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Attentional modulation of crowding

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ABSTRACT

Outside the fovea, the visual system pools features of adjacent stimuli. Left or right of fixation the tilt of an almost horizontal Gabor pattern becomes difficult to classify when horizontal Gabors appear above and below it. Classification is even harder when flankers are to the left and right of the target. With all four flankers present, observers were required both to classify the target's tilt and perform a spatial frequency task on two of the four flankers. This dual task proved significantly more difficult when attention was directed to the horizontally aligned flankers. We suggest that covert attention to stimuli can increase the weights of their pooled features.

1. Introduction

In the periphery, differences between adjacent visual stimuli are obscured by neighbouring stimuli, a process described in the literature as "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; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Wilkinson, Wilson, & Ellemberg, 1997; 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, Cavanaugh, & Intriligator, 1996; Intriligator & Cavanaugh, 2001).

Many authors (e.g. Nazir, 1992; Scolari, Kohnen, Barton, & Awh, 2007; Wilkinson et al., 1997) have sought direct evidence for a link between crowding and attention by looking for an effect of spatial cues on target identification. The consensus from these studies is that exogenous pre-cues do not alleviate flankers' hindrance of target identification. Exceptions to this rule (Cavanagh & Holcombe, 2007; Scolari et al., 2007) require the asynchronous presentation of target and flankers. Consistent with both the rule and its exceptions is the recent proposition that the critical region of integration merely shifts with attention, its size and shape remaining wholly determined by the target's retinal position (Pelli & Tillman, 2008).

We wondered whether there might be a more effective way to manipulate attention. Whereas spatial cues alone produce notoriously small effects on contrast thresholds for detection (Solomon, 2004), Freeman, Sagi, and Driver (2001) and Freeman, Driver, Sagi, and Zhaoping (2003) reported relatively large attentional effects on contrast detection using flankers adjacent to the target. Contrast thresholds were lower when observers were required to concurrently identify the Vernier alignment of flankers almost collinear with the detection target than when they were required to concurrently identify the alignment of simultaneously present, perpendicularly oriented flankers. In both cases, the stimuli were identical. Detectability, therefore, cannot be wholly determined by stimulus configuration. It also depends on where observers direct their attention.

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. Previous research has shown that flankers presented along the radial axis cause more crowding than flankers presented along the tangential axis (Fang & He, 2008; Livne & Sagi, 2007; Toet & Levi, 1992). We therefore adopted a stimulus containing flankers on both axes, and examined whether attention to flankers on the radial axis would impair target identification more than attention to flankers on the tangential axis.

2. Methods

2.1. Observers

Two of the authors (IM and JAS) and four naïve subjects served as observers. All wore optical correction as necessary.

2.2. Apparatus

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

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(resolution: 1280 × 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.

2.3. Stimuli

All stimuli were composed of Gabor patterns. Each Gabor was the product of a sinusoidal luminance grating at 90% contrast and a circular Gaussian window (with spread $\sigma = 0.175°$). Target Gabors were almost horizontal (see below), and had a centre frequency of 2.85 c/deg (i.e. $\lambda = 0.35°$). Flanking Gabors were perfectly horizontal, and had either 2.85 or 4.10 c/deg. Regardless of frequency, the carrier always appeared in cosine phase with respect to the centre of its Gaussian window.

On each trial, the target Gabor was presented 5° to the left or right of fixation with equal probability. When radial flankers were present, one was left and one was right of the target. There was a 33.3% chance that one (but not both) of these flankers would have the higher spatial frequency. When tangential flankers were present, one was above and one was below the target. There was an independent 33.3% chance that one of these flankers would have the higher spatial frequency.

In Experiment 1, distances of 1.0°, 1.25° and 1.75° (2.9, 3.6 and 5.0 λ) were used to determine the optimal centre-to-centre spacing between target and flankers. In Experiment 2, the centre-to-centre distance between the target and each of its flanks was 1.25° (3.6 λ). We examined single-axis configurations containing only radial or tangential flankers, dual-axis configurations containing both radial and tangential flankers, and target-alone configurations. In all conditions, stimuli were presented for 170 ms.

2.4. Procedures

2.4.1. Single task (Experiments 1 and 2)

Observers fixated a small white square (2 pixels × 2 pixels, at the viewing distance of 57 cm, 1 pixel subtended 2.1 arcmin) that was present throughout the experiment. Thresholds were estimated using a method of constant stimuli and target tilts (anticlockwise with respect to horizontal) were randomly selected from the set {−10°, −8°, −6°, −4°, −3°, −2°, −1°, 1°, 2°, 3°, 4°, 6°, 8°, 10°} (though some observers also required ±15°). In any case, we ensured that the extreme orientations were always correctly identified. On single-task trials, observers indicated with a key press whether the target Gabor was tilted clockwise or anti-clockwise of horizontal. Different stimulus configurations were presented in separate blocks of trials. Observers completed a minimum of 480 trials per condition in blocks of 240.

2.4.2. Dual task (Experiment 2)

On dual-task trials, observers performed the aforementioned orientation task plus a spatial frequency task, in which they had to decide whether a flanker in the attended axis had the high spatial frequency. If not, they were instructed to use the keys "1" and "3" to indicate target orientation. If one flanker did appear to have the higher spatial frequency, observers were instructed to use the keys "4" and "6." The higher spatial frequency was selected to yield approximately 90% accuracy, thereby avoiding floor and ceiling effects, on the basis of a pilot study involving IM. Observers could use either hand, and several practice runs were performed before data collection. They had little difficulty learning to use the different keys. With the exception of IM, all observers performed the attend-radial and attend-tangential conditions in separate blocks. For IM, a cue at fixation informed her of the to-be-attended axis. Observers completed a minimum of 720 trials per condition in blocks of 240.

2.5. Threshold estimation

We use the threshold to quantify identification performance. Threshold estimates were obtained by fitting the proportion of "anti-clockwise" responses with a cumulative Normal distribution over the target's tilt. Threshold is defined as the reciprocal of the distribution's standard deviation (i.e. $1/\sigma$).

3. Results

3.1. Experiment 1

We took advantage of the radial superiority in crowding. The radial configuration of flankers impairs target identification more than the tangential configuration (Fang & He, 2008; Livne & Sagi, 2007). To maximize our chances of finding an attentional effect, we sought the target–flanker separation at which the effects of radial and tangential flankers were most different.

Fig. 1 plots the threshold ratio (radial/tangential) in single-axis conditions as a function of target–flanker separation. A clear peak appears at 1.25°, indicating that this is the ideal separation to use, when looking for an effect of attention.

Fig. 2a presents a further analysis of our results with the 1.25° separation. It illustrates the orientation thresholds for six observers, including MST and MPP, who did not otherwise participate in Experiment 1. There are 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 previous findings (Fang & He, 2008; Livne & Sagi, 2007). In a paired t-test, thresholds were significantly higher in the radial configuration than the tangential configuration [$t(11) = 4.96$, $p < 0.05$].

3.2. Experiment 2

To determine whether crowding depends on attention, we used the dual-axis configuration (see Fig. 2) inspired by recent investigations of attention's role in detection (Freeman, Driver, Sagi, & Zhaoping, 2003; Freeman, Sagi, & Driver, 2001). In the two key conditions, observers were given the secondary task of looking for a relatively high-frequency flanker on either the tangential or the radial axis (dual axis, dual-task condition). This is shown graphically in Fig. 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. Thresholds were significantly higher when attention was directed to the radial axis [$t(11) = 3.45$, $p < 0.05$ when visual fields kept sep-

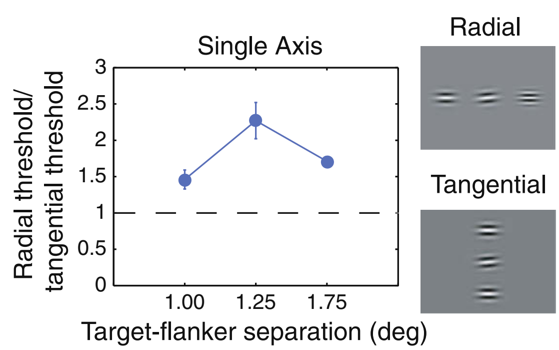

Fig. 1. Ratio of radial to tangential thresholds as a function of target–flanker centre-to-centre separation. Thresholds were geometrically averaged across observers and visual fields. Error bars are s.e.m. Equality in thresholds using radial and tangential configurations is represented by the dashed line. Examples of radial (top) and tangential (bottom) configurations appear at right.

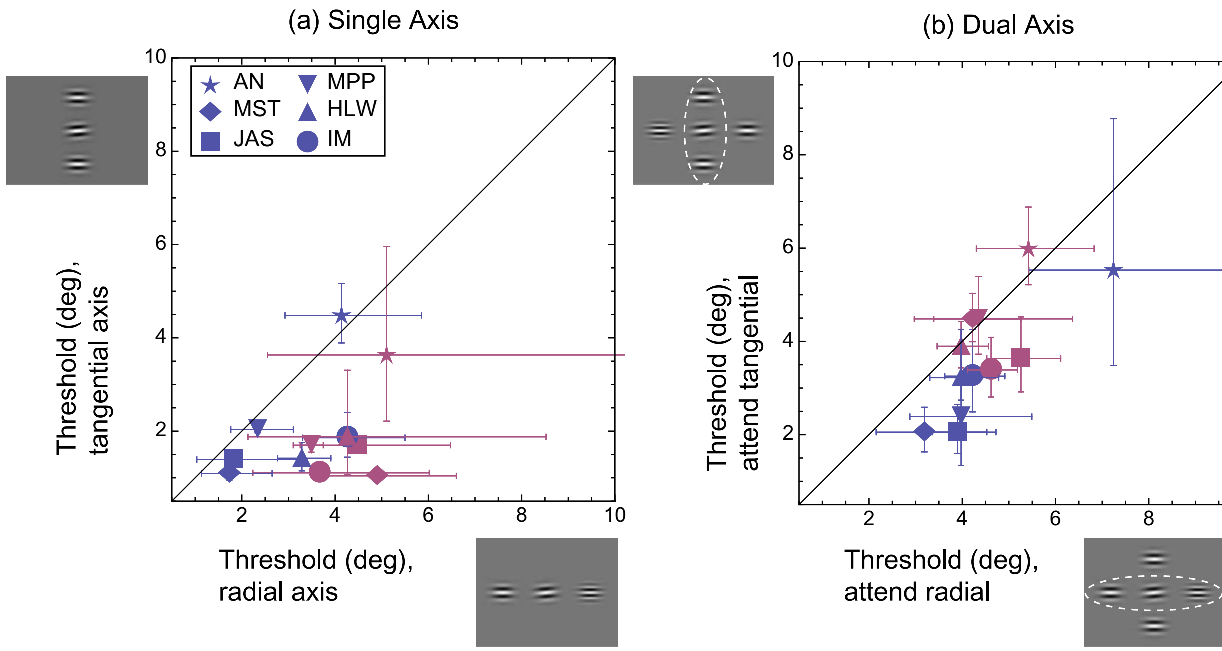

Fig. 2. Orientation thresholds measured using single and dual axis stimuli. Thresholds from left (blue) and right (red) visual fields have been plotted separately. Different symbol shapes represent different observers. Error bars contain four standard errors. Solid black lines depict equality. (a) Single-axis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

arate; $t(5) = 2.45$, $p < 0.05$ when visual fields pooled for each observer].

This dual-axis configuration was also used without any attentional manipulation, as in a conventional crowding experiment, and the results (geometrically averaged across observers and visual fields) are plotted in Fig. 3. Thresholds in this dual-axis, single task condition were virtually identical to those in Experiment 1's the single axis, radial condition (compare (a) and (e)). In other words,

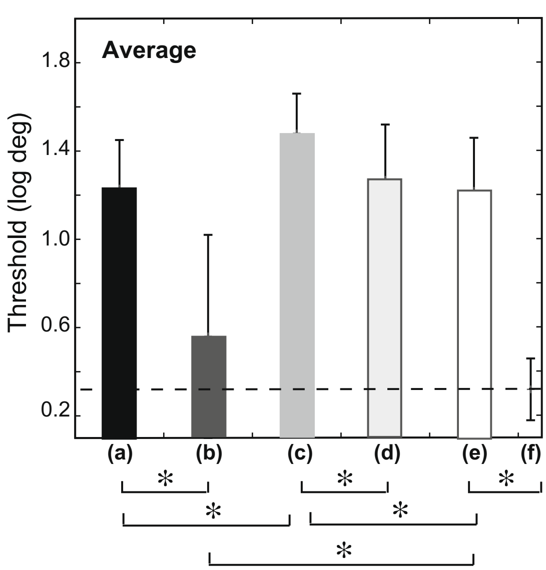

Fig. 3. Orientation (log deg) thresholds averaged across all six observers and both visual fields in six conditions. (a) Single axis radial. (b) Single axis tangential. (c) Dual axis, dual task, attend radial. (d) Dual axis, dual task, attend-tangential. (e) Dual axis, single task, and (f) dashed line is un-flanked target alone. Error bars are standard deviations and asterisks indicate significant differences (paired *t*-test, 11° of freedom). The dual-axis configuration causes strong crowding, thresholds are raised nearly fourfold compared to the target alone [$t(11) = 8.66$, $p < 0.05$].

tangential flankers had a negligible effect on threshold when radial flankers were also present.

The relative superiority of orientation identification in the attend-tangential condition suggests that there is a greater cost of attending to 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 radially and 81.9% when attending tangentially. Full attention operating curves (AOC) (Sperling & Melchner, 1978) are plotted in Fig. 4a. Points that lie on the axes reflect single-task performances (orientation on the horizontal axis, spatial frequency on the vertical axis). Average percent correct on the single task of spatial frequency when attending to the radial axis is 92.7% and 93.9% when attending the tangential 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 five of the six observers and found that they were not significantly different [$t(4) = 0.28$ n.s.]. Performance on the spatial frequency task was impaired when observers switched from a single task to dual task, but this decrease in performance on the spatial frequency was similar whether observers attended to the radial or to the tangential axis.

For a different comparison of how attentional resources were divided between primary and secondary tasks, we examined the error contingencies (Braun & Julesz, 1998; Lee, Koch, & Braun, 1999; Sperling & Dosher, 1986; Sperling & Melchner, 1978). 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 Fig. 4b). An example showing two of the error contingency matrices is shown at the bottom. This example illustrates the performance of JAS, when he performed the dual task and attended to the tangential (left) and radial (right) axes. These

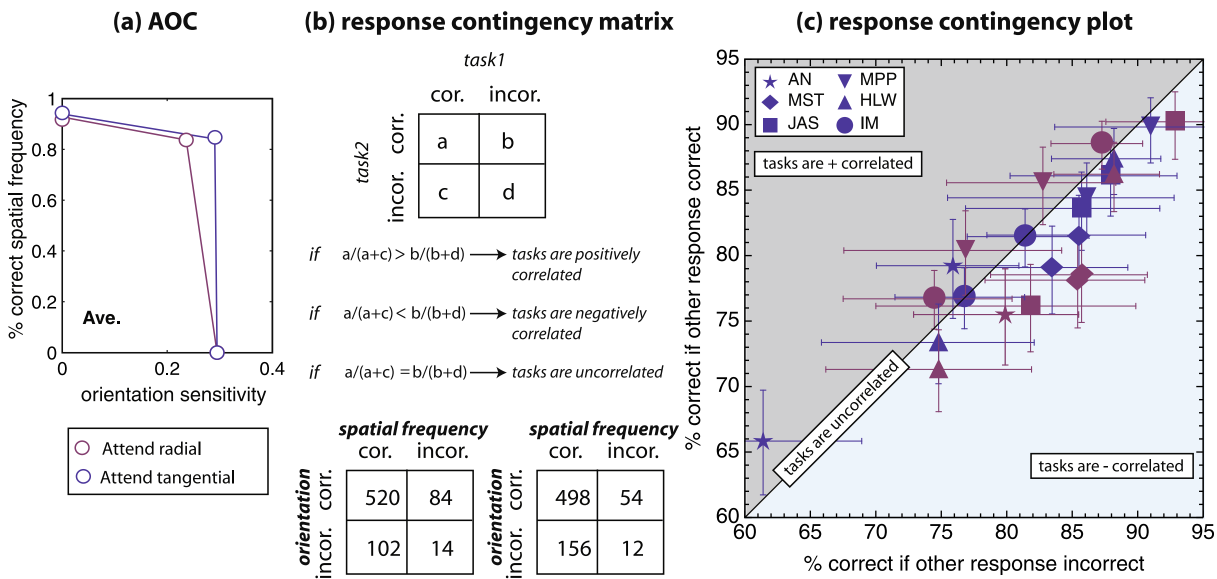

Fig. 4. Average attention operating curves and error contingency analysis. (a) AOC curves. Data points on the horizontal axis illustrate single-task orientation sensitivities (1/threshold). Points on the vertical axis illustrate single-task spatial-frequency discriminations. Points inside the graph illustrate dual-task performances. (b) Error contingency analysis. Inequalities derived from the four possible response categories 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 "task 1," and once using it as "task 2." An example is given at the bottom for observer JAS in the attend-tangential condition (left) and attend-radial condition (right). Accuracy on task 1 is plotted in (c). Red symbols illustrate the attend-radial condition, blue symbols illustrate the attend-tangential 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.

data appear as four (square) symbols in the error contingency plot (Fig. 4c). The attend-tangential data give us the two blue symbols and the attend-radial data give us the two red ones. One of each pair represents performance on the orientation task, when spatial frequency identification was correct; the other represents performance on the spatial frequency task when orientation identification was correct. Consistent with the proximity of blue symbols to the equality line, a chi-square analysis on the pooled data reveals no departure from independence in the attend-tangential condition [$X^2 = 0.44$ n.s]. On the other hand, there was a small but significant departure from independence in the attend-radial condition [$X^2 = 3.99$, $p < 0.05$]. This means that frequency discrimination on the radial axis benefited from less attention devoted to the orientation task and/or vice versa, at least on some trials.

Analogous analyses were conducted on each observer's data individually. None of these data sets differed significantly from what would be expected if observers devoted the same amount of resources to both components of each dual task on every trial, except one [MST, attend-radial condition; $X^2 = 3.97$, $p < 0.05$]. If all of his data are excluded from the group-wide contingency analysis, departures from independence are no longer significant [attend-tangential, $X^2 = 0.2$ n.s.; attend-radial, $X^2 = 2.8$ n.s.]. Nonetheless, thresholds remain significantly higher in attend-radial condition [$t(9) = 2.78$, $p < 0.05$ when visual fields kept separate; $t(4) = 2.63$, $p < 0.05$ when visual fields pooled for each observer]. Thus we can be reasonably confident that the greater crowding experienced by observers when they attended to the radial axis was not merely the result of fluctuations in their attentional state, nor can it be ascribed to their switching attention from one task to the other in this condition.

4. 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 in a tangential configuration.

The most straightforward interpretation of our results is that the impact of flankers increased when observers were required to attend to them. In particular, the radially configured flankers were weighted more heavily when orientations were pooled within the critical region. Thresholds were not significantly elevated when observers were required to attend the flankers on the tangential axis because those flankers have a negligible effect on threshold when radially configured flankers are also present.

An alternative interpretation of our results is suggested by the fact that the impacts of radially configured and tangentially configured flankers is most different at a target–flanker separation of 1.25° (i.e. 3.6 λ). This is similar to the separation that maximizes the facilitatory effects of flankers on target detection (Polat & Sagi, 1993). The same flankers that enhance the visibility of low contrast targets also impair contrast discrimination in high contrast targets (Chen & Tyler, 2002). Although it is unlikely that our target was any less visible when observers attended the radially configured flankers, it must be remembered that neurones responsible for contrast discrimination and target visibility are most likely those that are best stimulated by the target. On the other hand, those that are responsible for orientation identification are most likely tuned to even more extreme tilts (Mareschal, Dakin, & Bex, 2006; Regan & Beverley, 1985; Solomon, 2002). If attention to the radially configured flankers enhances their effectiveness (Scolari et al., 2007, Strasburger, 2005), then this enhancement may exacerbate any lateral inhibition between the neurones sensitive to the flankers and those mediating orientation identification.

Finally, it should be noted that our results in no way suggest that attention can alleviate the symptoms of crowding. In our physically unchanged stimulus, attending to either axis (dual axis, dual-task conditions) never caused thresholds to be lower than in the dual axis, single task (i.e. conventional crowding stimulus). 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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