# The Role of Target Salience in Crowding

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## ABSTRACT

We studied 'crowding' in the parafovea using orientation identification of a Gabor target as the task, and flanking Gabors on an iso-eccentric circle as distractors. Orientation-discrimination thresholds were raised by nearby flanking distractors. This 'crowding' effect was increased by the number of distractors and decreased by the spatial separation between target and distractors. Crowding was greatest when the target was in the centre of the distractor array and smallest when the target was on the edge of the array. A cue indicating the position of the target improved performance when the position was otherwise unknown and the spatial separation between target and distractors was large, but the cue had no significant effect when separation was small. Increasing the contrast of the target relative to the distractors reduced crowding, but targets of smaller contrast than the distractors are even harder to identify than those of the same contrast. Putting the target and distractors in different depth planes decreased crowding for some observers, but there were qualitative individual differences. A large (*e.g.* 45 deg) difference in orientation between target and distractors caused the target to 'pop out' in a presence/absence task, despite the evidence from other studies that crowding is still found in these conditions. We conclude that salience has--at best--modest effects on crowding.

## INTRODUCTION

“Crowding” (Stuart & Burian, 1962) refers to the deficit in identifying peripherally viewed targets, such as letters, when other shapes are nearby. Typically, these other shapes (‘distractors’) are similar to the target in studies of crowding. Kooi, Toet, Tripathy & Levi (1994) justified this practice, noting that crowding was reduced when distractors had a different colour, contrast or binocular disparity than the target. They argued that crowding was a consequence of the visual system’s compulsory grouping of similar shapes. More recently however, Chung, Levi & Legge (2001) found that crowding *increased* when distractors were given a greater contrast than the target. Rather than compulsory grouping, this result supports Korte’s opinion (1923; quoted by (Pelli, Palomares & Majaj, *in press*): 'it is as if there is a pressure on both sides of the [target] that tends to compress it. Then the stronger, i.e. the more salient or dominant [distractors], are preserved, and they 'squash' the weaker, i.e. the less salient [target], between them.'

We decided to pursue this notion that crowding would be decreased by manipulations designed to increase target salience. We define an operation that increases salience of a target as one that leads that target to 'pop out' from distractors in a task where the observer has to detect the singularity, but not necessarily to identify it. One well-known operation to increase salience in this sense is orientation difference between target and distractors (Nothdurft, 2000). Using an orientation-defined target we recently encountered evidence seemingly at odds with both Korte's and Kooi and colleagues' ideas (Solomon, Felisberti & Morgan, 2004). In this now-popular paradigm (Baldassi & Burr, 2000, Cameron, Tai, Eckstein & Carrasco, 2004, Carrasco, Talgar & Cameron, 2001, Felisberti & Morgan, 2001, Morgan, Ward & Castet, 1998) observers must identify the orientation (as clockwise or anticlockwise of some reference orientation, usually vertical or horizontal) of a parafoveally presented Gabor target, when flanked by iso-eccentric Gabor distractors. We found that orientation identification was most difficult when distractor and target orientations differed by 22.5 – 45 degrees (Solomon et al., 2004), contrary to the expectation that target salience would counteract crowding.

Our initial task was to determine whether this paradigm was really appropriate for studying crowding. Specifically, we wanted to make sure that distractors could be placed sufficiently close to the target so that (a) target identification would be impaired, but (b) not so close as to impair visibility. Once the critical separation for crowding was established, we took a brief detour from the effect of target salience to investigate whether critical separation should be expressed in terms of visual angle, multiples of target size and or multiples of target wavelength. We then moved on to assure ourselves that orientation differences between 22.5 and 45 degrees did produce 'pop-out,' i.e. a salient texture boundary between target and distractors. Next, we re-visited Kooi and colleagues' (1994) manipulations of contrast and binocular disparity. Consistent with their notion that crowding depends on target/distractor similarity, Kooi et al found reduced crowding when binocular disparity made targets appear more salient, i.e. when the target appeared in front of the distractors. We thought it important to see what happened when the target appeared in back of the distractors. Finally, we investigated the effects of distractor number (i.e. set size) and target position. In particular, we were curious as to whether previously reported set-size effects might merely reflect the frequency with which (putatively less crowded) targets appeared at the ends of iso-eccentric arrays.

## METHODS

### *APPARATUS AND STIMULI*

Stimuli for all experiments were generated by a Cambridge Research Systems VSG 2/3 graphic card with 12-bit luminance resolution. The stimuli were displayed in a Mistubishi DiamondPro 20 monitor (512 x 512 pixels; display area 24 x 24 cm; frame rate 100 Hz). The gamma functions of the display were measured by a Cambridge Research Systems photometer, and the data were used to construct linear look-up tables. Observations were carried out in a dark room in front of a display with 19 $cd/m^2$ mean luminance and the viewing distance was approximately 70 cm.

Suprathreshold-contrast Gabor patches (in cosine phase) were displayed along an imaginary parafoveal circle, notionally divided in four quadrants. The eccentricity in the initial two experiments was 3.8 deg, while in the remaining experiments the eccentricity was 4.0 deg. The carrier spatial frequency of the Gabor patches was 3.6 c/deg ($\lambda$= 7.5 pixels), and the Gaussian envelope constant was $\sigma_x=\sigma_y= 0.19$, except in Experiment 2, where these dimensions were varied. The contrast of each Gabor was 0.99, except in the experiment where contrast was varied. Target and distractors were separated by 3 wavelengths ($3\lambda$) of the carrier grating except in Experiment 1, where spacing was varied. Target position in 'cued' conditions was indicated with a line (see Fig. 1) or a small, eccentric spot (diameter 0.14 deg, eccentricity 4.6 deg; see Fig. 3). In the 'uncued' conditions, target and distractor positions were similarly indicated (see e.g. Fig 1). These spatial cues appeared for 100 msec, just before the target and distractors appeared.

### *PSYCHOPHYSICS*

We measured the frequency with which observers identified the tilt of the target as clockwise (CW) or anticlockwise (ACW) from horizontal (Experiments 1, 2 and 4) or from vertical (Experiments 3, 5 & 6). On each trial, the target appeared with one of eleven tilts (five CW, five ACW and one neither), pre-selected to produce a wellsampled psychometric function. Each block consisted of 100 trials and each observer performed a minimum of two blocks per experiment.

The observers had normal visual or corrected-to-normal acuity; three were the authors (FF, MM, JAS), two were naïve to the aim of the experiments (AJ, JG) and one was a well-informed postdoctoral student in our lab (CG).

Psychometric functions were collected relating the probability of a CW response to the size of the tilt, with ACW tilts counting as negative. The data were (maximum-likelihood) fit to two-parameter cumulative Gaussian functions using the gradient-descent method in MATLAB. Analysing the data in this way, rather than plotting percent correct as a function of absolute tilt away from reference made it possible to separate the effects of sensitivity ($\sigma$ is threshold) from bias ($-\mu$). Confidence intervals were estimated by a bootstrap procedure (Efron, 1979, Efron, 1982). That is, maximum-likelihood estimates of $\mu$ and $\sigma$ were used to define a simulated observer, who performed the same experiment as our human observers, 120 times. After each simulation, threshold and sensitivity were estimated anew, and the 95% confidence interval for threshold is bounded by the fourth largest and fourth smallest of these new threshold estimates.

## RESULTS

### EXPERIMENT 1: Critical Spacing for Crowding?

According to Parkes, Lund, Angelucci, Solomon & Morgan (2001), crowding requires an impairment of identification, even when there is no uncertainty as to the location of the target. We tested the effect of spatial cueing on tilt identification for various target/flank separations.

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Fig. 1 about here

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Fig. 1 shows a schematic representation of the stimulus arrays and Fig. 2 presents the results. In this experiment, the target randomly took up one of the three middle positions in the array, which was presented randomly either to the upper left or lower right quadrant. In the 'uncued' condition there were three lines, pointing to all three of the middle positions in the array.

Crowding, i.e. distractor-induced elevation of identification thresholds for cued targets, occurred for all separations ≤ 6λ. Neither cueing nor (for 2 out of 3 observers) spacing had much effect with separations of 2 and 3λ. Thresholds did not fully recover to baseline (i.e. the threshold with no distractors present) until the separation was 12λ, in the cued condition. In the uncued case, thresholds remained elevated at large separations, as would be expected from the effects of spatial uncertainty (Palmer et al., 1993; Morgan et al., 1998).

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Fig. 2 about here

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Our results allow us to be extremely confident that 3λ is less than the critical spacing for crowding (Pelli et al, *in press*). It could be argued that the cue failed to reduce positional uncertainty at separations <= 3 wavelengths because its own position suffers from uncertainty due to crowding. Since, however, the separation between cueing positions was ~ 0.8 deg, much larger than the conventional resolution limit, and even larger than thresholds for venire acuity, this amounts to saying that crowding limits the grain of positional resolution ( He, Cavanagh and Intrilligator , 1996). This is the conclusion we wish to draw from the data.

**EXPERIMENT 2: Degrees or Wavelengths?**

Previous studies of crowding with letter identification have suggested that the critical spacing for crowding at a given eccentricity is independent of the size (Pelli et al, *in press*) and spatial frequency content (Chung et al., 2001; Levi, Hariharan & Klein, 2002) of the target and distractors. For example, Levi et al found no effect of carrier frequency with envelope size held constant. On the other hand, they did find a complicated effect of envelope size with frequency held constant. However, no study seems to have varied size and frequency conjointly, so that separation remains constant in units of wavelength. We carried out such an experiment using the aforementioned 5-element display. Separation was kept constant at 3λ while spatial frequency varied in between 1.8 and 5.5 cycles/degree The space constant of each Gaussian was a constant multiple of the wavelength. Results are shown in Fig. 3 in terms of the threshold elevation (threshold in crowded condition/threshold in absence of distractors).

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Fig. 3 about here

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If crowding were solely determined by separation, the curves in Fig. 3 would be monotonically increasing from low to high spatial frequency, as the separation decreased. We did not find this. If crowding depended only on the separation in wavelength units, the curves would all be horizontal. Approximately this pattern was found in two observers (MM and CG) when spatial frequency was at 2.4 cycles/deg or higher. Only one observer showed a very small monotonic increase in crowding as predicted by the spatial separation hypothesis. Note that crowding was always found (threshold elevation greater than unity) even at the lowest spatial frequency. This is consistent with (Pelli et al, i*n press*) who found crowding with separations up to 2.3 deg at an eccentricity of 4 deg. The eccentricity in our experiments was 3.8 deg and we found crowding with 1.8 cycle/deg Gabors separated by 3$\lambda$ that is, by 1.67 deg of visual angle.

In summary, these results are not consistent with the simple story that crowding depends only on the separation (in degrees of visual angle) between the target and the distractors. Individual observer differences were found. Using Gabor patches in the range 1.8 to 3.6 cycles/deg, we find that the threshold elevation due to crowding in one observer is approximately constant as a function of separation expressed in wavelength units, not in visual angle. At higher frequencies only one observer showed an increase in threshold. The reason for the discrepancy with previous data is not clear. Both Pelli and colleagues and Chung and colleagues used letters while we used Gabor stimuli. Another possible explanation is that we used a pre-cueing procedure.

**EXPERIMENT 3: Crowding and Pop-out?**

In agreement with Levi, et al (2002) we have reported that crowding for orientation identification is virtually abolished if the distractors are orthogonal to the target (Solomon et al., 2004). However, we found strong crowding (and a tilt illusion) when distractors differ from the reference target orientation by 45 deg. We found this surprising, for in the literature on 'pop out', large orientation differences are a strong cue for segmentation (e.g. Nothdurft, 2000). Perhaps 'pop out' does *not* occur under conditions that produce crowding. We investigated this by measuring accuracy for identifying which of two temporal intervals in a 2AFC paradigm contained a tilted target, amongst a set of vertical distractors. The geometry of the array was the same as in Solomon et al (2004) and as in that study, there was no postmask. The target could appear in any position in the array and was tilted 1, 8, 16, 32 or 64 deg away from vertical, randomly interleaved over trials. In the other interval, all the patches had the same orientation. The number of distractors was either 4 or 15 in different blocks of trials. The accepted criterion for 'pop out' is that accuracy of identifying the presence of a target should be independent of the number of distractors, or even show a modest decrease at very low distractor numbers (Nothdurft, 2000).

Our results (Fig. 4) showed that the target was very hard to detect when the orientation difference was only 8 deg, but increasingly easier to detect at larger angles. The difference between 4 distractors and 15 was small. Thus, we found 'pop out' with the very same configuration that produced crowding in our previous experiment (Solomon et al., 2004). In particular, note that performance was above 90% for an orientation difference of 32 deg, which produced strong crowding in our previous experiment.

The result tells us that 'pop out' does not necessarily protect against crowding. 'Pop out' could be accomplished by a texture-gradient-finding mechanism that is unable to identify the textons on either side of the texture boundary (Sagi & Julesz, 1984, 1985). 'Pop out' has an optimum spacing, neither too dense nor too sparse (Nothdurft, 2000; Sagi, 1990), unlike 'crowding', which -as our Experiment 1 shows- always increases with density. Interestingly, for Gabor textures saliency has an optimal spacing (3< spacing <9 lambda; Sagi 1990), which seems to be at the tail of crowding range described here.

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Fig 4 about here

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**EXPERIMENT 4: Target/Distractor Contrast Ratios.**

Previous experiments agree that crowding is reduced if the target is of higher contrast than the distractors, but not *vice versa* (Chung et al., 2001). Given the several differences between our tilt-identification task and this previous study, which used letters, we thought it worthwhile to verify the effect of contrast on crowding. A 5-element display was used with the target always in the centre. Separation was 3λ. Either the target contrast was fixed at 0.5 (for observer FF) or at 0.7 (observers AJ and JAS) and the distractor contrast was varied, or the distractor contrast was fixed at 0.5 and target contrast was varied. This last condition acted as a control and data were collected only for one observer (FF). Results are shown in Fig. 5, where threshold elevation (threshold in crowded condition/threshold in absence of distractors) is plotted as a function of the ratio between target and distractor contrast. Results were broadly as expected. Accuracy increased as the target increased in contrast relative to the distractors, and at a ratio of 3:1 crowding was insignificant. Giving the target lower contrast than the distractor decreased accuracy relative to the case where they had the same contrast.

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Fig. 5 about here

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This result could mean that a high-contrast target has greater salience, and thus evades crowding. Equally, however, it is consistent with a pooling model (e.g. Parkes, et al, 2001) in which the contribution of the target to the pool is increased by its contrast.

**EXPERIMENT 5: Binocular disparity.**

Another procedure that might be expected to affect target salience, and thus to reduce crowding, is depth. Kooi and colleagues (1994) reported that the effects of crowding were reduced if the target and distractors were in different depth planes. In another experiment, not directly related to crowding but relevant to it, Harris and Morgan (1993) measured the accuracy with which observers could classify the spatial separation between two small coloured circles. They found biases if the circles were placed inside clusters of similar circles of a different colour. The biases were in the direction of the centroid of the dot cluster as a whole. As in the case of crowding, then, observers were unable to abstract the feature information of the target independently of the distractors, in this case the positional information. However, placing the target dot in a different depth plane from the distractors decreased the biases, as did moving the target dots. We wondered whether a similar effect would be found for orientation identification.

Ferromagnetic goggles with frame interleaving at 120 Hz were used to generate binocular disparities, and the target was placed either in front, behind or in the same depth plane as the distractors, with relative disparities of +0.5λ, -0.5λ or 0, respectively. In two versions of the zero-disparity condition, all the elements had either a +0.25λ or a –0.25λ disparity relative to the fixation point in the centre of the screen. The stimulus array consisted of 5 elements, with the target always in the centre position (no spatial cues were used). Separation was 2.5λ. Results are shown in Fig. 6 with the two zero-disparity conditions combined ('Same') and the no-distractor threshold as the rightmost point.

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Fig. 6 about here

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The results suffer from strong individual differences. Both JAS and FF benefited significantly from having the target appear behind the distractors. But putting the target in front only helped JAS. (It helped to the extent of completely eliminating crowding!) AJ, who had normal stereoacuity on the TNO test, showed very little crowding in any condition, and no significant effect of disparity. Despite these individual differences, our results are clearly inconsistent with the notion that objects appearing closer are more salient than those appearing further and that this results in a greater release from crowding.

**EXPERIMENT 6: Distractor Number and Target Position.**

Using orientation identification as the task with tilted Gabors, Morgan et al (1998) found that accuracy decreased with the number of distractors, even with spacing held constant. This could have been because the target was more likely to fall at the edge of the array when there were fewer distractors and thus to be flanked on one side only. Using orientation identification of a **T**, Toet and Levi (1992) noted that in pilot experiments they found no effect of a single flanker, consistent with the idea that the target must be flanked on both sides for crowding to occur. In contrast, Pelli and colleagues (*in press*) found threshold elevation for letter identification with a single flanker, although it was less than the effect of 2 or 4 flankers, which themselves did not differ. Parkes and colleagues (2001), using orientation identification of Gabors, found that thresholds fell linearly when the number of targets in a 9-element display was increased from one (the typical crowding situation) to 9. This result is predicted from the pooling model, which says that there is obligatory pooling of feature information before the decision stage. Although not reported in their paper, Parkes and colleagues found in pilot experiments that thresholds rose with distractor number even when there was single target, as predicted by the pooling model, provided all the elements fall within the putative pooling region.

To clarify the effects of distractor number and target position for orientation identification, we repeated Experiment 1 using either 0, 2, 3, 4 or 5 distractors, varying the position of the target within the array. Thus, for example, with 2 distractors, the target could fall either in position 1 (the most anticlockwise position in the array), in position 2 (the middle), or in position 3 (the most clockwise position in the array). The spatial cue was a small, eccentric spot (see Methods) and the spacing between the elements in the array was kept constant at 3λ. Results are shown in Fig. 7.

Fig. 7 about here

In the cued condition, we found strong effects of both distractor number and target position. Threshold was lowest when the target fell at one edge of the array, and was thus flanked on one side only. The largest effects of position were found with 4 or 5 flankers, for which there was an almost complete absence of crowding at the outermost positions. In contrast, there was almost no effect of spatial position with only two distractors. The extent of crowding was much smaller with two distractors than with 4 or 5 in the centre target positions. There were no systematic effects of position in the uncued condition, although as expected from spatial uncertainty, thresholds rose as the number of distractors increased.

The 'edge effect' could be explained by the target being more salient when it is on the edge of the array, and thus more easily picked out by attention. Using the 'searchlight' metaphor for attention, we could surmise that the position of the beam can be adjusted to light up an extreme position without including any distractors, while the centre position cannot be illuminated without including distractors. Equally, however, the same could be said about the position of the second-stage receptive field in the pooling model. The data do not discriminate between these alternatives. Our finding that 5 flankers cause more crowding than 2 is inconsistent with Pelli and colleagues (2003). Possible differences include the task (letter identification vs. orientation identification), stimulus geometry (our distractors were iso-eccentric) and the fact that the target position was always central in the Pelli et al experiment, while in ours it varied over trials and was cued. This matter remains to be resolved.

## GENERAL DISCUSSION

Classification of an unambiguously cued, parafoveal, Gabor target was similarly impaired by iso-eccentric Gabor distractors, 2 and 3λ away. Distractors 12λ away had no effect on tilt classification. Our data unequivocally show that the spatial frequency content of target and distractors has an influence on the critical spacing for crowding, as measured in degrees of visual angle. However, the range of spatial frequencies we used was not large. (We could not use higher frequencies because they became increasingly hard to see at the eccentricity we used, and lower frequencies were difficult because size increased and rapidly filled up the notional circle along which the stimuli were arranged.) Nonetheless our results suggest that critical spacing expressed in wavelengths only weakly depend upon spatial frequency.

In arrays containing a single target and more than one distractor, sensitivity to tilt is lowest when the target occupies the central positions. When the target is the central element, there is more crowding from 4 and 5 distractors than from 2. When all the distractors fall on one side of the target, there is some residual crowding, but it is not large.

In agreement with previous studies, we found a marked reduction in crowding when the target had higher contrast than the distractors. Crowding increased when the target had lower contrast than the distractors. Such results could mean that a high contrast target has greater salience, and thus evades crowding. Equally, however, they are consistent with a version of the pooling model in which the contribution of the target to the pool is increased by its contrast.

Placing the target behind the distractors by binocular disparity decreased crowding significantly in two of three observers, but placing the target in front of the distractors decreased crowding for only one. This result is at odds with the notion that objects appearing closer are more salient than those appearing further and that this results in a greater release from crowding.

Decisive evidence against the saliency hypothesis comes from the effects of orientation 'pop out'. Large orientation differences (e.g. 45 deg) between target and distractors make the target 'pop out' but do not reduce crowding. Note that we established 'pop out', by measuring accuracy for classification. Traditionally it has been measured with reaction times. Instead, we have adopted Palmer, Verghese and Pavel's (2000) more contemporary criteria for controlled studies of visual search.

We conclude that subjective saliency probably has little influence on the mechanics of crowding. This is consistent with the view of He, Cavanagh and Intrilligator (1996), that the 'grain' of attention is inherently limited outside the fovea, and with the growing consensus that crowding depends on a form of feature integration that is inappropriate to the demands of object resolution.

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## FIGURE CAPTIONS

**Fig. 1** Sketches of stimulus arrays used in the experiments. The stimulus array is either in the top left or in the bottom right quadrant of the isoeccentric circle (radius 3.8 deg) centred on the fixation point. The array consists of four distractors and one target, which can occur in any of the three inner positions. (**a**) A centrifugal bar indicates the position of the target to the observer in an array with elements closely spaced (cued condition). (**b**) An example of the uncued condition in an array with more widely-spaced spaced elements. The three potential target positions are indicated by three lines. In both cases, the target tilt is anticlockwise of horizontal.

**Fig. 2** Results of Experiment 1 in which the spacing between the target and distractors was varied in both cued (filled circles) and uncued (rectangles) conditions. The top three panels (**a-c**) show how threshold (ordinate) varied as a function of spacing (abscissa) for three different observers (FF, MM and JAS). The bottom three panels (**d-f**) show biases. The error bars are 95% confidence intervals derived from the bootstrap procedure described in the Methods section.

**Fig. 3** Results of Experiment 2, in which the spatial frequency and size of the stimuli were conjointly varied, keeping target/distractor separation constant in wavelength units (3λ) (**left**). Sketch of a low spatial frequency array. (**right**) The results for three observers (FF, CG and MM) are shown by different symbols. The measure of crowding (ordinate) is the ratio of the threshold when distractors are present to the threshold when they are absent. A ratio of unity indicates no crowding effect. If crowding depended only on the spatial separation in degrees of visual angle, the curves should be monotonically rising with spatial frequency. If crowding depended only on spacing in wavelength units, the functions should be flat. Neither result obtains exactly.

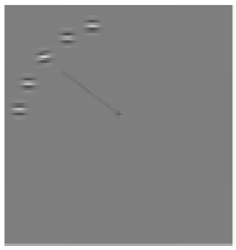
**Fig. 4**: Results of Experiment 3, measuring the accuracy (% correct, ordinate) with which observers identified the target interval in a 2AFC paradigm. In the target interval the single target had a different orientation from the distractors (abscissa); in the other interval all elements were vertical. Closed squares: 15 distractors. Open circles: 4 distractors. Position of the target in the iso-eccentric array was random, except that the end positions were excluded. (**a**) CG, (**b**) MJM, (**c**) JAS, (**d**) Mean.

**Fig. 5**. Results for three observers (FF, AJ, JAS) in Experiment 4, where the relative contrast was varied between target and distractors. Threshold elevation due to crowding (ordinate) is measured as in Fig. 3. The contrast ratio (abscissa) is the ratio Target Contrast/Distractor Contrast. (**a**) For subjects AJ and JAS the target contrast was fixed at 0.7 and the contrast of the distractors was varied, while for FF the target contrast was fixed at 0.5. (**b**) Data for FF when the distractor contrast was fixed at 0.5 and only the contrast of the target was varied. Error bars contain 95% confidence intervals.

**Fig. 6**. Results of Experiment 5, in which the target had either a different binocular disparity from the distractors (±0.25λ relative to fixation point) or had the same disparity. The three stereo conditions (ordinate) are: 'Diff', the target has a different disparity from the distractors; 'Same', the target and distractors have the same disparity; 'None', the distractors are absent entirely. Each panel shows the results for a different observer: (**a**) FF, (**b**) JAS and (**c**) AJ. Error bars are 95% confidence intervals, with bold bars showing the confidence limits when the target disparity is uncrossed ('back'), and dotted bars showing the limits when the target disparity is crossed ('front').

**Fig. 7.** Results of Experiment 6, in which the number of distractors and the position of the target were varied. In different panels, results are shown separately for two observers, FF (left) and JG (right) and for the cued (**a**,**b**) and uncued (**c**,**d**) conditions. The different symbols show data for different numbers of stimuli. Threshold (ordinate) is shown as a function of the position of the target within the array, from extreme anticlockwise (position 1) to extreme clockwise (position depends on the number of distractors). Note that an array with 6 locations, for example, has 5 distractors. For legibility, 95% confidence intervals are shown for the cued condition only.

Figure 1


(a)

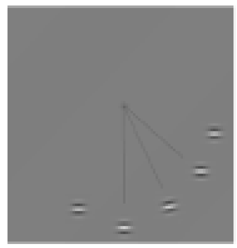

(b)

Figure 2

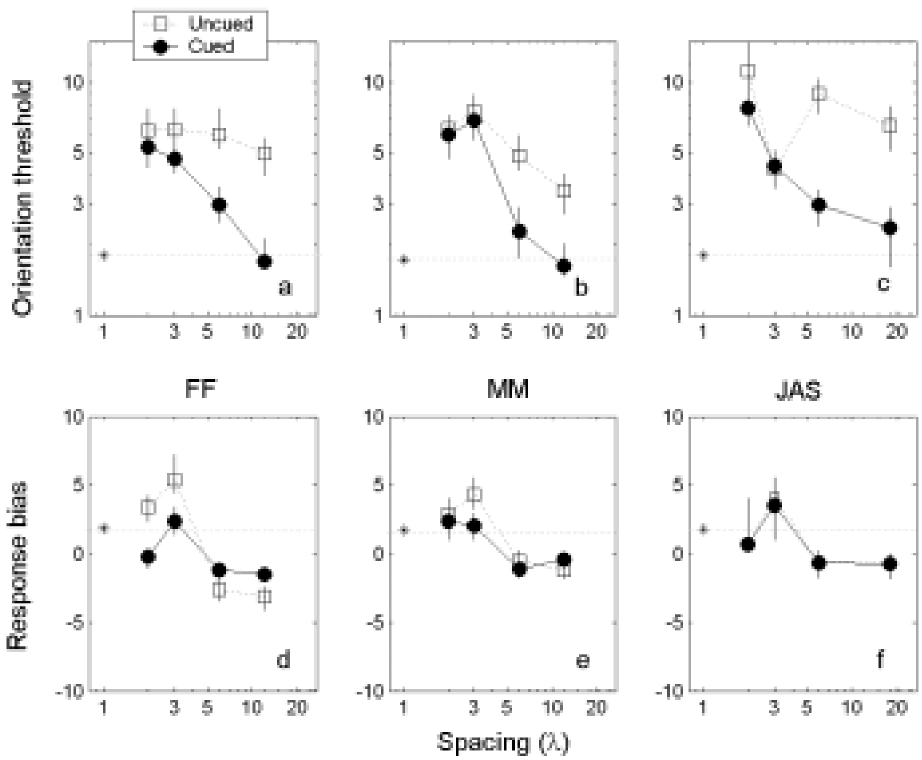


Figure 3

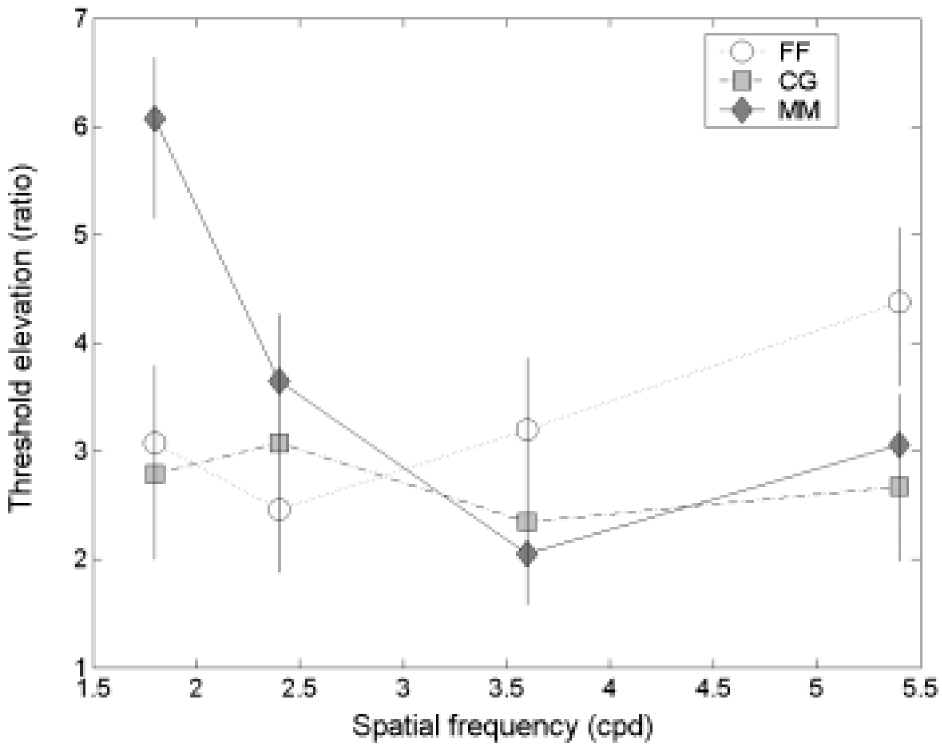
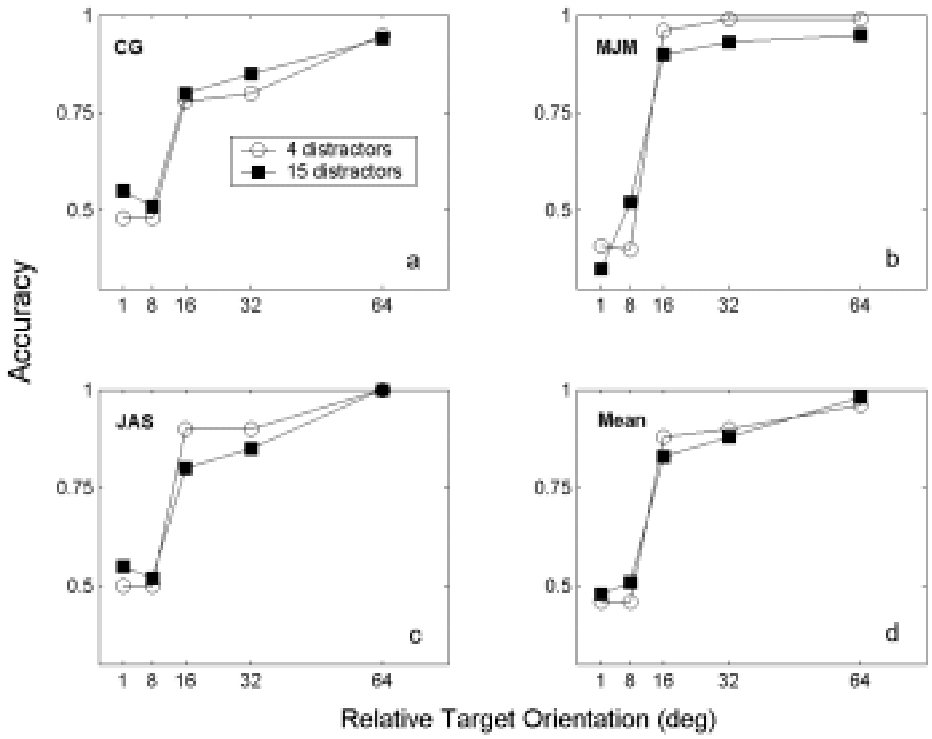
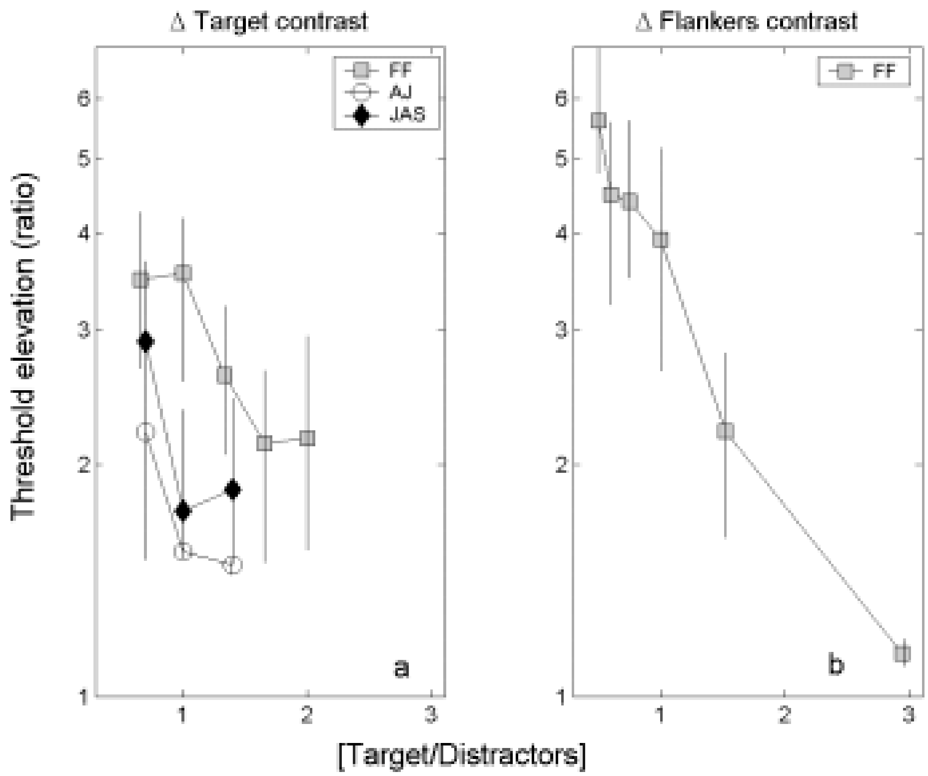

FF
CG
MM
Threshold elevation (ratio)
Spatial frequency (cpd)
7
6
5
4
3
2
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

Figure 4



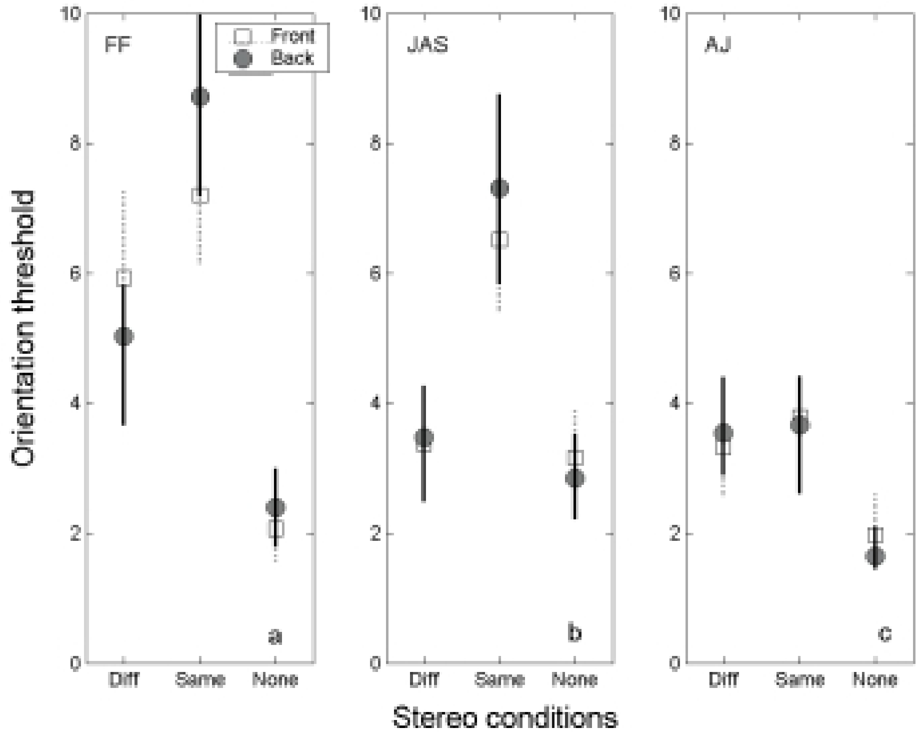
Accuracy
CG
MJM
JAS
Mean
4 distractors
15 distractors
a
b
c
d
1
0.75
0.5
1 8 16 32 64
Relative Target Orientation (deg)

Figure 5



Δ Target contrast
Δ Flankers contrast
FF
AJ
JAS
FF
Threshold elevation (ratio)
6
5
4
3
2
1
a
b
1
2
3
[Target/Distractors]

Fig 6



Orientation threshold
FF
Front
Back
JAS
AJ
a
b
c
Diff
Same
None
Stereo conditions

Figure 7