PERGAMON

Vision Research 39 (1999) 4161–4171

Vision Research

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Detecting collinear dots in noise

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Received 25 November 1998; received in revised form 17 May 1999

Abstract

We estimated the sensitivity for detecting a row of collinear target elements (usually dots) by measuring the maximum density of randomly positioned noise elements that allowed 75% correct detection of the orientation of alignment (binary choice: horizontal versus vertical) of the target elements. We varied the number of target elements, their mode of generation, and their accuracy of positioning. As reported previously (Moulden (1994) *Higher-order processing in the visual system.* Ciba Foundation Symposium 184. Chichester: Wiley), target detection improved rapidly until the number of target elements reached about seven, and then improved more slowly beyond this point. However, this break was reduced (and often removed entirely) when the target array was formed by repositioning pre-existing noise elements lying close to the target location, rather than by superimposition of additional target elements onto the noise array. This almost linear slope of improvement, coupled with the observation that target detection was disrupted more by random jitter of target elements at right angles to their axis of alignment than by jittering along this axis, argues against a two-stage process of perceptual grouping (Moulden, 1994) and supports instead an explanation based on the operation of a single mechanism. This single mechanism explanation is further supported by the observation that intrinsic positional uncertainty (estimated from the results of jitter experiments) was independent of target element number. Additional experiments showed that target detection is facilitated by aperiodic noise dots that fall close to the target axis. The results are discussed in relation to alternative explanations of perceptual grouping. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Perceptual grouping; Positional noise; Collector units; Collators; Association fields; Spatial filters; Gestalt theory

1. Introduction

The visual system is adept at detecting meaningful groups of discrete target elements embedded in large numbers of similar but randomly-arranged distractor or noise elements. The immediacy of this type of performance suggests the existence of preattentive processes that detect features for subsequent ‘object’ processing. At the descriptive level Gestalt psychologists identified fundamental principles such as good continuation, proximity, and similarity (Wertheimer, 1938). At the computational level, the processes underlying perceptual grouping attracted early interest (e.g. Beck, 1966; Uttal, 1975; Beck, 1976) and have recently become the subject of detailed investigation and modelling (e.g. Smits, Vos & van Oeffelen, 1985; Field, Hayes & Hess, 1993; Kovacs & Julesz, 1993; Kovacs, 1996). The following series of experiments are designed to characterise processes underlying perceptual grouping on the basis of differential density, alignment, and spacing.

The present experiments employed a paradigm similar to that of French (1954) and Uttal (1975) that was most recently used by Moulden (1994) to measure detectability of collinear arrays of line segments embedded in a background of randomly oriented and positioned line segments. His performance measure was the number of ‘noise’ elements within the stimulus aperture required to mask the ‘target’ elements. When the log of this density measure was plotted against the log of the number of target elements the result was well-fit by two straight lines: a steep line of slope 1 for targets consisting of up to seven elements, and a shallower line with a slope of approximately 0.5 for targets of greater than

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PII: S0042-6989(99)00125-X

seven elements. This pattern of results was interpreted as evidence for two consecutive stages of orientation processing implemented by groupings of approximately seven collinearly-arranged spatial filters having similar orientation preference feeding into second-stage 'collator' units[1]. The response of these collators (and corresponding target detectability) might be expected to increase in direct proportion to the number of target elements ('physiological summation') up to about seven elements, beyond which further improvement in detectability would be due to recruitment of neighboring collators (via 'probability summation'). We have had difficulty with the theoretical basis for Moulden's assertion that 'physiological summation' would result in a slope of 1 when the background noise density is plotted against the number of target dots using log/log axes, for according to standard theory the masking power of the random dot background would increase as the square root of dot density, not linearly, so the theoretically predicted slope on log/log plots is steeper than Moulden's results (and our own) show them to be. We have set out this theory in the Appendix.

Although our experiments were provoked by early encouraging support for the collator explanation, we were also interested in addressing issues raised by two alternative classes of explanation of perceptual grouping: (i) Spatial frequency explanations that typically propose a linear combination over the receptive fields of single units that are large enough to allow simultaneous excitation from the target elements (e.g. Caelli, 1985; Beck, Sutter & Ivry, 1987; Bergen & Adelson, 1988; Compton & Logan, 1993); and (ii) association explanations that postulate local cooperative interactions between neurones with similar spatial selectivity that are in close proximity (e.g. Beck, Prazdny & Rosenfeld, 1983; Grossberg & Mingolla, 1985; Smits et al., 1985; Beck, Rosenfeld & Ivry, 1989; Nothdurft, 1991; Field et al., 1993; Polat & Sagi, 1993, 1994).

In the present experiments we repeated Moulden's experiment using dots instead of short line elements, and replicated the bilinear slope of improvement he reported. However, we also conducted a variant in which the target dots were made by rearrangement of pre-existing noise dots nearest to the required target position, rather than simply adding a target dot at that position to the noise array. This radically changed the result, essentially eliminating the break at seven elements reported by Moulden, with resultant performance adequately described by a single slope. Additional experiments looked in more detail at the effects of the spatial configuration of the noise dots in the immediate vicinity of the target, and the effects of spatial configurations (and perturbations) of the target dots. These experiments showed that grouping processes are more sensitive to alignment jitter than to separation jitter, with intrinsic positional uncertainty of underlying mechanisms (estimated from the jitter experiments) shown to be independent of the number of dots comprising the target. In addition these experiments showed that noise dots falling close to the target axis actually facilitated performance whereas those falling away from the axis hindered performance. The implications of our findings for various explanations of perceptual grouping will be considered further in Section 4.

[1] Morgan and Hotopf (1989) suggested the existence of similar mechanisms with orientated sub-units and referred to them as 'collector units' (also see Morgan & Baldassi, 1997). We have used the term 'collator units' solely in order to be compatible with Moulden (1994), whose findings motivated the current study.

2. General methods

2.1. Observers

Observers were two of the authors and one naive observer. All three were highly practiced at making psychophysical judgements.

2.2. Apparatus and stimuli

All stimuli were generated by a Silicon Graphics computer, and displayed on a TFS6705KG-SG monitor having a frame rate of 67 Hz and viewed from a distance of 1.3 m. Stimuli consisted of noise and target elements which were either all 'dots' or all 'lines' presented within a 10.1° diameter area. The dots were squares of side 5.5 arcmin, and the lines were rectangles 8 arcmin long and 1.8 arcmin wide; a patch of screen with no dots or lines had a luminance 0.9 cd m^{-2}, and when completely filled by these dots or lines it had a luminance of 78.2 cd m^{-2}.

Unless stated otherwise, the target was a set of aligned and equally spaced dots (dot separation centre-to-centre was 24.3 arcmin) embedded in random dot noise. The target consisted of 3, 4, 5, 6, 7, 8, 9, 10, 14, 16 or 20 dots aligned horizontally or vertically. The centre of the target was randomly displaced from the centre of the stimulus aperture by up to 30.4 arcmin in the horizontal and vertical directions. On each trial target and distractor dots were simultaneously presented for a duration of 210 ms. Within a block, the number of target dots was kept fixed while the number of noise or distractor dots (or background noise density, since the stimulus area was held constant) was varied. Observers reported the perceived orientation of the target using a left (vertical) or right (horizontal) button press and the percent of correct responses for each distractor number was recorded.

2.3. Procedures

Target detection limits were measured using a self-paced method of constant stimuli. Each block consisted of 180 trials with a fixed number of target elements; the nine levels of number of distractor dots were tested 20 times in pseudo-random order (i.e. random selection without replacement). The nine levels were equi-spaced on a linear scale and chosen so that the responses covered a large part of each observer's psychometric function. Between blocks the number of target elements was varied. Detection limits were based on the combined results of multiple runs (at least two blocks per condition), and are reported as the number of background dots giving 75% correct performance, according to a cumulative normal Gaussian fit to the percent correct data as a function of the number of distractor dots, with its lower asymptote set at 50%, and its upper asymptote set at 100% (as in Moulden, 1994). We refer to this estimate of the number of background dots in the 10.1° diameter field yielding 75% correct performance as the sensitivity of the observer[2]. Preceding the actual collection of data observers received practice at all levels of target dot number until their performance stabilised.

3. Results and discussion

3.1. Experiment 1: bilinear versus linear slope of improvement

Evidence in support of collator-type processes rests mainly on Moulden's observation that, on double logarithmic coordinates, the density of noise elements required to mask lines with varying numbers of target elements follows two straight lines, and that the inflection point of this bilinear function is unaffected by the separation between target dots. We reasoned that this bilinearity may be an artefact, since the density of the elements across the stimulus is not uniform but increases where the target is. Such an artefact would have a greater effect on the detection limit for targets composed of few elements, where the masking density is low, but would have a minimal effect on the detection limit for targets composed of a large number of elements, where the number of masking elements at the detection limit is large and the addition of a few more elements would not significantly alter element density.

To test this notion, when we added the target elements to the distractor elements, we also removed the distractor element that was nearest to each target element. In other words, targets were produced by rearrangement of the closest pre-existing distractors. Fig. 1 shows a schematic representation of the stimuli for the conditions with the nearest distractor retained and with the nearest distractor removed, respectively. We refer to these two conditions as the uncompensated and the compensated conditions, respectively, since the removal of the nearest distractor is a pseudo-compensation for the addition of the target element. Fig. 2 shows a typical psychometric function obtained and the resulting estimate of the sensitivity as described above in Section 2.

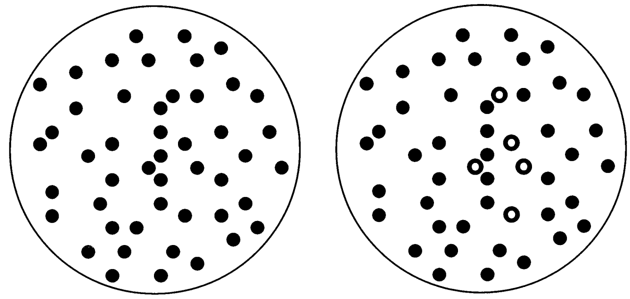

Fig. 1. A schematic representation of the stimulus. On the left is shown the uncompensated stimulus used in experiment 1, with the target dots superimposed on the background of randomly positioned noise dots. On the right is shown the corresponding compensated stimulus, wherein the open circles represent dots that were removed from the background dots in order to compensate for the superimposed target dots. The figure is not drawn to scale, with the dots being shown relatively larger and the dot densities being much lower than those used in the experiments.

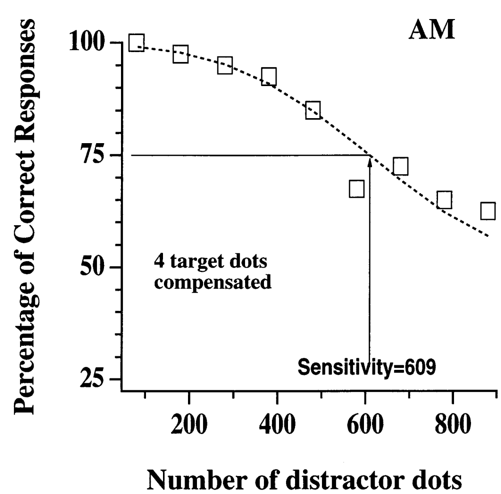

Fig. 2. A sample psychometric function for observer AM for a target consisting of four target dots, with the background having been compensated for the addition of the target dots. The dashed line represents a reversed cumulative normal fit to the data points. The arrow marks the 75% correct point on the fit and the corresponding abscissa value of 609 represents the sensitivity of the observer for the above conditions.

[2] We could have defined sensitivity as the number of background target elements yielding 84% correct responses ($d' = 1$). While this would have made our results more easily interpretable, it would have made comparison with Moulden (1994) more difficult.

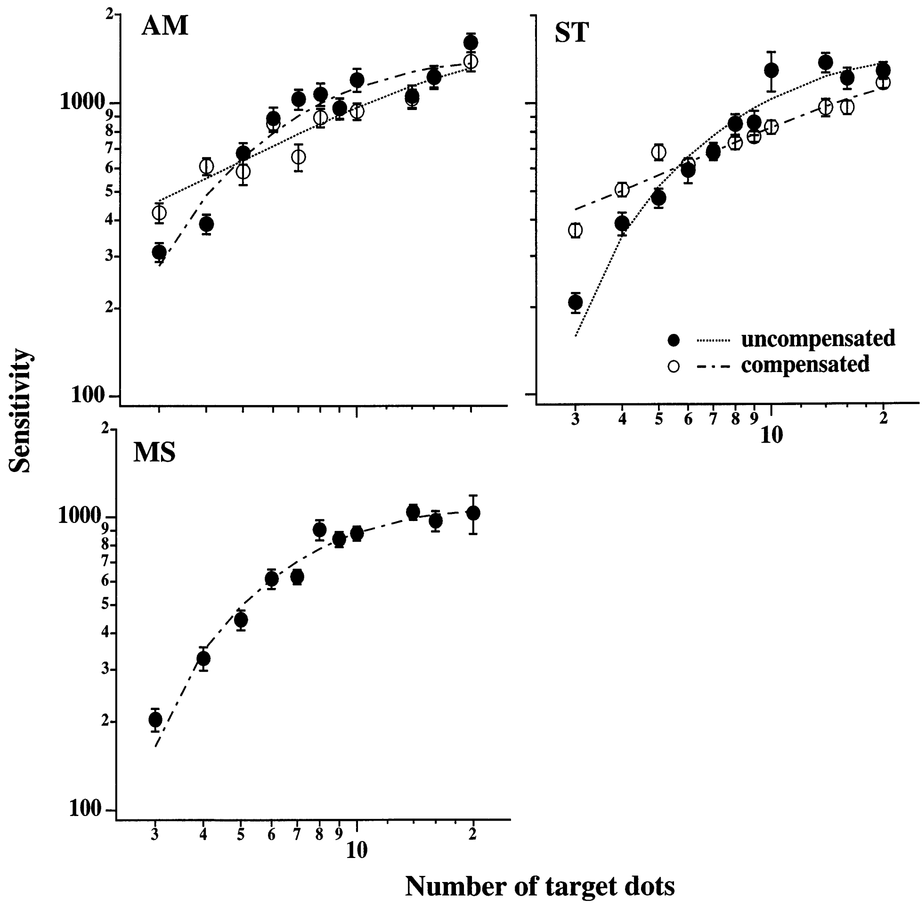

Fig. 3. The sensitivity of the observers plotted against the number of target dots. The data have been fitted by exponential curves. The filled symbols represent data for the uncompensated stimulus and the open symbols represent those for the compensated one. Error bars represent ± 1 S.E.

Fig. 3 shows the results for three observers for the uncompensated stimulus, and two observers with the compensated stimulus. In this experiment dots were employed both as targets and distractors. The figure represents observers' sensitivity as a function of target dot number (plotted on log–log axes). The fitted curves are exponentials but because of the theoretical importance of the inflection point, and of the slopes of the two linear components, we also fit two straight line segments (bilinear fits) to the data and show the results in Table 1.

Inspection of Fig. 3 reveals that for the uncompensated stimulus performance was clearly bilinear, with respect to target dot number: For all observers the inflection point occurred at around seven dots (see Table 1), with the initial slope of improvement (>1.0) greater than the second slope of improvement (<0.5). Thus, Moulden's original result was confirmed when dots were used in place of short line segments.

For the compensated stimuli, an entirely different pattern of results was obtained. In order to quantify these differences objectively two criteria were employed: (i) was it possible to fit a bilinear function to the data? (ii) were the two slopes (less than seven elements versus greater than seven elements) different? For neither observer's data was it possible to fit bilinear functions that had a *stable* point of inflection. Given this, and in order to make direct and objective comparisons of slopes, the inflection points derived from the uncompensated data were applied to the compensated data, and bilinear fits performed (i.e. the inflection points were treated as constants in these fits). The results from these fits are included in Table 1, and show that for both observers the slope of the function for targets of less than seven elements (approximately 0.6) was very similar to the slope for targets of greater than seven elements (approximately 0.5). Together, these results suggest that a single linear function was adequate to describe performance over the range of target dot numbers tested. In summary, the results of experiment 1 to some extent undermine previous evidence supporting second-order collator mechanisms.

In considering the results of experiment 1, it is important to note that our method of dot placement only partially compensated for changes in element density resulting from the addition of target elements. In fact, for linearly arranged target elements, perfect compensation is mathematically impossible. For example, even if two-dimensional dot density is constant across the entire stimulus, a projection of all the target and background dots onto any straight line orthogonal to the target axis would show a peak in the one-dimensional density at the location of the projection of the target dots. Other studies have taken greater pains to attempt to compensate for density (e.g. Field et al., 1993; Kovacs & Julesz, 1993; Braun, 1999), but the simplicity of our method permits mathematical analysis as outlined in the Appendix.

In our experiments, when the number of background dots was small, our method had the disadvantage of introducing 'holes' along the sides of the target. These 'holes' were presumably responsible for the improved sensitivity for small target numbers when compensation was used (see Fig. 3). However, our purpose was to show that a small change in the strategy for placing the noise dots can eliminate the bilinear response function that Moulden (1994) reported; a complete compensation for density was not intended. Presumably, the slight change in the dot placement strategy would not have resulted in a change in the mechanisms involved in target detection: if collator units were involved in the original Moulden experiments, then the same units were involved in our experiments. But the absence of bilinearity in our data questions previous interpretations based on physiological summation within, and probability summation between, collator units.

Table 1
Results of bilinear fits: experiments 1 and 3 with 2D-jitter[a]

Collinear dots				
2D-jitter		±0 min	±6 min	±12 min
		Uncompensated		
AM	Inflection	6.1	6.6	6.7
	Slope 1	1.71	1.06	1.83
	Slope 2	0.38	0.62	0.08
ST	Inflection	8.0	8.4	8.0
	Slope 1	1.5	1.06	1.08
	Slope 2	0.42	0.56	0.55
MS	Inflection	8.0	–	–
	Slope 1	1.39	–	–
	Slope 2	0.23	–	–
		Compensated		
AM	Inflection	6.1*	6.6*	6.7*
	Slope 1	0.71	0.78	0.98
	Slope 2	0.50	0.54	0.42
ST	Inflection	8.0*	8.4*	8.0*
	Slope 1	0.55	0.63	0.65
	Slope 2	0.47	0.40	0.28
Replication of Moulden (1994)				
		Uncompensated	Compensated	
AM	Inflection	7.4	7.4*	
	Slope 1	0.74	0.46	
	Slope 2	0.32	0.38	

[a] Standard error values are all less than 5%.
* From the uncompensated-data fit.

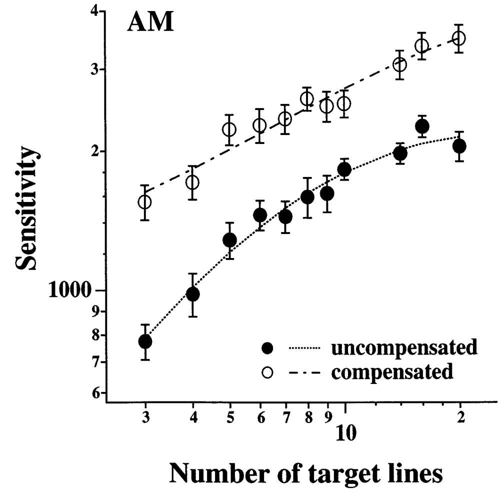

Fig. 4. Sensitivity plotted against the number of lines making up the target. The filled and open symbols represent data for the uncompensated and compensated stimuli, respectively.

Since we used dot stimuli, whereas the majority of Moulden's (1994) data were obtained using line segments, experiment 1 was repeated using line segments. The methods were the same except that: (i) target lines were always parallel to global target orientation (e.g. vertical targets were always composed of vertical line segments); and (ii) distractor lines were randomly mixed composites of vertical, horizontal, left-oblique, and right-oblique. Inspection of Fig. 4 (and the summary statistics for bilinear fits, included in Table 1) clearly shows bilinear perceptual grouping performance for the uncompensated stimulus, and linear perceptual grouping performance for the compensated stimulus, when the results are plotted on double logarithmic coordinates (note, the orientation of the distractor was ignored when removing the nearest distractor).

While performance was very similar whether the target and noise elements were all dots or all lines, there was a difference between the two conditions. Compensation by removing nearby background elements caused an increase of sensitivity under all conditions with line elements, whereas with dot elements it enhanced performance for small target numbers and lowered performance for large target numbers. For lines, the elements removed usually had a different orientation from the row of elements, so their removal perhaps led to a greater improvement of signal/noise ratio than that resulting simply from the removal of a dot element. It is more difficult to account for the decrease of performance resulting from removal of the dots that was observed when the number of dotted targets was large, but a possible explanation, based on the notion that noise dots lying close to the target alignment axis might assist detection, is explored in the following experiment.

3.2. Experiment 2: coaxial versus orthogonal neighbouring elements

The spatial configuration of the noise dots may influence grouping performance and we modified our stimulus to test this hypothesis. To construct this modified stimulus we split the region around each target dot into four quadrants using two virtual lines passing through the target dot and inclined at $\pm 45°$ to the axis of alignment of the target dots. In one experimental condition, for each target dot, the nearest neighbouring background dot was removed from within the coaxial quadrants (i.e. the two quadrants that were bisected by the target axis), and in the other condition it was removed from the orthogonal quadrants (i.e. the remaining two quadrants). Nearest neighbours within the coaxial quadrants, being closer to the axis of the target, might influence performance to a different extent from nearest neighbours within the orthogonal quadrants.

Fig. 5 shows data for two observers for the two conditions tested. Comparing performance in the two conditions, for almost all target numbers, the observers performed better when the nearest neighbour was removed from the orthogonal quadrants. A comparison of these results with those of Fig. 3 shows that for target numbers greater than seven, removing the nearest coaxial neighbouring dot resulted in a drop in performance (MS showed a smaller effect) relative to that for the uncompensated stimulus in experiment 1; removing the nearest orthogonal dot resulted in relatively enhanced performance. Taken together these observations provide a plausible explanation for the non-intuitive finding in experiment 1: when the noise dots are removed from any quadrant some of the removed dots would be from coaxial quadrants and some would be from orthogonal quadrants. Removal of the former would result in a drop in performance and the latter an enhancement in performance; the net effect is the small drop in performance seen in Fig. 3.

The present results thus suggest that noise dots that fall very close to the axis of the target actually facilitate detection of the target. By varying the angle between the virtual dividing lines and the target axes we could more accurately separate out excitatory and inhibitory regions. We have not done this explicitly. However, our results in Fig. 5 point to the existence of such excitatory and inhibitory regions in the vicinity of the target. Similarly, Uttal (1975) showed that the sensitivity for detecting collinear dots in noise is reduced when slight non-periodicities are introduced into the positioning of the target dots. The drop in performance with removal of coaxial noise dots indicates that additional dots that are non-periodic and close to the target axis also enhance detection. The following experiment explores the influence of target dot periodicity on perceptual grouping.

3.3. Experiment 3: perceptual grouping with positional jitter

It is well known that alignment of target elements is important for perceptual grouping (e.g. Beck et al., 1989; Field et al., 1993). We conducted experiments to obtain additional information on the spatial properties of mechanisms underlying the detection of collinear dots by adding a random component (a 'jitter' of ± 6 or ± 12 min) to the selected positions of the target dots forming the lines. We began with jitter of target dots in both directions, and then measured separately the effects of alignment and separation jitter. Figure 6 summarises results for two observers without and with compensation (the data from experiment 1 are included

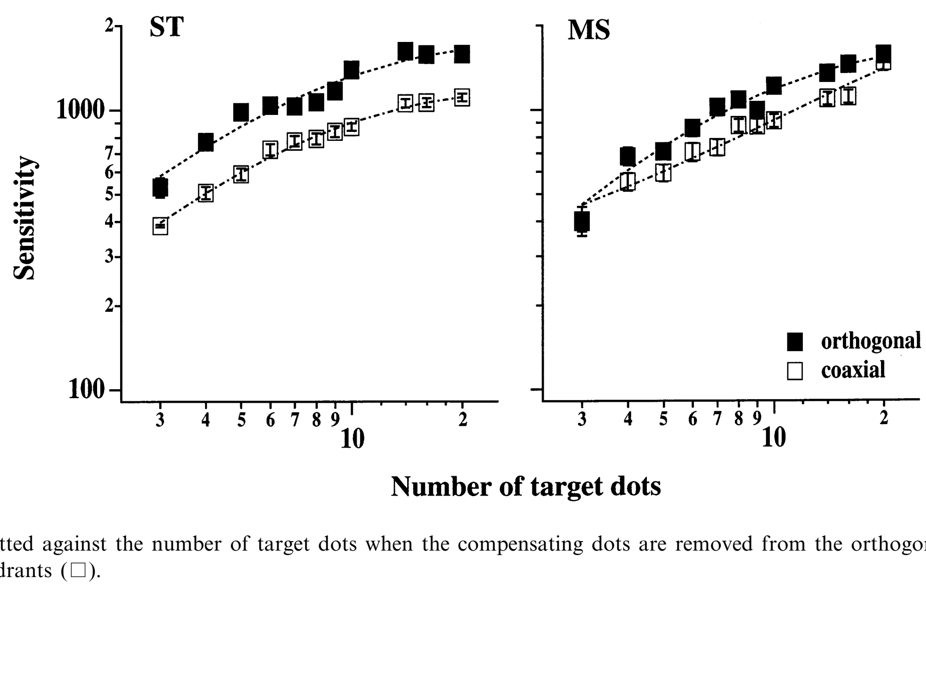

Fig. 5. Sensitivity plotted against the number of target dots when the compensating dots are removed from the orthogonal quadrants (■) and from the coaxial quadrants (□).

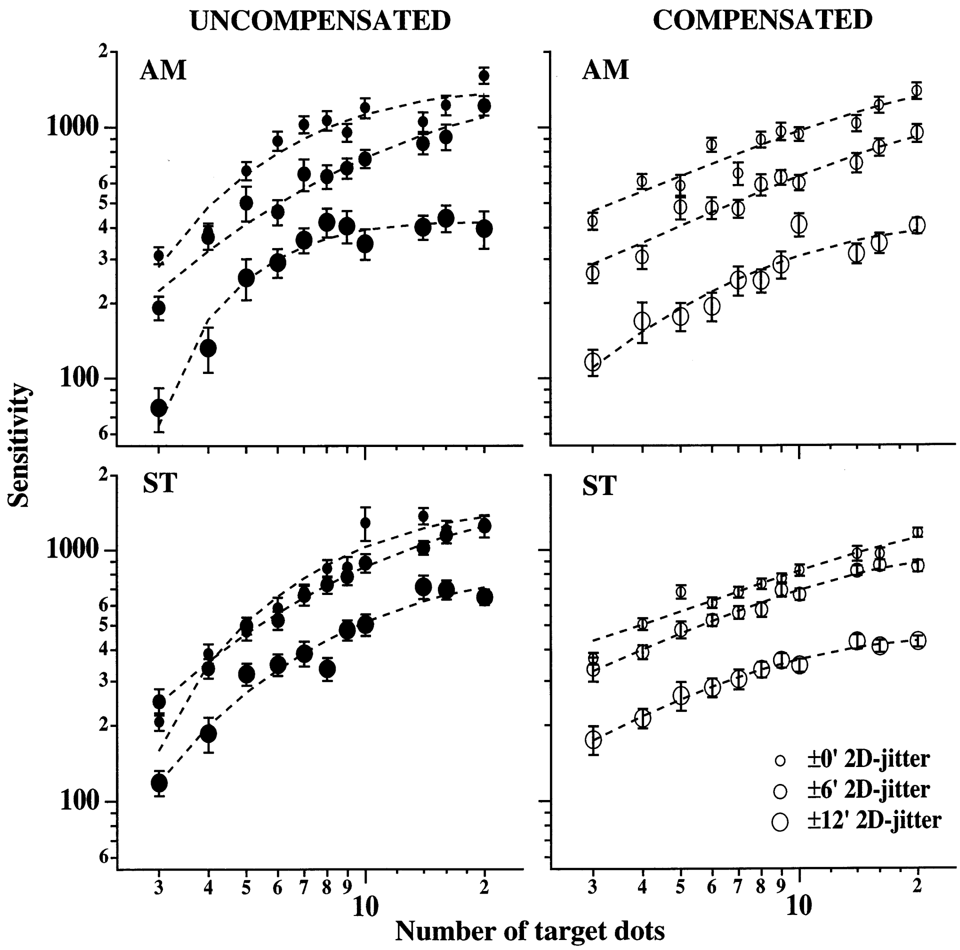

Fig. 6. Sensitivity plotted as a function of the number of target dots for uncompensated stimuli (left column) and compensated stimuli (right column). Each panel shows data for three conditions: no positional jitter, up to ± 6 arcmin jitter, and up to ± 12 arcmin jitter added to the position of each target element. Larger symbol sizes represent greater amounts of target jitter.

as 0-jitter controls). Inspection of the figure shows that positional jitter decreased sensitivity for target detection uniformly across all target dot numbers tested. These data also confirm the results of experiment 1 over all levels of positional jitter tested: removal of nearest neighbour distractor dots changed the form of the relation similarly with and without jitter (refer to Table 1 for details of bilinear fits).

Fig. 7 shows the ability to detect the lines with one level (± 12 min) of alignment jitter versus separation jitter. Since these data were obtained in the compensated condition following removal of proximal distractor dots, slopes of improvement were quasi-linear (refer to Table 2 for details of bilinear fits). Inspection of the figure clearly shows that the ability to detect the line is disrupted more by alignment jitter than separation jitter. These results are consistent with all explanations of perceptual grouping in that these explanations have in common the assumption that underlying mechanisms are elongated and thus more susceptible to misalignment around this axis of elongation. For example, both collators and their subunits are taken to possess elongated receptive fields, as are the spatial filters underlying spatial frequency explanations, and the subunits that comprise association fields.

3.4. Experiment 4: intrinsic positional noise as a function of target dot number

Collator and association explanations have in common the notion that increasing target element number will lead to recruitment of additional subunits that are maximally responsive to the elements. These explanations predict fixed spatial-frequency tuning, and thus fixed sensitivity to positional jitter with increasing target element number. However, spatial frequency explanations propose that a single filter underlies detection of grouped elements, with larger/longer element configurations necessitating larger/longer filters (i.e. of lower spatial frequency). One can propose a variant of spatial frequency explanations in which perceptual grouping of long chains of elements is coded for by the

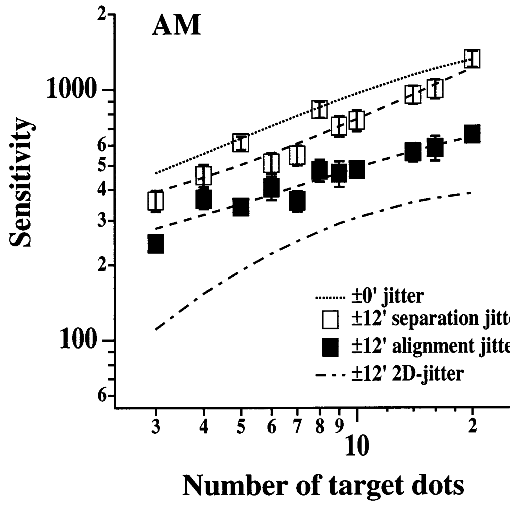

Fig. 7. Sensitivity for a stimulus with a target having a ±12 arcmin separation jitter is compared with one having a target with ±12 arcmin alignment jitter. Also shown are the fits to data obtained with no target jitter and when the target elements were jittered by ±12 arcmin along both the separation and alignment directions.

combined activity of chains of high spatial-frequency filters, but this model is essentially an association field and thus offers no novel prediction. We measured target detection as a function of both target dot number (3, 7 and 20) and of two-dimensional positional jitter of target dots (from ±0 to ±12 min) in order to obtain estimates of intrinsic positional uncertainty of the underlying processes. The rationale for this is that random jittering of target dots should affect target detection only when this *extrinsic positional jitter* becomes comparable to or exceeds the *intrinsic positional uncertainty* of underlying mechanisms. The relationship is given by

$$\theta = k\sqrt{(\sigma_e^2 + \sigma_i^2)}$$

where θ is threshold, k is a constant, σ_e is extrinsic positional jitter, and σ_i is intrinsic positional uncertainty (cf. Barlow, 1978; Pelli, 1990). When extrinsic and intrinsic uncertainty are quantitatively equal, the threshold is elevated by a factor of $\sqrt{2}$ or sensitivity is reduced by a factor of $1/\sqrt{2}$. In Fig. 8, the results are shown in terms of sensitivity as a function of external jitter. As expected on the basis of experiment 3, performance deteriorated with increasing jitter. The data were fit with noise functions, and resultant values of σ_i (i.e. the external jitter required to *reduce* sensitivity to $1/\sqrt{2}$ of the asymptote) are shown by vertical lines in the figure. Inspection of the figure shows that the decrement in performance with increasing target jitter (when plotted on log–log axes) varied slightly and irregularly with target dot number. This indicates the involvement of the same processes in detection of both small targets and large targets. This result contradicts a simple spatial-frequency explanation of perceptual grouping.

Table 2
Results of bilinear fits: expt 3 with 1D-jitter[a]

		Alignment jitter ±12 min	Separation jitter ±12 min
AM	Inflection	6.7*	6.7*
	Slope 1	0.48	0.52
	Slope 2	0.44	0.67

[a] Standard error values are all less than 5%.
* From the uncompensated-data fit.

4. Discussion

The main interest of the results contained in this paper lies in their implications for the mechanisms by which the eye can pick out a row of aligned dots in a random background. Although the experiments were planned to add support to existing ideas about these underlying mechanisms, the results do little to support any existing theory. Thus, the case for Moulden's (1994) two stage mechanism is much weakened by finding that the break in his curves is largely dependent on the mode by which the targets are produced: that is, by adding new dots (and thereby increasing local density) to a pre-existing background array rather than by rearranging pre-existing dots within this background array (Fig. 3). In addition, the straightforward noise theory set out in our Appendix predicts a slope of 2 on a log/log plot for element numbers below seven, not one as Moulden claimed.

The experiment looking at the effects of the spatial configuration of the noise dots by rearranging noise dots lying either in coaxial or in orthogonal quadrants showed that 'noise' dots falling close to the axis of the target actually facilitated the detection of the target whereas noise dots falling further from the axis masked the target. This suggests that while periodicity has an important influence on performance (Uttal, 1975, and Fig. 7), non-periodic dots can also facilitate performance.

The experiments with jitter were designed to test the hypothesis that neurones responsive to larger, lower spatial frequency, components of the image were responsible for detecting the targets containing large numbers of dots, for one would expect the allowable range of jitter to increase along with the lowering of optimum spatial frequency. In fact, the analysis of these data shown in Fig. 8 suggests that there is little if any increase in allowable jitter with increasing number of dots in the target.

In Section 1 three main classes of explanation were mentioned: collator theories, spatial frequency theories, and association theories. Overall, we think our results are probably compatible with this last class, but these explanations do not make specific predictions about

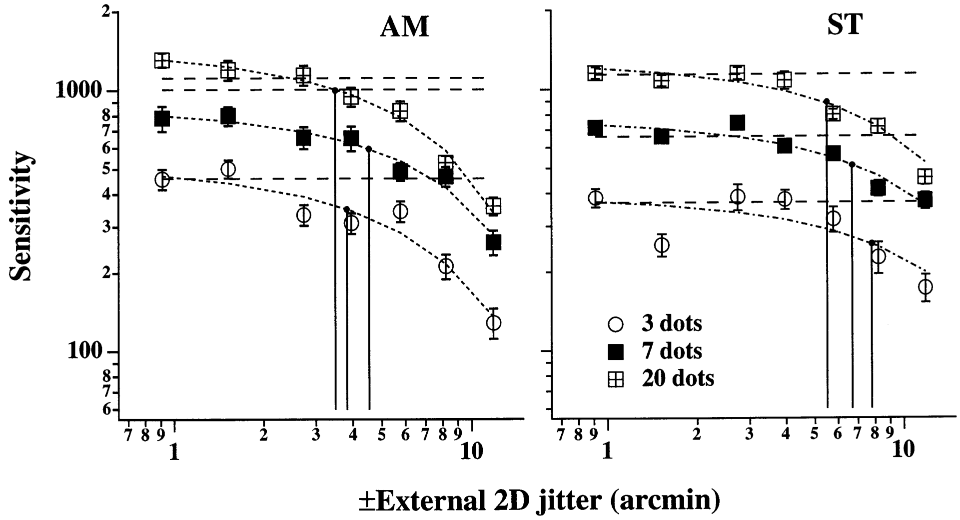

Fig. 8. Sensitivity plotted as a function of the amount of jitter added to the target elements along both the separation and alignment directions. Data is shown for targets consisting of 3, 7 and 20 dots. The dashed horizontal lines indicate sensitivity for the unjittered stimulus, larger target numbers being associated with greater sensitivity. Dots and sticks mark the internal jitter of the observer as indicated by a drop in sensitivity to $1/\sqrt{2}$ of the asymptotic value of the fit to the data.

either the form of the relation with number of dots in the target line, or the effects of jitter, or the absolute values of masking density to be expected, so our results cannot be claimed to add much support to them.

In summary, our results show that contrary to Moulden's proposal a single mechanism is adequate to describe human performance for detecting a target of collinear dots among noise dots. This detection can be facilitated by having additional non-periodic 'noise' dots falling close to the axis of the target. The detecting mechanism is very robust to positional jitter of the target dots. The internal positional jitter of the mechanism is independent of the number of target elements, which further supports the single mechanism hypothesis. Several simplified models have been proposed and their implications for performance discussed. However, at this moment none of these models can satisfactorily explain all our data.

Acknowledgements

Supported by the Australian Research Council, BBSRC (UK) and The Wellcome Trust (UK). Some of these experiments described here were previously presented at the European Conference on Visual Perception, 1996 and 1998.

Appendix A. Simple template theories for detecting rows of dots

The simplest model we can think of for detecting a row of dots postulates a rectangular template that gives an output proportional to the number of dots within it and is applied at all positions and all orientations in the field at which a line may occur. At most positions the output will follow the calculable statistics for the random background at whatever mean dot density is being considered, but where the row of dots falls completely within the template this number is incremented by the number of dots in the row.

The masking dots have density D per unit area, the number of dots in the row is N (assumed to be greater than 2), and the parameters of the template are length L and width W, the units of length and area being given by the separation of dots in the row (24.3 arcmin) and its square (0.164 deg^2).

The predicted threshold density D_0 for the masking dots is the value where the standard deviation of the number falling within the template allows 75% correct responses in the 2-AFC test with an N dot separation of noise-alone and signal-plus-noise distributions. This occurs when the two distributions corresponding to masking dots alone, and masking dots with the N target dots added, are separated by 1.349 times the standard deviation of the number from the masking dots. We give the simple theoretical predictions for three cases:

1. The template is of fixed length, which we think is closest to the theory Moulden had in mind. The width is also fixed.
2. The optimal performance occurs if the template is adjusted to accommodate the exact number of dots in the target, so $L = N$. The width is assumed constant and of value w times the separation of the dots.
3. The length is as above, but the width increases in proportion to the length, so $W = kL$

(i) *Template of fixed length and width*

The expected number of dots $\langle \Delta S \rangle$ falling within the template from the background alone is LwD, and this can be taken to be Poisson distributed with variance LwD. When the aligned dots are added to the background, the number will be incremented by N. Hence we can say:

$$\langle S \rangle = LwD \pm \sqrt{LwD}$$

$$\langle \Delta S \rangle = N$$

For 75% correct the separation corresponding to N dots is 1.349 $\sigma(S)$, so

$$N = \langle \Delta S \rangle = 1.349\sqrt{LwD_\theta}$$

$$D_\theta = N^2/1.82Lw$$

(ii) *Template of length matching the row of dots and fixed width*

Here $L = N$ and $\langle \Delta S \rangle = N$ as before, so for 75% correct

$$N = \langle \Delta S \rangle = 1.349\sqrt{NwD_\theta}$$

$$D_\theta = N/1.82w$$

(iii) *Template of length matching row of dots and width proportional to length*

Here in addition to the above, $W = kL = kN$, so for 75% correct

$$N = \langle \Delta S \rangle = 1.349\sqrt{kN^2D_\theta}$$

$$D_\theta = 1/1.82k$$

To summarize, the simplest template theory we can devise predicts a slope of 2 on the log/log plot if the template is of fixed length and width, a slope of 1 if the length is adjusted to the length of the row of dots and the width is constant, and a slope of zero if the template is adjusted in length and the width is adjusted in proportion. We do not see how to reconcile these results with Moulden's prediction of a slope of one in his collator model, though the observed slopes are actually greater than 1 (see Table 1).

Notice that, making reasonable assumptions about the width of the template, the masking densities predicted on these models are considerably higher than those actually measured. For instance on the first model if $w = 0.5 = 12.15$ arcmin, $N = 3$, and the template is assumed to be 7 dot separations long, the predicted masking density is 8.6 dots/deg^2, or 689 per field, whereas the experimental values for AM and ST are 310 and 207. For $N = 7$, the prediction is 3760, compared with experimental values of 1031 and 684.

Future template models

The above models would not be expected to apply if the row of dots is longer than the fixed length of the template, or longer than the maximum length to which it can be adjusted, though it should be possible to extend the models by including the idea of probability summation. The models would not be expected to apply to the results obtained when removing proximal distractors, for this will tend to create zones with reduced dot densities lying parallel to the row of dots. However the present results do not rule out such models, and the results with jitter and with selective removal of distractors from different quadrants surrounding the dots in the row offer interesting material to test them against.

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