



The extent of crowding in peripheral vision does not scale with target size

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Abstract

Identifying a target is more difficult when distracters are present within a zone of interaction around the target. We investigated whether the spatial extent of the zone of interaction scales with the size of the target. Our target was a letter T in one-of-four orientations. Our distracters were four squared-thetas in one-of-two orientations, presented one in each of the four cardinal directions, equidistant from the target. Target–distracter separation was varied and the proportion of correct responses at each separation was determined. From these the extent of interaction was estimated. This procedure was repeated for different target sizes spread over a 5-fold range. In each case, the contrast of the target was adjusted so that its visibility was constant across target sizes. The experiment was performed in the luminance domain (grey targets on grey background) and in the chromatic domain (green target on equiluminant grey background). In the luminance domain, target size had only a small effect on the extent of interaction; these interactions did not scale with target size. The extents of interaction for chromatic stimuli were similar to those for luminance stimuli. For a fixed target visibility, decreasing the duration of the stimulus resulted in an increase in the extent of interaction. The relevance of our findings is discussed with regard to a variety of proposed explanations for crowding. Our results are consistent with an attention-based explanation for crowding.

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1. Introduction

Locating an object in a cluttered environment is more difficult than when there are no other objects nearby. In general, a target is more difficult to either find or identify if distracters are presented in its vicinity. The deterioration of our ability to identify targets in the presence of distracters is referred to as “crowding”,¹ “contour interaction”, or “spatial interaction” (Bouma, 1970; Ehlers, 1936, 1953; Flom, Weymouth, & Kahneman, 1963; Jacobs, 1979; Stuart & Burian, 1962). The effects of crowding are small in normal foveal vision, but are

noticeably larger in amblyopic foveal vision and in normal peripheral vision (Levi, Klein, & Aitsebaomo, 1985; Toet & Levi, 1992). The mechanisms responsible for crowding remain poorly understood, particularly in peripheral vision. In this study we psychophysically examine several potential mechanisms for the phenomenon of crowding in peripheral vision.

For stimuli consisting of targets and distracters, the effects of crowding are negligible when the target–distracters separation is very large, but become more pronounced when the separation is reduced. At some intermediate separation, the distracters begin to hinder the identification of the target, provided the identification of the target is not a trivially easy task. We define this separation to be the *extent of spatial interaction*, the centre-to-centre distance between target and distracters.² For smaller target–distracter separations identification performance will be significantly hampered, but not for larger separations. With appropriately chosen

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¹ Recent papers have attempted to separate the spatial interactions described here into masking and crowding (the residual effects after masking has been accounted for), e.g. Levi, Hariharan, and Klein (2002) and Levi, Klein, and Hariharan (2002). In this paper we use the terms spatial interactions and crowding interchangeably. Where we refer to the masking component of the spatial interactions, it is explicitly stated.

² See Methods section for a quantitative definition of the *extent of interaction*.

target and distracters, the extent of interaction can extend as far as half the retinal eccentricity of the target (Bouma, 1970; Kooi, Toet, Tripathy, & Levi, 1994; Toet & Levi, 1992).

In the current study we investigate how the extent of interaction varies with target size. We focus on peripheral vision, because that is where the effects of crowding are more pronounced. Most previous studies measured the effects of crowding only for a fixed target size at each retinal eccentricity. At each eccentricity, the target size was selected such that a particular level of performance (say 90% correct) was obtained for identifying the maximum contrast target. Since most of these studies provide data for only one target size at each eccentricity, the influence of target size on the extent of spatial interaction cannot be inferred from them. But this relationship is important as it constrains the potential explanations for crowding as discussed below.

Several potential explanations have been proposed for the crowding phenomenon. These explanations fall in three broad categories: neuronal, computational and attentional. Listed below are several explanations, grouped by category, and their predictions for the consequences of varying target size.

1.1. Neuronal proposals

These proposals are based on the physiology of receptive fields and how they vary with target size and/or eccentricity.

(1) One could postulate a neuron with a large receptive/perceptive field having a central excitatory region and a surrounding inhibitory region. The target must fall within the excitatory region in order to be identified. Distracters within the inhibitory region hinder the identification of the target. If the target size were increased, then a neuron with a larger receptive/perceptive field would be required to detect the target. This larger receptive field would have larger excitatory and inhibitory regions. Increasing the target size should increase the extent of interaction proportionately.

(2) Long-range horizontal connections that extend over distances up to 6–8 mm have been reported in layers II and III of primate and cat primary visual cortex (Callaway & Katz, 1990; Gilbert, 1992; Gilbert & Wiesel, 1979, 1983; Martin & Whitteridge, 1984). These are the axon collaterals of pyramidal cells. These long-range horizontal connections connect neurons with similar response properties, in particular similar spatial frequency and colour preferences (Gilbert & Wiesel, 1989). Since crowding is greater when target and distracters have similar characteristics (Kooi et al., 1994; Nazir, 1992), it is plausible that crowding is mediated by these long-range horizontal connections in primary visual cortex (Gilbert, 1992; Gilbert, Hirsch, & Wiesel, 1990; Gilbert & Wiesel, 1990; Hirsch & Gilbert, 1991; Tripa-

thy & Levi, 1994). From this viewpoint, the cortical extents of the horizontal connections when projected on to the visual field determine the extents of interaction; the area of interaction should include the area covered by the target itself and all regions within some fixed distance (determined by the horizontal connections) of the target's outer boundary. As the target size increases, the spatial extent of interaction should then scale directly with target size. A related proposal involves the cortical magnification factor; specifically, the extent of crowding represents a fixed cortical distance at any eccentricity, although now not limited to the 6–8 mm characteristic of the horizontal connections. This is supported by Levi et al. (1985) and Levi and Klein (1985) for vernier stimuli with flanking bars and not supported by Strasburger, Harvey, and Rentschler (1991) who used numeric characters for targets and distracters. Again, since the range of interaction is given by this fixed distance from each point on the target, the extent of interaction will scale directly with the target size.

(3) A similar idea relies on perceptive hypercolumns or psychophysical spatial processing modules (Barlow, 1981; Westheimer, 1981; Levi et al., 1985) which are fixed in location. Levi et al. (1985) proposed that for vernier stimuli, crowding occurred either within a perceptive hypercolumn or across adjacent hypercolumns. According to Levi et al. (1985), the perceptive hypercolumn size is consistent with the projection to the classic V1 hypercolumns (Hubel & Wiesel, 1977) and would span about 1° at 9.2° eccentricity. Since the largest target size in our experiment is 1.85° , this model would predict that targets, once they were greater than about 1° in size, would cover an increasing number of hypercolumns. The spatial extent of interaction should increase with target size above 1° .

1.2. Computational proposal

This proposal is based not on the receptive fields that encode the stimulus but on the strategy for combining information across fields.

(4) Crowding is a consequence of the compulsory pooling of local orientation signals, with access to the information content in the individual orientation signals being compromised (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). Seen in this light, the extent of interaction probably reflects the spatial extent over which orientation information is pooled. If information is always pooled over a fixed region of space, then the extent of interaction should be independent of target size. On the other hand if larger targets invoke integration over larger areas, then the extent of interaction should increase with target size.

(5) Several studies have investigated spatial frequency based masking explanations for crowding. While such

explanations have yielded reasonable predictions for crowding in foveal vision (Hess, Dakin, & Kapoor, 2000a; Levi, Hariharan, & Klein, 2002; Levi, Klein, & Hariharan, 2002), spatial frequency based contrast masking has generally failed to provide an adequate explanation for crowding in peripheral vision (Chung, Levi, & Legge, 2001; Hess, Dakin, Kapoor, & Tewfik, 2000b; Levi, Hariharan, & Klein, 2002; Levi, Klein, & Hariharan, 2002; Palomares, LaPutt, & Pelli, 1999). A simple spatial frequency based approach would predict that if the size of the target is scaled, the extent of spatial interaction should proportionately increase. However, any spatial frequency based approach cannot explain the gross anisotropy seen in the extent of crowding in peripheral vision (Bouma, 1970; Toet & Levi, 1992) and the difference in the extents of interaction in the upper and lower field (He, Cavanagh, & Intriligator, 1996); to provide a satisfactory explanation, a spatial frequency approach would need to take into account anisotropies in cortical magnification. The failure of simple masking explanations for crowding in peripheral vision has prompted the idea of a two-stage process. The first is a feature identification stage that is shared by both masking and crowding mechanisms. The second is a feature integration stage, involving divisive inhibition along the lines of Foley (1994). Its operation is similar for both crowding and masking, but extends over a larger extent in the case of crowding (Chung et al., 2001; Pelli & Palomares, 2000; Levi, Hariharan et al., 2002; Levi, Klein et al., 2002). The extent of crowding would no longer be linked to the spatial frequency of the stimulus but to the spatial extent over which the divisive inhibition is pooled. However, the two-stage process has not been elaborated in sufficient detail to permit quantitative predictions for the effect of target size on the extent of interaction.

1.3. Attentional proposals

These proposals are based on the spatial and capacity limits of the high-level mechanisms that select the target information.

(6) Crowding represents the limits of attentional acuity which is much coarser than visual acuity (Intriligator & Cavanagh, 2001). If items are spaced more closely than the smallest possible region of attentional selection then more than one item will be selected as a group and access to the individual identities is not possible. If the target is the only item within the selection region, then it can be identified until it is too small to be visually resolved. The smallest available region of selection scales with eccentricity and moves to be centred on the target. As long as the target is smaller than this smallest selection region, target size should not affect the spatial extent of interaction in the crowding task. If the target is bigger than the smallest selection size, the

spatial extent of interaction will increase directly with the target size.

(7) Crowding represents an interaction between the attentional capacity and perceptual load. Lavie and Tsai (1994) propose that in the search paradigm, the amount of attentional resources allocated cannot be less than the total attentional capacity available. Under low load conditions there are surplus attentional resources available beyond that required for the task at hand. These resources are compulsorily used to process any neighbouring distracters. Under high load conditions, no surplus resources are available for processing the distracters. A similar mechanism could operate for crowding. If we presume that the visibility of the target determines the perceptual load, then as long as the visibility remains fixed, the extent of interaction, which is presumably a measure of the surplus capacity available, should remain fixed, regardless of the target size.

These proposals make three types of predictions. First, proposal 7 based on attentional capacity suggests that the extent of interaction is fixed no matter what the target size (at least for crowding tasks of constant difficulty).

Second, proposals 3 and 6 assume a fixed size for the mechanism which mediates the lateral interaction so there would be no effect of target size at least until the target is comparable in size to the region of analysis (a perceptive hypercolumn, or an attentional receptive field). For targets that extend beyond the size of a single region of analysis, the spatial extent of interaction will recruit further regions of analysis and increase in step with target size. Beyond the critical size, a 1° increase in target size would trigger 1° increase in the spatial extent of interaction. The critical size (about 1°) for the perceptive fields of Levi et al. (1985) is smaller than the largest target, so an increase in spatial extent of interaction would be expected in our experiment over the larger target sizes. The critical size for the attentive fields is larger (about 2°) and no increase is expected in the range of sizes tested in our experiment.

Proposals 1 and 2 suggest an increase in the size of the area of interaction that is proportional to the target size over all target sizes. Finally, for proposal 5, the extent of interaction would depend on our assumptions regarding the spatial extent over which divisive inhibition extends at the second stage.

Thus, knowing the relationship between target size and the extent of spatial interaction in a crowded display can provide valuable insight into the mechanisms responsible for crowding. Is the relationship proportional to target size or is it flat? Does it show a slope of one but only for targets larger than a certain size? If so, what is that critical size? In this study we systematically investigate this relationship. Strasburger et al. (1991) have previously addressed a similar question: Does the target size influence the extent of interaction? They measured

in central and peripheral vision, contrast thresholds for identifying numeric character targets in the presence of numeric character distracters. One of their main findings was that target size had an influence on the extent of interaction. In addition they showed that in peripheral vision, a critical parameter that affected the identification of the target was the target–distracter separation expressed as an absolute visual angle, not as a relative measure expressed in multiples of target size. However, since their extent of interaction was not defined in quantitative terms, the actual relationship between extent of interaction and target size is not obvious. In the current study we define the extent of interaction quantitatively and estimate this directly so that the relationship between target size and extent of interaction can be made more explicit. More recently, Levi, Hariharan et al. (2002) investigated the same question in peripheral vision using stimuli and methods very different from ours and obtained results substantially different from ours. The differences between the two studies are taken up in the Discussion section.

We also evaluated the effect of target size for chromatic tests. The rationale was that many aspects of early neuronal processing such as receptive field size and horizontal connections should be different for tests defined by luminance and tests defined by colour. The chromatic pathways cover a lower range of spatial frequencies with an upper limit of 10–12 cycles per degree (Mullen, 1984). The spatial extent of interaction may be larger for chromatic stimuli if the interaction is mediated by the spatial properties of early receptive fields.

Our target was the letter T in one of four orientations. Our distracters were squared-thetas in one of two orientations. In one experiment, the stimuli were defined in the luminance domain (grey stimuli on grey background) and in the other they were defined in the chromatic domain (green stimuli on an equiluminant grey background). We varied target size, ensuring that the resulting targets were all equally visible in terms of proportion of times the isolated target was identified correctly; visibility was equated by reducing contrast or presentation duration when target size was increased. For different target sizes at a fixed retinal eccentricity we measured the extent of interaction. Our main finding was that the extent of interaction does not scale with target size; the effect of target size on the extent of interaction was minor.

2. Methods

2.1. Apparatus

The stimuli were generated by a Power Macintosh 7500 and displayed on a Sony E400 monitor using Vision Shell stimulus generating software. The screen

resolution was 1024 (H) \times 768 (V) pixels. Screen dimensions were 34 \times 25 cm, roughly subtending 36.9 \times 27.5° at a viewing distance of 51 cm (each pixel subtended \approx 2.22 arc min in the horizontal and vertical directions). The screen had a frame rate of 75 Hz; frame duration was 13.33 ms.

The experiment was conducted in a dark room with most of the illumination being provided by the monitor screen. The screen background luminance was either 31.0 cd/m² (PC) or 42.3 cd/m² (ST). Chin and forehead rests stabilised the observer's head.

The two authors with corrected-to-normal visual acuity and normal colour vision participated as observers. Observers binocularly fixated the spot presented on the monitor screen and responded to stimuli centred at an eccentricity of 9.2° in the lower visual field.

2.2. Experimental procedure

The stimulus is shown in Fig. 1. Each trial had a target presented either in isolation (Fig. 1(a)) or in the presence of 4 distracters (Fig. 1(b)). The target consisted of a letter 'T' presented in one of four cardinal orientations. The distracters consisted of four squared-thetas, one in each cardinal direction with respect to the target, with each being equidistant from the centre of the target. The distracters could be in one-of-two orthogonal orientations.³ On trials with distracters, the width and height of each distracter matched that of the target. The target–distracter separation was varied between trials. Target (and distracter) size was fixed within a block and varied between blocks. The observer's task was to report the orientation of the target T on each trial by pressing one of four keys.

The method of constant stimuli was used. Each trial was either without distracters, or had distracters with one-of-seven target-to-distracter separations. Each block consisted of 64 trials: eight trials without distracters and 56 trials equally distributed among the seven target–distracter separations. Trials with isolated targets and trials with distracters were randomly interleaved within a block. The seven separations were pre-selected so that the observer's performance, i.e. the proportions of correct responses at the different separations, covered a

³ Our choice of target and distracters was driven by the following considerations:

- (i) a similar target has been effective for measuring spatial interactions in peripheral vision (Kooi et al., 1994; Toet & Levi, 1992),
- (ii) distracters are more effective in masking the target, the more similar they are to the target in size, shape and colour (Nazir, 1992; Kooi et al., 1994),
- (iii) the squared-theta distracters were as effective as T-distracters with regard to interfering with the identification of the target (presumably because they share all of the contours of a T),
- (iv) if T-distracters had been used instead, observers might have occasionally mistaken one of the distracters for the target.

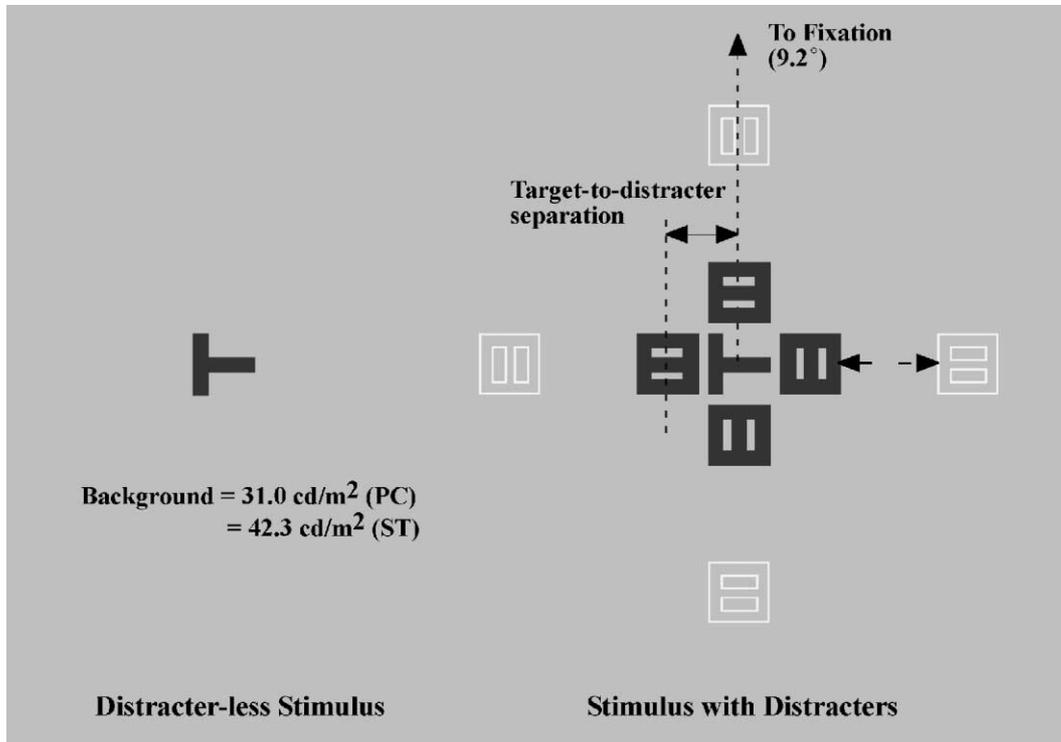


Fig. 1. The stimulus used in the experiment. The stimulus could either be (a) an isolated target (a T in one-of-four possible orientations), or (b) a target surrounded by four distracters (square-Os in one-of-two orientations) with varying target-to-distracter separations. Separations were always measured from centre of the target to centre of the distracter.

reasonable proportion of the range of the psychometric function. Typically at least 4 blocks were run per condition, yielding 32 trials per separation and 32 distracter-less trials (at least 256 trials per psychometric function).

For each target size, the raw data obtained was plotted as the percentage of correct responses vs. target–distracter separation. An example of this is shown in Fig. 2. To estimate the spatial extent of interaction, we:

- (i) fit a cumulative normal density curve to the raw data, with the lower asymptote of the curve fixed at 25% (dashed line in figure),⁴
- (ii) determined the point on the fitted curve that corresponded to a drop in performance by a factor of $1/e$ ($e = 2.718$) from the upper asymptote of the fitted curve. The abscissa of this point was our estimate of the spatial extent of interaction. (In Fig. 2, the amplitude (A) of the fit was 59.1%, the upper asymptote was at 84.1%, and the extent of interaction was 3.26° corresponding to a percentage of correct responses $= A(1 - 1/e) + 25\% = 62.4\%$).

⁴ When fitting the data, the “distracters” on the distracter-less trials were presumed to be at a target–distracter separation of 5000 pixels ($\approx 73^\circ$ visual angle). The upper asymptote of the fit was a free parameter and was normally within a few percent of the performance for the distracter-less stimulus.

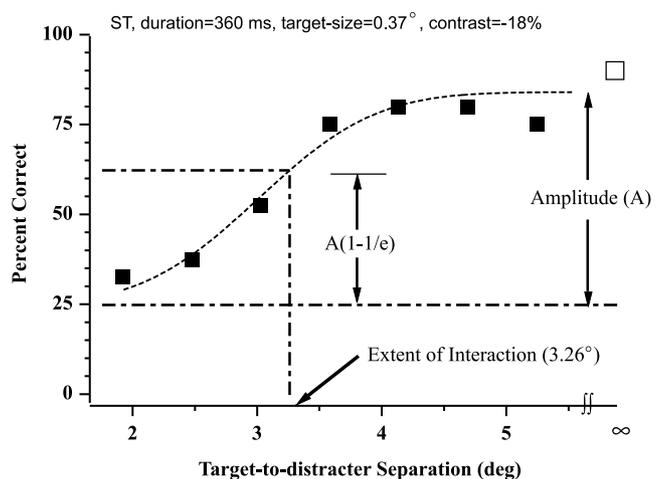


Fig. 2. Estimating the spatial extent of the interaction for a sample data set. Filled symbols show the observers performance for identifying the target in the presence of distracters, while open symbols show the performance in the absence of distracters, i.e. when the distracters were at an infinite distance from the target. The dotted line shows the best fitting cumulative normal curve to the data. The extent of the interaction is identified by the point on the curve that corresponds to a drop in the percentage of correct responses by a factor $1/e$ (where $e = 2.718$) from the unflanked performance.

2.2.1. Estimating extents of interactions for luminance defined stimuli

The first set of experiments was performed in the luminance domain; i.e. the targets and distracters were

grey on a grey background. The extents of interaction were estimated for several different sizes of the grey target. Initially, when we changed target size we also changed its contrast and stimulus duration, by trial and error, in order to roughly equate target visibility (as measured by the proportion of correct identifications of the isolated target). However, we found that stimulus duration had a profound influence on the spatial extent of interaction (see Results). Subsequently we separated our data into groups, each with fixed presentation duration for target and distracters. These were 27 and 360 ms for PC, 13 and 360 ms for ST. The targets of different sizes were only roughly matched for visibility. Any differences in target visibility were taken into account when estimating the extents of the interactions since these estimates were made *relative* to the performance for identifying the isolated targets (or more specifically, relative to the upper asymptote of the fits to the data). By selecting target contrast and size such that the observer's percentage of correct responses averaged less than 100% for the isolated targets, we ensured that our estimates of the extents of interaction were not contaminated by saturation effects. We attempted to cover a 5-fold range of target sizes, from 0.37° to 1.85° , measured along a side; however, this was not always possible because the smallest targets were sometimes not adequately identifiable even with maximum contrast. Table 1 lists the target sizes, presentation durations and Michelson contrasts used in this experiment. Strasburger et al. (1991) measured contrast detection thresholds as a function of target size for numeric characters in foveal and peripheral vision. These thresholds plotted in their Fig. 2(C) compare reasonably with our contrasts in Table 1. Only a rough comparison of the two results is possible because:

- (i) their thresholds were measured at 67% correct responses. We used trial and error to get a target size and contrast that yielded roughly 90% correct responses,
- (ii) their presentation duration was 100 ms, while ours was varied as shown in Table 1,
- (iii) their figure shows data at eccentricities of 8° and 12° (and other eccentricities), while our tested eccentricity was 9.2° .

2.2.2. Estimating extents of interactions for chromatic stimuli

The second set of experiments was performed in the chromatic domain; i.e. the targets and distracters were green and were equiluminant with the grey background. The extents of interaction could be estimated for only a very narrow range of target sizes. Since the luminance of the target was fixed a small increase in target size caused the observers performance to saturate and a small decrease in target size resulted in performance that was close to chance.⁵ For each target size selected, the extent of interaction was estimated using a similar technique to that used in the luminance domain.

Equiluminance for the target and background was subjectively determined and then verified. An 11 Hz flickering green isolated T (chromaticity co-ordinates: $x = 0.291$, $y = 0.585$) was continuously presented on a grey background ($x = 0.280$, $y = 0.303$; luminance = 31.0 cd/m^2 (PC) and 42.3 cd/m^2 (ST)) at the eccentricity at which the extent of interaction was to be estimated. The observer quickly adjusted the luminance of the T until it was least visible, taking care to minimise adaptation effects. At this point the test was considered to be equiluminant with the background for that observer. At equiluminance, the test was at 34.9 cd/m^2 for PC (on a background of 31.0 cd/m^2) and 43.4 cd/m^2 for ST (on a background of 42.3 cd/m^2).

In order to verify that the above setting for each observer was reasonably close to his equiluminance point, we measured how each observer's ability to identify the orientation of an isolated T changed as the size of the T changed (Fig. 3). These measurements were made for the conditions when the target:

- (i) was green and at the observer's equiluminant setting for the background (open circle),

Table 1
Stimulus parameters for the experiment in the luminance domain

Size (deg)	Duration (ms)	Contrast (%)
<i>PC</i>		
0.92	27	-15.96
1.48	27	-18.08
1.85	27	-7.08
0.37	360	-45.76
0.92	360	-4.46
1.48	360	-2.53
<i>ST</i>		
0.55	13	-60.58
0.74	13	-30.16
1.11	13	-19.51
1.48	13	-14.69
1.85	13	-10.5
0.37	360	-20.74
0.74	360	-6.02
1.11	360	-3.24
1.48	360	-2.7
1.85	360	-2.15

⁵ For example, for observer ST, with a stimulus duration of 360 ms, the range of target sizes for which interactions could be measured was 1.20 – 1.67° . At the time of doing the experiment, we were unaware of the strong effect of stimulus duration on the extent of interaction; we consequently varied duration in order to equate visibility. We now realise that we cannot compare extent of interactions across durations. Consequently, comparisons between chromatic and luminance extents of interaction are valid only when the stimuli are matched for target size and at least coarsely matched for duration.

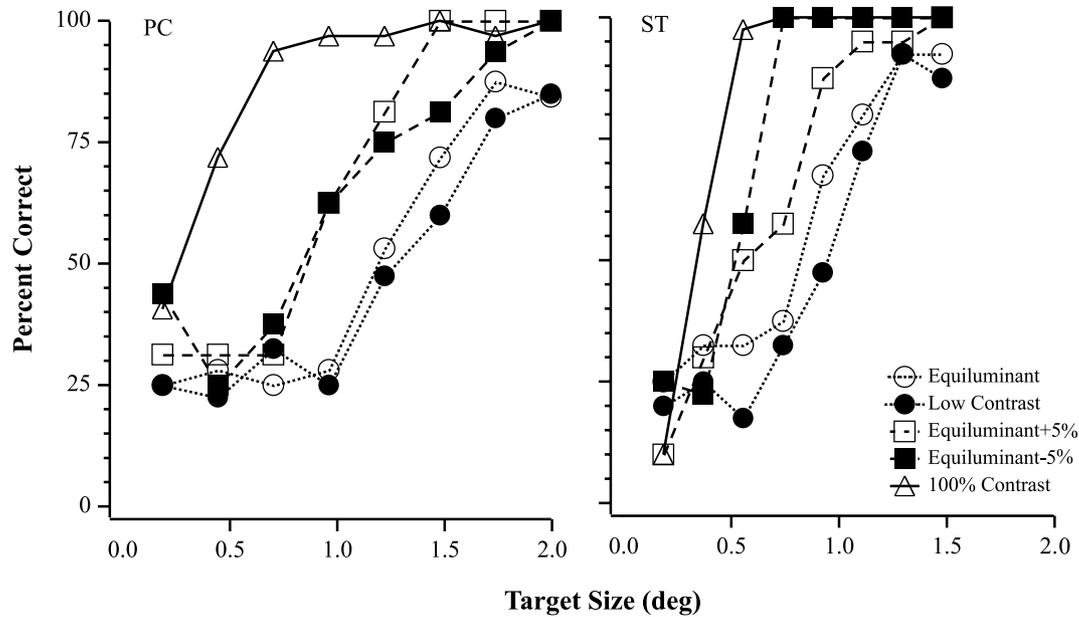


Fig. 3. Verifying the equiluminance setting for the target. Open circles show how each observer's ability to identify the isolated green target varied with target size, when the target was at the setting that appeared to be equiluminant to the background. Closed circles show data for a low contrast stimulus those match the data at equiluminance. When the target's luminance was increased (open squares) or decreased (closed squares) away from equiluminance, performance rapidly improved. For comparison, performance for a target at -100% luminance contrast is also shown (open triangles).

- (ii) was grey and had its contrast adjusted (by trial and error) so that the observer's ability to identify the isolated T was similar to that for the equiluminant target in (i), (closed circle). The luminance target that was roughly as visible as the chromatic target had a Michelson contrast of -2.2% for PC and -3.3% for ST,
- (iii) was green and had a luminance that was 5% greater than that at equiluminance (open square),
- (iv) was green and had a luminance that was 5% less than that at equiluminance (closed square),
- (v) was grey and had a contrast of -100% (open triangles).

For each of the above conditions, the Method of Constant Stimuli was used. On each trial the target T was presented with a randomly selected orientation (one-of-four), with its size selected from eight predetermined sizes covering the range of the observer's psychometric function. Stimulus duration was 360 ms. The observer reported the perceived orientation of each target presented. Each block consisted of eight trials at each of the 8 target sizes. At least four blocks were run for each of the five conditions, yielding at least 32 trials per target size per condition.

Over the range of sizes tested, the visibility of the chromatic target was roughly comparable to that of a luminance defined target with a contrast of about 3%. The targets in conditions (iii) and (iv) were *both* more visible than the targets in condition (i), confirming that

our settings in condition (i) were sufficiently close to the equiluminance point for the green target on the grey background.

3. Results

3.1. Extents of interaction for luminance defined stimuli

For luminance defined stimuli, Fig. 4 shows the extent of interaction on a logarithmic scale plotted against the target size. Data are shown for two stimulus durations each for PC and ST. A straight line was fitted to the data that corresponded to each stimulus duration. The slopes ranged from -0.43 (ST, 13 ms) to $+0.19$ (PC, 27 ms), but over a five-fold increase in target size, the change in the extent of the interaction (as estimated from the fits) ranged from -14.4% (PC, 360 ms) to $+6.3\%$ (PC, 27 ms). In absolute terms, the targets increased in size by between 1 and 2° of visual angle and the spatial extent of interaction increased by no more than 0.2° in one case (PC, 27 ms) and decreased in all others. Decreasing the stimulus duration increases the extent of interaction almost uniformly over all target sizes tested. This had not been anticipated at the start of the experiment; we had manipulated both contrast and duration in our efforts to equate the visibility of the isolated targets. Subsequent to data collection, the data for the different stimulus durations were analysed separately. Differences in stimulus duration can result in

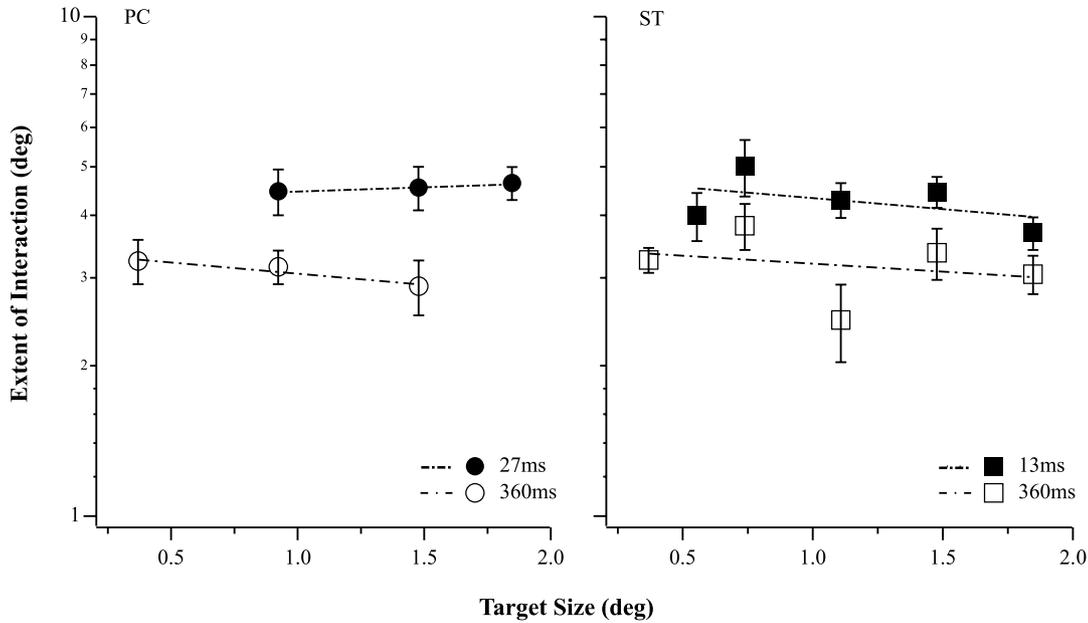


Fig. 4. Extent of interaction for luminance defined targets as a function of target size. The extent of interaction in logarithmic co-ordinates has been plotted against the target size for stimulus durations of 27 and 360 ms for PC and 13 and 360 ms for ST. The target was luminance defined; i.e. was grey on a grey background. The dashed lines are straight-line fits to the data. Error bars represent ± 1 standard deviation.

differences in measured extents of interaction, even if the stimuli have been equated for visibility.

3.2. Extents of interaction for chromatic stimuli

For chromatic stimuli, Fig. 5 shows the extent of interaction on a logarithmic scale plotted against the target size. Data are shown for stimulus duration of 360 ms for both observers and of 54 ms for ST. These data were distributed between 2.9° and 4.0° for stimulus duration of 360 ms and 4.5° for stimulus duration of 54 ms. A comparison of Figs. 4 and 5 indicates that extents of interaction for chromatic stimuli are comparable to those for luminance-defined stimuli, provided stimulus durations for the two types of stimuli are taken into account. The smallest isolated chromatic target that could be reliably identified was about 2.5–4.0 times larger than the smallest identifiable, isolated, luminance defined target. Yet the extent of interaction for the chromatic stimuli fell reasonably within the range of those for the luminance stimuli.

4. Discussion

4.1. Effect of target size on the spatial extent of interaction

In the Introduction we asked whether the spatial extent of interaction between the target and distracters scaled with target size. As discussed in the Results sec-

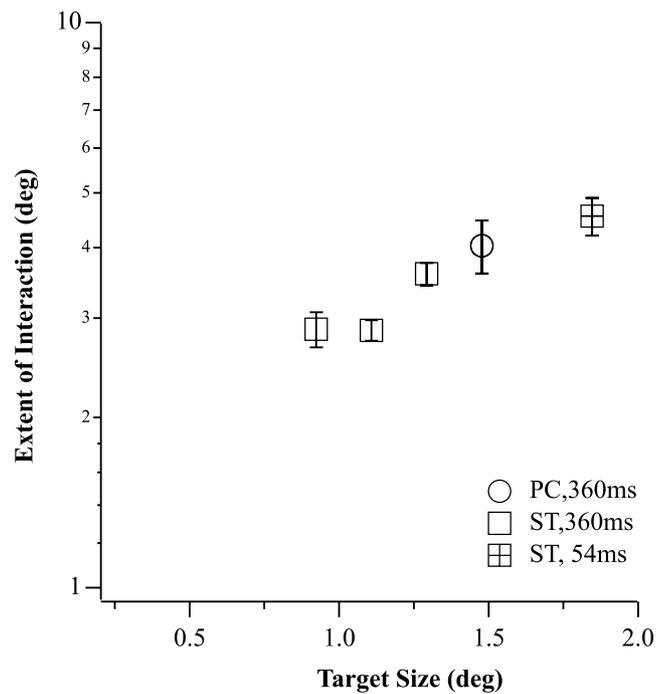


Fig. 5. Extent of interaction for chromatic targets as a function of target size. The extent of interaction in logarithmic co-ordinates has been plotted against the target size for stimulus durations of 360 ms for PC and 54 and 360 ms for ST. The target was chromatically defined, i.e. was green and equiluminant with the grey background. Error bars represent ± 1 standard deviation.

tion, when target and distracters were defined in the luminance domain, the extent of interaction clearly did not scale with target size. The extents were not entirely

independent of target size; small but consistent effects of target size were observed, as can be seen from the fits in Fig. 4. When the target and distracters were defined in the chromatic domain, the smallest identifiable target was more than 2.5 times larger, along each side, than the smallest luminance defined target. Yet, the spatial extents of interaction were comparable to those seen in the luminance domain, provided presentation duration of the stimulus was similar in the two cases. In peripheral vision, the spatial extents of interaction do not scale with target size. A 5-fold change in target size produced less than a 15% change in the spatial extent of interaction. To a first approximation, the extents were invariant with changes in target size. This has important implications for potential explanations for crowding as described below.

4.2. Relevance to proposed explanations for crowding

In the Introduction we discussed potential neuronal, computational and attentional proposals for crowding. Here we discuss the relevance of our findings to each of these proposals.

4.2.1. Neuronal proposals

The simple idea of an optimal receptive field that scales with target size predicts that the extent of interaction should also scale with target size. This runs contradictory to our findings. Even if the receptive fields that optimally encode the target's shape scale with the target's size, the inter-item interactions that we have measured do not.

In contrast, if the long-range horizontal connections mediate the crowding phenomena, we do expect that the extent of interaction will increase with target size. At 9.2° eccentricity, the 6–8 mm of the horizontal connections (perhaps twice that in humans) corresponds to 3–6°. Although this agrees with our measured extent of interaction, the extent does not increase with target size as we would expect if horizontal connections mediated the interactions.

If perceptive hypercolumns mediate crowding, then for the range of target sizes we used, we expect there should be no effect of target size on the extent of interaction for target sizes smaller than 1° and a linear increase for larger target sizes. Our results showed only a small effect of target size and so rule out an explanation for crowding based on perceptive hypercolumns.

4.2.2. Computational proposals

Crowding could be a consequence of the compulsory pooling of orientation information, as proposed by Parkes et al. (2001), and the spatial extent of interaction could represent the area over which this pooling is carried out. Our experimental findings suggest that the hypothetical area over which orientation information is

pooled is independent of the size of the target, provided the visibility of target and distracter are matched and stimulus duration is held constant; if the stimulus duration is decreased, this area of pooling increases.

The idea that crowding is limited by the physics of the stimulus and not the physiology of the visual system seems to hold for foveal vision (Hess et al., 2000a; but see Liu, 2001) but not for peripheral vision (Hess et al., 2000b). Since our experiments were in peripheral vision, we did not investigate this explanation for crowding further.

Several studies appear to have converged on a two-stage process for crowding involving feature identification followed by feature integration (e.g. Palomares et al., 1999). We discuss each of these with relevance to our findings.

Palomares et al. reported that in peripheral vision (4° eccentricity), the crowding produced when target letters are presented simultaneously with adjacent distracting letters has very different characteristics from the masking produced by distracting gratings or noise masks. They proposed that masking results from interactions at the feature identification stage, and crowding from interactions at the feature integration stage.

Chung et al. (2001) measured the spatial interactions, in foveal and peripheral vision, between spatially band-passed filtered targets and distracters. They found masking to be maximal when target and distracter spatial centre-frequencies were close to each other, regardless of the letter spacing. This is consistent with a masking explanation for the observed spatial interactions. However, they found that the spatial extents of their interactions were independent of letter spatial frequency. This is inconsistent with a masking explanation. Chung et al. propose a two-stage process, a linear process that is shared by crowding and masking, and a process involving divisive inhibition that is similar for the two phenomena, but in the case of crowding extends as far as half the retinal eccentricity. In our experiments our targets and distracters were similar, but not identical, so that any masking/crowding effects would be close to maximal, while causing no confusion as to which item is the target to be reported. Chung et al. did not find an effect of spatial frequency on extent of interaction, for fixed target size. Our extents of interaction did not scale with target size. The two findings are complementary and argue against a simple masking based explanation for crowding in peripheral vision.

Levi et al. studied spatial interactions between a target letter E constructed from a set of appropriately positioned Gabor/Gaussian patches and similarly constructed flanking bars (Levi, Hariharan et al., 2002; Levi, Klein et al., 2002). They varied target size and observed that the extent of interactions did not scale proportionately. Levi et al. concluded that spatial interactions in peripheral vision were not size invariant

and they favour a two-stage process similar to that proposed in Chung et al. for the spatial interactions observed in peripheral vision. Like Levi, Hariharan and Klein (2002) we find that the extent of interaction does not scale with target size. However, in their study, for stimuli constructed from Gaussian patches, the extent of interaction increased with a shallow slope as target size was increased (see their Fig. 3), whereas in ours the extent is either invariant or decreases slightly. Furthermore, their finding that the extent of interaction is approximately equal to $0.1 \times$ (effective eccentricity) does not generalise to our stimulus. These differences are most likely a result of the differences in defining and measuring the extents of interactions. In particular

- (i) In the Levi et al. study as the target size increased, detection threshold would have decreased. But the flank contrast remained fixed. So the relative contrast of target to flank would have been lowered, increasing the extent of interaction. In our study the contrasts for target and distracter were matched so that relative contrast is not a confounding variable (Kooi et al., 1994).
- (ii) Levi et al. plots target-to-flank separation as the distance between the centre of the Gabor patches that make up the flanking “bars” and the centre of the nearest limb of the target E, whereas our study plotted separation between target and distracter centres. For our study the centre-to-centre measure is the more appropriate to capture the underlying scale of interactions as the information registered for the targets and distracters is not restricted to their nearest contours but distributed over their shapes.

If a two-stage process mediates crowding (proposal 5 in the introduction), our findings hint at the extent over which the second-stage divisive inhibition operates. If the stimulus duration is fixed and the target and distracters are matched for visibility, the inhibition extends over a fixed distance (dependent on eccentricity). An increase (decrease) of stimulus duration results in shrinkage (expansion) of the zone of inhibition. This would be consistent with a transient inhibitory process that decays more rapidly than the representation of the target does.

4.3. Attentional proposals

If crowding represents the attentional limit to the resolution of images, the target size at which the spatial extent began to rise would indicate the smallest region of attention selection available at the 9.2° of eccentricity tested in our experiments. Since no increase in the spatial extent of interaction was found, the critical size must be larger than largest target we used. Data from Intriligator and Cavanagh (2001) indicate that for the ec-

centricity of 9.2° in the lower visual field, the size of the attentional selection region should be about 2° in the radial direction. Since our biggest target here was less than 2° , our data are consistent with the attentional proposal but not diagnostic since we didn't test any targets larger than the supposed attentional field.

Crowding could be a consequence of surplus attentional capacity being used to compulsorily process the neighbouring distracters under the low load condition. If we presume that visibility is a measure of the attentional load in the current task, then equating visibility for the different target sizes should equate attentional load. This leads to the prediction that the spatial extent of interaction will be independent of target size, as long as the visibility has been equated. This would be consistent with the findings for fixed presentation duration. However, when the presentation duration is varied there should be no effect on the extent of interaction, since the visibility and hence perceptual load are held fixed. This prediction is inconsistent with our experimental result that as presentation duration decreases the extent of interaction increases, in spite of equating visibility.

4.4. The locus of crowding

Our experimental results show that the extent of interaction for crowding is the same whether measured in the luminance domain or in the chromatic domain. It is possible that crowding occurs independently in the parts of the brain that process luminance information and the parts that process colour information and the resulting two extents of interaction happen to be similar, coincidentally. A more parsimonious explanation is that crowding occurs either before the separation of visual information into the luminance and chromatic streams, or it occurs later at a higher, common level, perhaps subsequent to attentional selection where feature binding takes place. In the former case, the horizontal connections in primary visual cortex would be a plausible mechanism for the crowding phenomena. Chromatic information is processed in the cytochrome-oxidase blob regions of layers 2 and 3 of the primary visual cortex and orientation information is processed in the interblob regions (Ts'o & Gilbert, 1988). The horizontal connections in layers 2 and 3 of primary visual cortex connect regions of similar spatial frequency and colour preferences (Gilbert & Wiesel, 1989) and this makes them likely candidates for mediation of crowding phenomenon.

An alternative to be considered is that for both luminance and chromatic stimuli the interactions occurred in the luminance domain due to residual luminance cues in the chromatic stimuli. For example, magnocellular units do respond to the chromatic transients (Lee, Martin, & Valberg, 1988; Schiller & Colby, 1983) at the onset and offset of our chromatic target and flankers and

although the adjustment of relative luminance minimizes this effect, it does not eliminate it. Two other sources are less likely contributors to any luminance artefact. First, the effects of longitudinal chromatic aberrations (Flitcroft, 1989; Howarth & Bradley, 1986) are minimized for the combination of green on gray background that we choose (compared to, say, green on red). Moreover, these edge artefacts have opposite polarity on opposite sides of the target attenuating their effectiveness for identification and interference. Second, our equiluminance settings were optimal for the target at its location, and even though the adjacent distracters were at different locations, there is not much variation of equiluminance settings with location at the eccentricity of our tests (Bilodeau & Faubert, 1997). Nevertheless, some combination of these residual luminance cues may have mediated the identification of the target and/or the interference from the flankers. Our data show that, to a first approximation, crowding with chromatic stimuli and flankers has much the same characteristics as that for luminance stimuli. A chromatic test embedded in dynamic luminance noise (Troschianko, 1994) would be the next step in removing luminance effects to more accurately verify the spatial extent of crowding for chromatic stimuli.

Finally, additional evidence suggests that in awake monkeys, cortical area V4 is involved in tasks involving feature selection as well as crowding interactions such as those observed in our study (Motter, 1994a,b; Motter, 2002). Crowding interactions can extend as far as half the target's retinal eccentricity and Motter (2002) points out that V4 is the first visual area capable of integrating over such a large area. Neurons in V4 showed suppressive responses to distracters presented within their classical receptive field. Facilitatory responses were also observed in V4 neurons when the target–distracter separation was below 0.5° . While V4 might be involved during active search (and for crowding), it is not necessarily *the* locus for active search (or crowding). A switch in the feature to be attended to results in a corresponding shift in the neuronal response with a delay of 200 ms, about three times the latency of V4 neurons; feature-selection (and crowding) might involve feedback from other cortical areas (Motter, 1994a). In the context of previously discussed theories, V4 could potentially serve as the locus for the divisive inhibition in the second stage of the two-stage process. Alternatively, it could be the locus where the resolution of attention is constrained.

4.5. *Effect of stimulus duration on crowding*

Initially we had presumed that visibility was the primary parameter determining the extent of interaction and as long as the visibility of the target was kept fixed, measuring the relationship between target size and extent of interaction was relatively straightforward. So we

varied both contrast and presentation duration simultaneously in order to equate visibility. When we plotted the extents of interaction as a function of target size, the data were noisy and no clear relationship was seen. It was only later that the systematic effect of presentation duration was noticed. The data presented in Fig. 4 are for the two presentation durations for each observer at which we had substantial amount of data. A decrease in presentation duration results in an increase in the extent of interaction, even when target visibility has been equated. This may reflect masking interactions between transient and sustained channels in the visual system (Breitmeyer, 1984; Breitmeyer & Ganz, 1976). An alternate explanation based on contrast is equally plausible. When the stimulus duration is decreased, the contrast of the target must be increased, if visibility is to be equated. Since our target and distracter contrasts were matched, distracter contrast increased with decreasing stimulus duration. The increased extent of interaction at short durations could represent either greater masking at brief presentations or greater masking from high contrast distracters (even if presented briefly). Previous studies have looked at the effect of distracter contrast on target detection threshold (e.g. Chung et al., 2001; Palomares et al., 1999). However in these studies the duration of stimulus presentation was kept constant. So, the relative contribution of stimulus duration and contrast is difficult to tease out without further experimentation.

4.6. *Effect of contrast on crowding*

Our results show crowding at all stimulus contrasts tested. Fig. 3 shows the extent of interaction as target size (and contrast) is varied. The contrasts for the shown data ranged from -2.15% to -60.58% . The extents of interaction decreased slightly as target size was increased, i.e. when target contrast was decreased, but in all cases robust crowding effects were observed. This is consistent with the findings of Pelli and Palomares (2000), who showed that distracters produce crowding at all contrasts, provided these contrasts are above detection thresholds. These two studies are in apparent contradiction to other studies that did not find crowding at low contrasts (Kothe & Regan, 1990; Simmers, Gray, McGraw, & Winn, 1999). This contradiction is probably a consequence of the stimulus eccentricity tested in the different studies. Our study focussed on peripheral vision, whereas the studies that did not find crowding at low contrasts were studying foveal vision. Strasburger et al. (1991) measured crowding in both central and peripheral vision. They found almost no crowding in foveal vision, but strong crowding effects were already evident at eccentricities as small as 2° . Toet and Levi (1992) measured the extent of crowding at the fovea to be about $4'$, and suggest that these extents were too

small to be revealed by the low contrast stimuli used by Strasburger et al., 1991. The same may apply to the other studies that did not find crowding at low contrasts in foveal vision.

4.7. Summary

Our main findings are:

- (i) The extent of interaction for crowding in peripheral vision does not scale with target size. Target size has only a small effect on the extent of interaction, provided target visibility is held constant.
- (ii) Stimulus contrast has little effect on the extent of interaction, provided target and distracter contrasts are matched. Robust crowding was observed at all contrasts tested.
- (iii) Crowding also occurs for chromatic targets displayed on equiluminant backgrounds. The extents of interaction are similar to those observed for targets defined in the luminance domain.
- (iv) The extents of interaction increase if the duration of presentation of the stimulus is decreased. This is true even if the visibility of the target has been equated for the different durations.

We conclude that the basis for crowding lies in a fixed zone of interaction at each eccentricity. This allows us to rule out mechanisms of lateral interaction that operate from every point of a stimulus as these must scale in size with the stimulus. The data are inconsistent with perceptible hypercolumns at an early level that are common to luminance and colour analysis as these would predict an increase of the extent of spatial interaction for targets in the range of 1–2° in size. The data are consistent with the idea that crowding is mediated by attentional receptive fields that have a fixed minimum size at each eccentricity.

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