Attentional modulation of crowding

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Abstract

Although effortless in central vision, figure-ground segregation can be problematic when we do not look straight at the figure. When one object appears with others nearby, the visual system pools their features, making it difficult to determine which feature belongs to which object. This “crowding” depends not only on the separation between objects, but also their relative configuration. Here we demonstrate that covert attention can increase the strength of crowding by changing the weighting attributed to attended features within an entirely unchanged stimulus.

Introduction

In the periphery, differences between adjacent visual stimuli are obscured via crowding. This is believed to represent an undesired binding of a target's features with those from adjacent items, in a critical region of integration (e.g. Bouma, 1970; Loomis, 1978; Wilkinson, Wilson & Ellemberg, 1997; Chung, Levi & Legge, 2001; Parkes et al. 2001; See Pelli & Tillman, 2008 or Levi 2008 for reviews). However, a different theory proposes that crowding results from the limited spatial resolution of attention (He, Cavanagh & Intriligator, 1996; Intriligator & Cavanagh, 2001).

Recently, Freeman et al. (2001, 2003) used a dual-axis stimulus to examine whether attention could modulate low-level processes involved in contrast facilitation. Their stimulus contained two axes, one optimized for contrast facilitation (e.g. target and flanker carrier's were collinear) and one known to cause little or no facilitation (target and flanker carriers were perpendicular). The authors found that when observers attended to the collinear axis designed to promote contrast facilitation, observers' contrast detection thresholds were lowered, but not when they attended to the perpendicular axis. Freeman et al. (2001; 2003) therefore demonstrated that in an entirely unchanged stimulus, the strength of contrast facilitation could be modulated simply by where observers directed their attention in the stimulus.

The results of attention on crowding remain more contentious. Wilkinson et al (1997) found that a pre-cue indicating where a target was located in an array of Gabors did not improve contrast detection thresholds. Similarly, Scolari et al (2007) and Nazir

(1992) failed to measure an improvement in performance when observers directed their attention to parts of the stimulus with the aid of an exogenous pre-cue. Using a gap distance measurement to determine the minimum separation between target and flankers for observers to perform at criterion levels, they did not find a significant change in the gap size with attention. However, one experiment did find that attention could break crowding. Cavanagh and Holcombe (2007) reported that the strength of crowding could be reduced when a coloured spotlight highlighted a crowded moving target. In our study we modified the paradigm employed by Freeman et al. (2001, 2003) in order to determine what happens to the critical region when observers attend to different parts of an unchanged crowded stimulus.

Methods

Two of the authors (IM and JAS) and four naïve observers served as subjects. All wore optical correction as necessary. An Apple Macintosh G4 computer running MATLAB™ (MathWorks Ltd) was used for stimulus generation, experiment control and recording subjects' responses. The programs controlling the experiment incorporated elements of the PsychToolbox (Brainard, 1997). Stimuli were displayed on a Value Vision monitor (resolution: 1280 x 1024 pixels, refresh rate: 60 Hz) driven by the computer's built-in graphics card. We achieved true 14-bit contrast resolution in grey-scale using a Bits++ system (Cambridge Research Systems). The display was calibrated using a photometer and linearised using look-up tables in software.

All targets were presented 5 degrees to the left or right of fixation for 170 ms. At the viewing distance, one pixel subtended 2.1 arcmin. The target Gabor was the product of a sinusoidal carrier (2.85 c/deg) and a circular Gaussian window (with spread σ = 0.175 deg). The carrier always appeared in cosine phase within its window. Most flankers had the same spatial frequency as the target and had horizontally oriented carriers. On dual axis trials, there was a 33.3% chance that either the top or bottom flanker (but not both) would have a higher spatial frequency (4.10 c/deg). There was also an independent 33.3% chance that either the left or right flanker would have this higher frequency. On single axis trials, there was a similar 33.3% chance that a flanker would be of a higher spatial frequency.

1 Single task

Observers fixated a small square (2 pixels x 2 pixels) that was present throughout the experiment. Target orientations (with respect to horizontal) were randomly selected from the set {-10º, -8º, -6º, -4º, -3º, -2º, -1º, 1º, 2º, 3º, 4º, 6º, 8º, 10º} (though some observers also required ±15º). In any case, we ensured that the extreme orientations were always correctly identified. The observers' task was to indicate with a key-press whether the target Gabor was tilted clockwise or anti-clockwise of horizontal. Observers completed between a minimum of 480 (single axis) and a minimum of 720 trials (dual axis conditions) per condition in blocks of 240.

2 Dual task

All observers except IM performed the attend-collinear and attend-perpendicular conditions in separate blocks. The dual task consisted of observers performing an orientation task on the target and a spatial frequency task, in which they had to decide whether one of the distracters in the attended axis had been of a higher spatial frequency than the other. If observers thought there was no spatial frequency difference, keys “1” and “3” were used to indicate counter-clockwise and clockwise responses respectively. If the observers thought there was a spatial frequency difference answer keys “4” and “6” were used. Observers performed practice runs before data collection, but had little difficulty learning to use the different keys.

Results

Angular thresholds for discriminating clockwise from anti-clockwise tilts in six conditions appear in Table 1. In all cases, the tilted target was a nearly horizontal Gabor pattern on the horizontal meridian of either the right or the left visual field. In one of these conditions (the collinear condition; see Figure 1) parallel, flanking Gabors appeared right and left of the target. In another condition (perpendicular condition; see Figure 1) parallel flankers appeared above and below it.

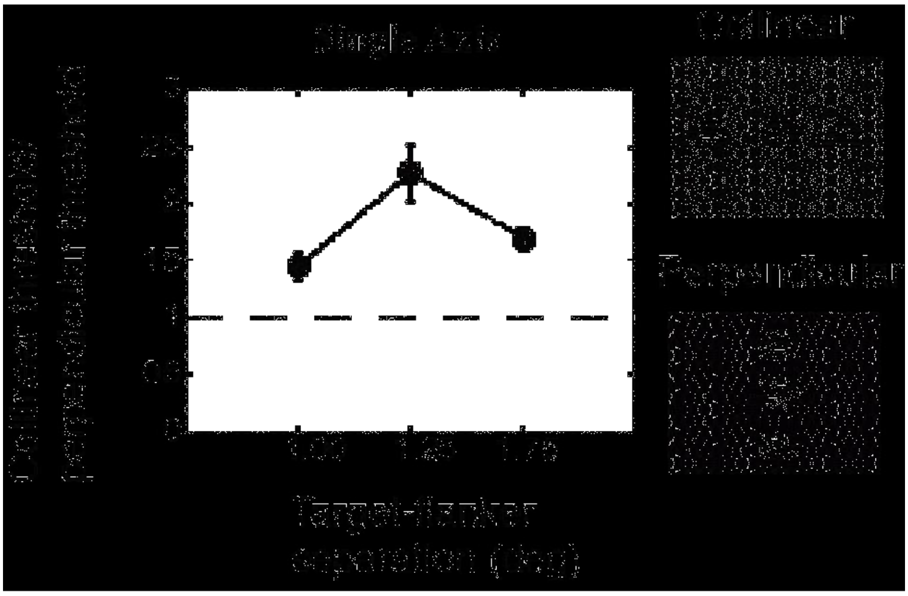


Figure 1. Ratio of collinear to perpendicular thresholds as a function of target-flanker center to center separation. Thresholds were geometrically averaged across observers

and visual fields. Error bars are s.e.m. Equality in thresholds using collinear and perpendicular stimuli is represented by the dashed line.

To maximize our chances of finding an attentional effect, we sought the target-flanker separation at which the effects of collinear and perpendicular flankers were most different. Figure 1 plots the threshold ratio (collinear/perpendicular) in these single-axis conditions as a function of separation. A clear peak appears at 1.25 degrees. Unless noted otherwise, all of the succeeding analyses were performed on data obtained with this target-flanker separation.

The same conditions are again illustrated in Figure 2a, which plots orientation thresholds for 6 observers (two points per observer; one for the left visual field and another for the right visual field). Note that most points fall below the unity line, consistent with the finding (Livne & Sagi, 2007; Fang & He, 2008) that a radial configuration of flankers impairs target identification more than the tangential configuration. In a paired t-test, thresholds were significantly higher in the collinear configuration than the perpendicular configuration, t=4.96; p<0.05.

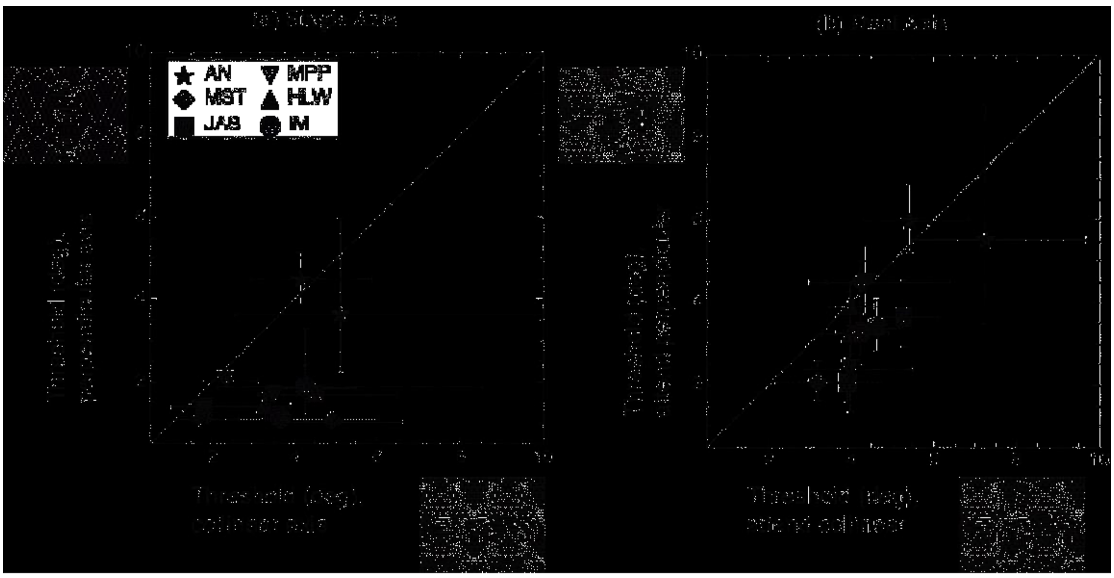
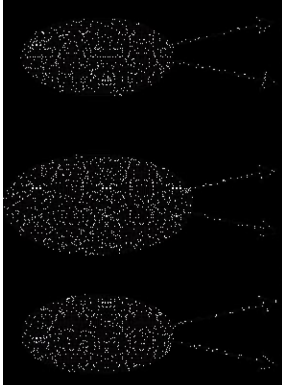


Figure 2. Orientation thresholds measured using single and dual axis stimuli. Thresholds from left (blue) and right (red) visual fields have been plotted separately. Different symbol shapes represent different observers. Error bars contain four standard errors. Solid black lines depict equality. (a) Single axis conditions: Perpendicular versus Collinear. (b) Dual axis conditions: Attend-Perpendicular versus Attend-Collinear. Note that the attended axis is highlighted for illustrative purposes only, it was not highlighted in the experiment.

To determine whether crowding depends on attention, we used a dual-axis configuration (see Figure 2) inspired by recent investigations of attention's role in detection (Freeman, Sagi & Driver, 2001; Freeman et al. 2003; Freeman & Driver, 2008). This configuration was also used without any attentional manipulation. Thresholds in this dual-axis, single task condition were virtually identical to those in the collinear condition (see Table 1). In other words, tangentially configured flankers had a negligible effect on threshold when radially configured flankers were also present.

In the two key conditions, observers were given the secondary task of looking for a relatively high-frequency flanker on either the radial or the tangential axis. We found that thresholds were significantly higher when attention was directed to the radial axis ($t_{11} = 3.45$; $p < 0.05$ when visual fields kept separate, or $t_5 = 2.45$; $p < 0.05$, when visual fields pooled for each observer). This is shown graphically in Figure 2b: most of the data points fall below the line of equality. For 5 of these 12 symbols, the line of equality passes above and to the left of both vertical and horizontal (95%) confidence intervals.



Condition	Threshold (log deg)
Single axis collinear	1.23 ± 0.22
Single axis perpendicular	0.96 ± 0.46
Dual axis attend collinear	1.48 ± 0.18
Dual axis attend perpendicular	1.27 ± 0.25
Dual axis single task	1.20 ± 0.24
Un-flanked target alone	0.92 ± 0.14

Table 1. Orientation (log deg) thresholds averaged across observers and visual fields in the six conditions tested. Asterisks indicate significant differences (paired t test, 11 degrees of freedom). The dual axis configuration causes strong crowding, thresholds, are raised nearly four fold compared to the target alone ($t_{11} = 8.66$; $p < 0.05$).

The relative superiority of orientation identification in the attend-perpendicular condition suggests that there is a greater cost of attending radially configured flankers. However, another possibility is that observers devoted more resources to the secondary task in the latter condition. Evidence against this possibility is the finding that observers performed this spatial-frequency discrimination similarly well in the two conditions. The average accuracies were 82.7% when attending collinear and 81.9% when attending perpendicular. Full attention operating curves (AOC) are plotted in Figure 3c. Points that lie on the axes reflect single-task performances (orientation for the x-axis, spatial frequency for the y-axis). Points inside the graph reflect dual-task performances. To determine how the orientation task might have affected performance in the spatial frequency task, we measured the slopes of the left portions of the AOC for the five observers and found that they were not significantly different (t_4 = 0.28; n.s.). Attention to the radial axis and attention to the tangential axis therefore had similar effects on performing the spatial frequency task.

For a more meaningful comparison of how attentional resources were divided between primary and secondary tasks, we examined the error contingencies (Sperling & Melchner, 1978; Sperling & Dosher, 1986; Braun & Julesz, 1998; Lee, Koch & Braun, 1999). Each trial in our dual-task conditions produced a pair of responses. These responses necessarily fall into one of four categories: both correct, both incorrect, only orientation correct or only spatial frequency correct (see Figure 3a). Importantly, this pattern is the same whether observers attended to the collinear or perpendicular axis (all points except two fall within the 95% confidence intervals) suggesting that there was no change in how observers performed the dual task in the two conditions. Chi-square analysis on the pooled observers data reveals no departure from independence on the two tasks in the attend-perpendicular condition (X^2=0.44, n.s), but a small but significant departure from independence in the attend-collinear condition (X^2=3.99, $p<0.05$). A more relevant analysis however is to examine only the observers who showed a significant effect of axis of attention in the individual data in order to determine whether the change in their thresholds reflected attentional changes between the two conditions. When only these observers were examined, chi-square analysis revealed no significant departure from independence in either the attend-collinear (X^2=0.1, n.s.) or the attend-perpendicular (X^2=0.2, n.s.) tasks. The significantly greater crowding these observers experienced when they attended to the collinear axis is neither the result of fluctuations in their attentional state nor in their switching attention from one task to the other in this condition.

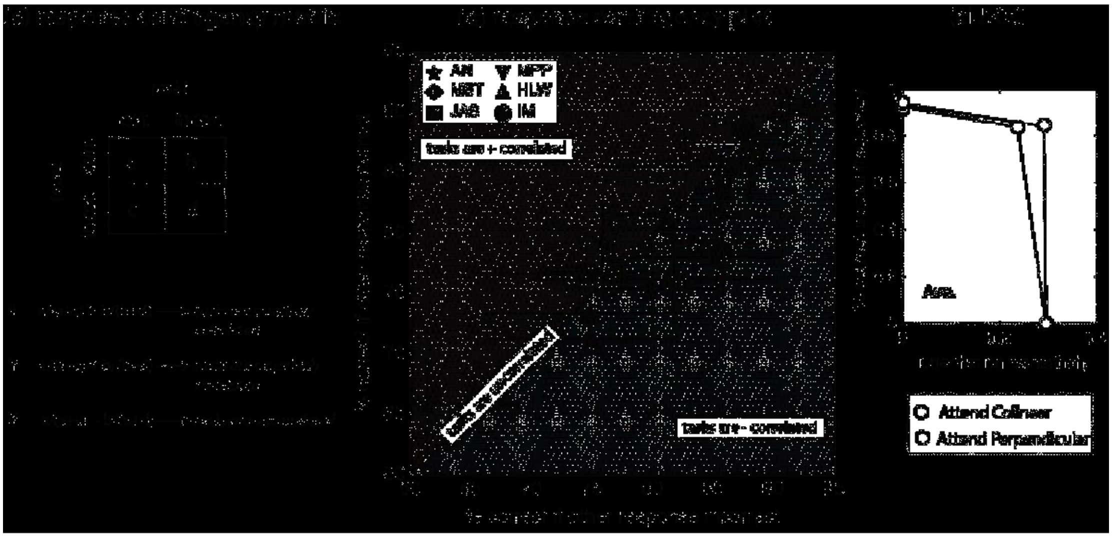


Figure 3. Error contingency. Inequalities derived from the four possible response categories (a) reveal whether performance on task 1 is positively correlated, negatively correlated or uncorrelated with performance on task 2. Two separate contingency analyses were performed for each observer in each dual-task condition; once using the primary (orientation) task as “task1,” and once using it as “task2.” Accuracy on task1 is plotted in (b). Red symbols illustrate the attend-collinear condition, blue symbols illustrate the attend-perpendicular condition. Symbols in the grey area indicate positively correlated performances, whereas symbols in the blue area indicate negatively correlated performances. Error bars contain 95% (binomial) confidence intervals. (c) Average attention operating curve. Data points on the x-axis are orientation sensitivity measured in the dual axis single task, points on the y-axis are performance on spatial frequency discrimination only in the dual axis single task, points inside the graph reflect performance on the dual axis, dual tasks.

Finally, we re-ran the dual-task conditions at three additional target-flanker separations to examine the falloff in thresholds with target-flanker separation (Chung, Li, & Levi, 2007). Figure 4 plots these data and reveals that the greatest difference in threshold elevation between the two conditions occurs at our chosen separation of 1.25 degrees, which maximized the single axis threshold difference. Although we did not find a significant difference in threshold elevations at the target-flanker separations of 1.0 and 1.75 deg, this is not entirely surprising given the results in figure 1. Indeed, at the greatest ratio condition (sep=1.25 deg) we find that attending to the collinear axis raised thresholds by about 17%. (table 1). We could therefore expect that the difference in thresholds between attend collinear and perpendicular would be roughly 5.5% at 1 deg and 8.5% at 1.75 deg (ratios are roughly 1/3 and 1/2 those at 1.25 deg in fig.1). We would therefore predict threshold elevations of 3.42 and 2.08 (rather than what we obtained of 3.34 and 1.90). However in both cases the predicted thresholds are within our measured thresholds' error bars, suggesting that the difference in thresholds for the single axis conditions at these two separations is not great enough to have a measurable effect using the attentional paradigm.

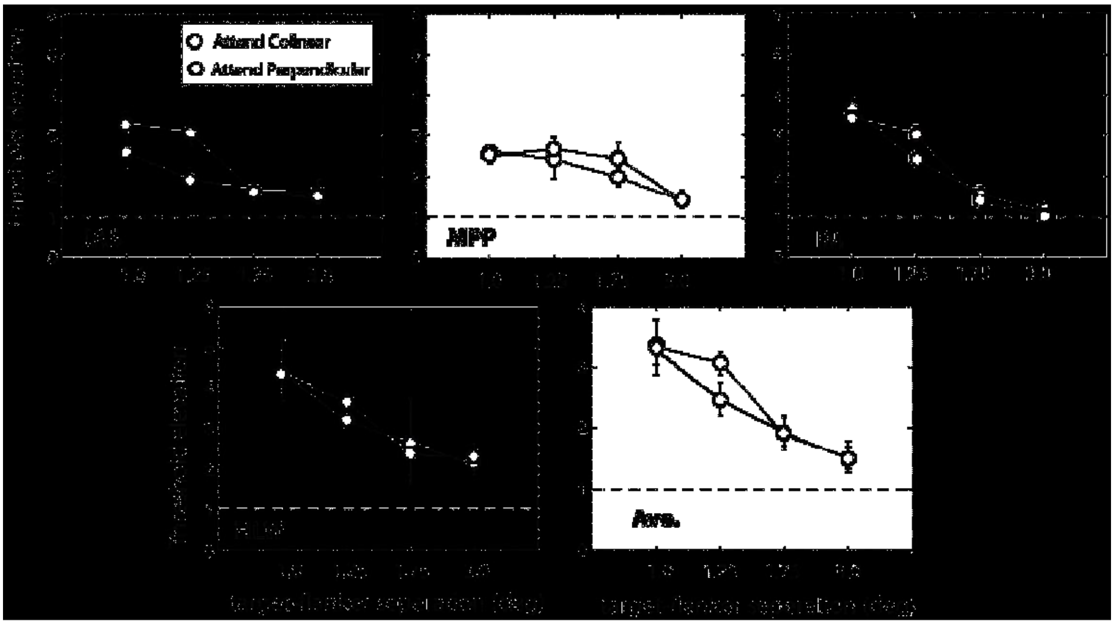


Figure 4. Threshold elevations for individual observers (threshold for "attend" conditions/threshold for target alone) and the group as a whole (geometric means, bottom right). Error bars are s.e.m, dashed line represents no crowding. Most observers display only a very small difference in thresholds at separations other than 1.25 degree.

Discussion

Crowding is thought to manifest from a compulsory pooling of features (Parkes et al. 2001) within a critical region, usually thought to have a radius roughly half the target’s eccentricity (Bouma, 1970; Pelli & Tillman, 2008). Single-feature (e.g. orientation) identification is probably the least complicated paradigm for investigating crowding. Within it, we can define the critical region as the collection of weights applied to the featural content in each position, before these features are pooled. This definition allows us to map out the critical region by placing flankers in various configurations and measuring their effect on target identification. The implications of our results with single-axis stimuli are thus consistent with other estimates of critical region (Fang & He, 2008; Toet & Levi, 1992): more weight is given to radially configured flankers than flankers with the perpendicular configuration.

On the other hand, our definition allows at least two possible interpretations of our finding of elevated orientation thresholds with attention to radially configured, collinear flankers. One possibility is that this manipulation somehow degraded information about the target’s feature content, e.g. by reducing its signal-to-noise ratio. This possibility would be the converse of spatial cueing, which has been shown in some cases to enhance the signal content in a variety of stimuli (Scolari et al. 2007; Strasburger, 2005), making them less susceptible to crowding. The problem with this interpretation is that attention to collinear flankers has been repeatedly shown to enhance the effective contrast of a collinear target between them (Freeman et al. 2001, 2003, 2007; Giorgi et al. 2004).

In contrast to this problematic interpretation is the alternative: thresholds were elevated because of an increase in the impact of radially configured flankers when observers were required to attend to them. Thresholds were not significantly elevated when observers were required to attend the tangentially configured flankers because those flankers have a negligible effect on threshold when radially configured flankers are also present.

Finally, it should be noted that our results in no way suggest that attention can alleviate the symptoms of crowding; in particular, attention is unable to shrink the size of the critical region. It therefore seems unlikely that the lower size limit of the critical region is determined solely by attentional resolution (Intriligator & Cavanaugh, 2001). Instead, the critical region seems to be a basic feature of early visual processing.

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