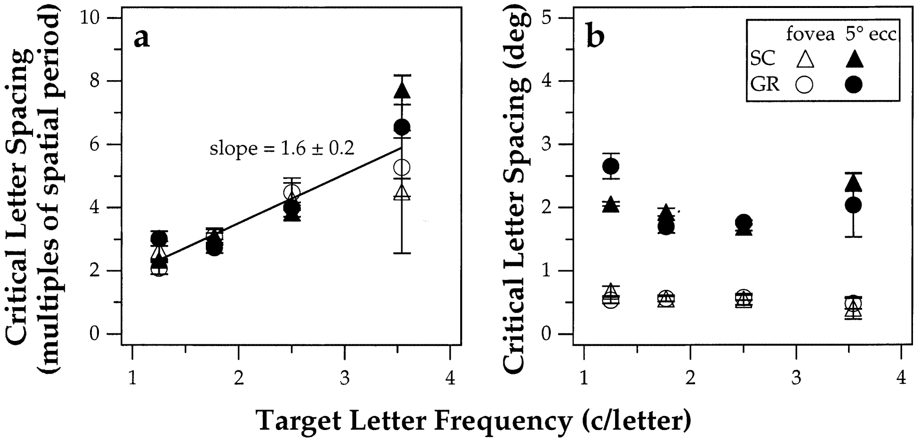

Fig. 8. Critical letter spacing, as derived from the intersection of the two-line fit in Fig. 7, is plotted as a function of target letter frequency (c/letter) for both observers and both retinal locations. When expressed as multiples of the spatial period associated with the peak frequency of the target letter (panel a), critical letter spacing increases with target letter frequency, with a slope of 1.6 ± 0.2. However, when converted to the absolute angular subtense (panel b), the critical letter spacing is more or less invariant with target letter frequency, but differs between the fovea and 5° eccentricity. Error bars represent ± 1 S.E. of estimate of the critical letter spacing.

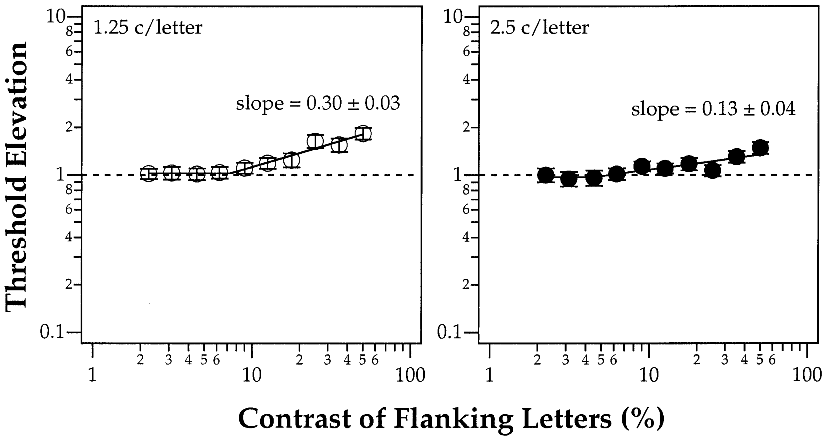

Fig. 9. Threshold elevation is plotted as a function of the contrast of flanking letters, for observer SC. The target and flanking letters had the same letter frequency, and was either 1.25 or 2.5 c/letter. Testing was conducted at 5 deg eccentricity. Letter size was 4x the local acuity. We fitted each data-set with a two-line fit (see text for details). The exponent of the second line is given in each panel. Dashed lines represent a threshold elevation of 1, i.e. no effect of the flanking letters. Error bars represent ±1 S.E.M.

6.1. Spatial-frequency specificity

Data from experiment 1 show that similar to masking, plots of threshold elevation versus flanking letter frequency show tuning functions, with the peak of the functions occurring at a flanking letter frequency close to that of the target letter.

Peak masking does not necessarily occur when the masker frequency is identical to the target frequency. In Fig. 11 we have replotted data from the studies of Legge (1979) and Wilson et al. (1983), where the frequency at which peak masking occurs is plotted as a function of target frequency. We fitted this combined data-set with a power function, the exponent of which is found to be 0.76. For comparison, we have included data from experiment 1 (gray filled symbols), where we have converted spatial frequencies from object-based to retinal-based frequencies. The good agreement between our letter-crowding data and the masking data of Legge (1979) and Wilson et al. (1983) suggest that crowding is similar to masking with respect to channel selection.

In this study, the bandwidth of the crowding functions averages 2.72 ± 0.79 octaves, and is independent of retinal eccentricity (at least for the two eccentricities tested) and target frequency. For sine-on-sine masking, where the target and the masker share the same orientation, reported bandwidth measurements ranged from 1.75 to 3 octaves (Legge, 1979; Legge & Foley, 1980; De Valois & Switkes, 1983; Switkes, Bradley, & De Valois, 1988). Apparently, parallel orientations of the target and the masker might introduce aberrant cues that could aid the subjects in detecting the presence of the target. Using an oblique masking paradigm which alleviated the problem of the relative phase between the target and the masker, Wilson et al. (1983) estimated that the bandwidth of the masking functions were approximately 2–2.5 octaves for low spatial-frequency targets (lower than 1.5 c/deg) and 1.25–1.5 octaves for target frequencies higher than 1.5 c/deg. Similar bandwidths have also been reported when the masker is not a sinusoid. Using noise maskers of 1-octave bandwidth, Stromeyer and Julesz (1972) obtained a bandwidth of masking of 1.25–1.5 octaves.

Are our estimates of the crowding bandwidth broader than those reported for sine-on-sine masking? In Fig. 12 we compared our bandwidth estimates as a function of target frequency (in c/deg), with those of Wilson et al. (1983). Also included in the plot is the 3.5 octaves bandwidth estimate of Palomares et al. (1999), for 0.3° letters flanked by Gabors. Clearly, for a com-

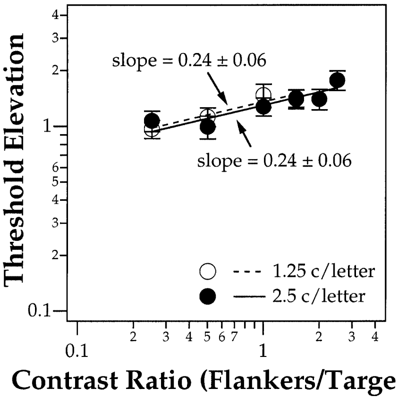

Fig. 10. Threshold elevation is plotted as a function of the ratio of contrast between flanking and target letters, for observer SC. The target and flanking letters had the same letter frequency, and was either 1.25 (unfilled symbols and dashed line) or 2.5 (filled symbols and solid line) c/letter. Testing was conducted at 5 deg eccentricity. Letter size was $4x$ the local acuity. The grouping-by-contrast hypothesis predicts that crowding should be strongest when the contrast of the target and flanking letters are equal (i.e. a ratio of 1); and decreases in strength when the flanking letter contrast is either lower or higher than the target letter contrast. Error bars represent ±1 S.E.M.

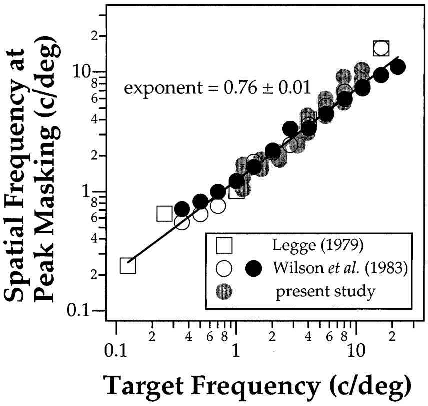

Fig. 11. Spatial frequency at peak masking is plotted as a function of the target frequency for the studies of Legge (1979) and Wilson et al. (1983). The two symbols representing the data from Wilson et al. are data from their two subjects. A power function fitted to the combined data set yields an exponent of 0.76. For comparison, data from our experiment 1 were included as gray filled symbols (data replotted from Fig. 5 bottom panel).

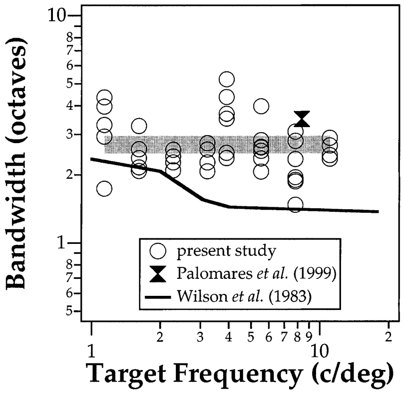

Fig. 12. Bandwidth of the crowding functions (replotted from Fig. 6 bottom panel) is plotted as a function of target frequency, in c/deg. The shaded region represents the 95% confidence interval of our bandwidth measurements. For comparison, bandwidth estimates from two other studies are included: Palomares et al. (1999), where letters were flanked by Gabors; and Wilson et al. (1983) where D6 or DOG stimuli were masked by sinewave grating.

parable spatial frequency, the bandwidth for crowding is broader than that for sine-on-sine masking.

There are at least two major differences between our crowding study and that of Wilson et al. (1983) (or other sine-on-sine masking studies in general). First, for most conditions, the target and the flanking letters were not superimposed in our study. Second, our letter stimuli are more complicated than sinusoids in their spatial-frequency, phase and orientation distributions. Using broad-band line stimuli, Waugh et al. (1993) and Levi and Waugh (1994) showed that the bandwidth for line detection in the presence of 1-octave noise maskers is about 3–3.5 octaves. This supports the notion that the broad bandwidth could be a consequence of using spectrally complicated stimuli.

6.2. Spatial extent of crowding

We found that the spatial extent of crowding is independent of target frequency. This finding is inconsistent with the result of Polat and Sagi (1993), who reported that peak masking for laterally displaced Gabor stimuli scales with target frequency, and occurs at a target-flank separation equivalent to one spatial period of the target. The discrepancy between our study and that of Polat and Sagi (1993) implies that the mechanisms underlying crowding and masking are not identical.

Our estimate of the spatial extent of crowding (approximately 0.5 deg in the fovea, and 2 deg at 5° eccentricity) gives an E_2, the eccentricity at which the critical letter spacing doubles in size, of ≈ 1.7 deg, which is substantially greater than the value of 0.34 as reported by Toet and Levi (1992). The discrepancy in these E_2 values could be due to the larger extent of crowding we found in the fovea (0.5 deg in this study vs. 0.06 deg in Toet & Levi (1992)). Note that, however, with respect to the letter size, the spatial extent is virtually identical in the two studies — 1.56x in this study vs. 1.44x in Toet and Levi (1992). This scaling of the extent of crowding with letter size in the fovea is consistent with the report of Levi (2000) in which the extent of crowding is found to be approximately 1.8x the target size.

In the periphery, the spatial extent of crowding has been reported to fall within the range of 0.1x to 0.5x eccentricity (Ecc). We found in the present study that the extent of crowding subtends approximately 2 deg at 5° eccentricity, or, 0.4x Ecc. Table 1 summarizes the extent of peripheral crowding as reported in the literature. An examination of the studies cited here suggests that the 0.5x Ecc relationship is usually found in studies that involved characters as both the target and the flanks (e.g. the present study; Bouma, 1970; Kooi et al., 1994). In contrast, the 0.1x Ecc relationship is usually found in studies in which the flanks are simple contours such as bars or lines, instead of the more complicated characters (Wolford & Chambers, 1984; Levi, 2000). Whether or not this speculation is true remains to be tested by future studies.

6.3. Lack of facilitation at low flanker contrast

Both sine-on-sine masking and Gabor-by-Gabor lateral masking demonstrate a facilitatory region where the threshold for detecting a target is reduced in the presence of low contrast maskers/flankers. Using low-contrast flanking letters, we did not find such a facilitatory effect for crowding. Instead, at low flankers' contrast, threshold elevation is independent of the flanking letter contrast. This threshold-independent region is also observed in pattern masking when the

Table 1
Extent of spatial interaction in peripheral vision as reported in previous studies

Study	Target	Target size	Flanks	Task	Eccentricity	Extent (multiples of eccentricity, Ecc)
Bouma (1970)	25 Lower-case letters	0.22°	Two lower-case letter ‘x’, one on either side of target	Letter identification	1–10.5°, Right or left visual fields	$0.5x$ Ecc
Wolford and Chambers (1984)	Square with a gap on one side	0.2°	Four bars ($0.2 \times 0.04°$), one on each side of target	Identify the position of the gap	2, 5°, Right or left visual fields	$0.12x$ Ecc at 2° ecc; $0.16x$ Ecc at 5° ecc
Strasburger et al. (1991)	10 Digits (0–9)	0.05–1.4°	Two digits, one on either side of target	Digit identification	2–16° Left visual field	$0.3x$ Ecc
Toet and Levi (1992)	Letter ‘T’	$1.5x$ Larger than the single-letter resolution threshold	Two Ts, one on either side of target (horizontal, vertical or oblique directions)	Identify the orientation of the letter ‘T’	2.5–10°, Inferior, nasal and inferior-nasal visual fields	Tangential to the fovea: $0.1x$ Ecc; radial to the fovea: $0.5x$ Ecc
Kooi et al. (1994)	Letter ‘T’ (varying parameters such as contrast polarity, color)	0.5°	Four Ts, similar to target stimulus, one on each side of target	Identify the orientation of the letter ‘T’	10° Inferior visual field	$0.1x$–$0.5x$ Ecc, depending on target parameters
Levi (2000)	Letter ‘E’ made up of 17 Gabor patches	Defined as the SD of Gabor, ranges from 0.5–25′	Four ‘bars’, each comprised of five Gabor patches	Identify the orientation of the letter ‘E’	5 And 10° inferior visual field	$0.1x$ Ecc
Present study	26 Lower-case letters	1.1° (Before filtering)	Two letters, one on either side of target	Letter identification	5° Inferior visual field	$0.4x$ Ecc

target and masker are out of phase (Foley, 1994; Zenger & Sagi, 1996).

Indeed, Zenger and Sagi (1996) found that facilitatory regions are only observed when the target and masker are of the same phase. Because letters have complex phase spectra, the odds that a target letter and its flanking letters share the same phase relationship are extremely low. This may explain why a facilitatory region is not observed in letter-by-letter crowding. Thus, the absence of a facilitatory region in our data does not necessarily imply that the underlying mechanisms of crowding and pattern masking are different.

6.4. *Effect of contrast of flanking letters*

In the presence of high-contrast maskers, the exponent of the threshold versus contrast function for sine-on-sine masking varies between 0.5 to 1, depending on various factors such as spatio-temporal properties (Burbeck & Kelly, 1981; Pantle, 1983; Lehky, 1985; Boynton & Foley, 1999), relative orientation of the target and the masker (Foley, 1994), and the novelty of the masker (Swift & Smith, 1983). Parallel studies in Gabor-by-Gabor lateral masking are scarce. The two studies that we knew of yielded exponents of 0.42 (Levi, unpublished data) and 0.53 (Zenger & Sagi, 1996). These exponents are all higher than those found in the present study, which fall within the range 0.13–0.3 (Figs. 9 and 10).

A plausible factor accounting for the low exponent found in crowding, compared with masking, is the relationship in phase or orientation between the target and the flankers/maskers. There is evidence that for superimposed masking, exponents as low as 0.25–0.35 are obtained when the masker is tilted with respect to the orientation of the target. This has been demonstrated for detection of D6 patterns in the presence of a sinewave mask (Wilson et al., 1983; Phillips & Wilson, 1984), line detection and Vernier discrimination in the presence of a noise mask (Waugh et al., 1993; Levi & Waugh, 1994). Table 2 summarizes the exponents of the threshold versus contrast functions reported in the literature, for different target and masker characteristics and different psychophysical tasks.

Another plausible explanation for the low exponent found in crowding is the difference in task. In our study, the task of the observers was to identify the target letter, rather than detecting a target, or discriminating which target contains an incremental contrast as in the case of pattern masking. Letter resolution tasks generally are not highly contrast-dependent (Ludvigh, 1941; Chung, 1995). Therefore it is not surprising that the exponent of the threshold versus contrast function is lower in letter-by-letter crowding than in pattern masking. Similar low exponents have also been reported in a recent study examining crowding, where different stimuli and paradigms were used (Yssaad-Fesseller & Levi, 2000).

Recently, Pelli and his co-workers, also using letter stimuli to study crowding, reported an exponent of 2 for their threshold versus contrast functions (Palomares et al., 1999). Subsequently, they demonstrated that the value of the exponent depends on the target-flank distance, such that a higher exponent is obtained when the target-flank distance is small (Pelli & Palomares, 2000). In experiments 2 and 3, the target-flank separation was the same as the x-height, corresponding to 2.2 deg. This separation was relatively large in comparison with those examined by Pelli and Palomares. For their largest separation of 1.5 deg, they found an exponent of approximately 0.4, which is in good agreement with the exponents found in our study.

6.5. *Grouping-by-contrast hypothesis of crowding*

According to the grouping-by-contrast hypothesis, crowding should be maximal when the contrast of the target and that of the flanking letters are the same, and decreases in strength when the contrast of the flanking letters is either higher or lower than that of the target. Our results did not confirm this prediction. Instead, we observed a monotonic increase in threshold elevation with the contrast ratio between the flanking and the target letter (Fig. 10).

Our data are consistent with those of Kooi et al. (1994), who examined the role of similarities and differences on the spatial extent of crowding. For most of the stimulus parameters they examined, including shape, color and contrast polarity, they demonstrated that crowding is maximal when the target and flanking letters share identical stimulus parameters. However, for the parameter of contrast, they tested all four combinations of high (83%) and low (29%) contrast for the target and flanking letters, but failed to show that crowding is maximal when the target and the flanking letter contrast were the same. Their contrast data, together with ours, imply that crowding is not a grouping-by-contrast phenomenon.

6.6. *Crowding versus masking*

By comparing several key properties of crowding with those of masking, we found that crowding is qualitatively similar to masking in several ways, such as spatial-frequency specificity, channel-selection characteristics for detecting and identifying the target, and contrast-response at high flanker contrast. There exist some quantitative differences among these properties, however. For instance, the bandwidth of the crowding function is broader than that of masking, and the exponent of the threshold versus contrast function is generally shallower than that of masking. Some of these

Table 2
Exponents of the threshold vs. contrast functions reported in previous studies

Study	Task	Target	Mask	Superimposed masking?	Orientation of mask relative to target	Exponent estimate
Legge and Foley (1980)	Detection	Grating	Grating	Yes	Parallel	0.6 (Average)
Legge (1981)	Contrast discrimination	Grating	–	–	–	0.6–0.7
Legge and Kersten (1983)	Contrast discrimination	Grating	–	–	–	0.51–1.17
Pantle (1983)	Detection	Grating	Grating	Yes	Parallel	0.62 (Average); (for abrupt onset-offset and steady-state targets)
Swift and Smith (1983)	Detection	Grating	Grating	Yes	Parallel	0.5–1.0
Wilson et al. (1983)	Detection	D6/DOG	Grating	Yes	Masker tilted at 14.5°	0.24–0.56
Phillips and Wilson (1984)	Detection	DOG	Grating	Yes	Masker tilted at 15°	0.40–0.55
Zenger and Sagi (1996)	Detection	Gabor	Gabor	No	Parallel	0.53 (Our estimate)
Levi (unpublished)	Detection	Gabor	Gabor	No	Parallel	0.42
Waugh et al. (1993)	Detection	Line	Noise	Yes	Masker tilted at 10°	0.29–0.35
Levi and Waugh (1994)	Detection	Line	Noise	Yes	Masker tilted at 10°	0.26–0.33
Waugh et al. (1993)	Discrimination	Vernier	Noise	Yes	Masker tilted at 10°	0.27–0.43
Levi and Waugh (1994)	Discrimination	Vernier	Noise	Yes	Masker tilted at 10°	0.33–0.39
Present study	Identification	Letter	Letters	No	Varied	0.13–0.3
Pelli and Palomares (2000)	Identification	Letter	Letters	No	Varied	0 (Target-flank separation = 1.5°) to 2 (target-flank separation = 0.32°)
Yssaad-Fesseller and Levi (2000)	Identification	E-like patterns made of Gabor patches	'Bars' made of Gabor patches	No, target-flank distance = 0.5°	Same or orthogonal	0.4–0.59 (Same orientation); 0.3–0.75 (orthogonal orientation)

discrepancies could be attributed to the difference in task, and the characteristics of the stimuli (phase, orientation, etc.). However, the finding that the spatial extent of crowding is independent of letter frequency is inconsistent with the spatial properties of masking.

Current models of spatial-frequency masking involve a first-stage spatial-frequency linear filtering process, followed by a divisive inhibitory mechanism (Foley, 1994). There is evidence that the divisive inhibitory process gives rise to broad spatial-frequency tuning (Ross & Speed, 1991), and a shallow exponent of the threshold versus contrast function (Foley, 1994). Also, a facilitatory region is not observed in the divisive inhibitory process (Foley, 1994). All of these properties found in the divisive inhibitory process are consistent with our findings in crowding.

Drawing from what we understand about masking, we postulate that crowding and masking are likely to share the same first stage linear filtering process, and perhaps a *similar* second-stage divisive inhibitory process, with the additional property that this second-stage process in crowding pools information over a spatial extent that varies with eccentricity. In peripheral vision, this pooling may occur over an extent up to about half the eccentricity.

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