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Asymmetries of saccadic eye movements in oriented-line-target search

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Abstract

Visual search for a line-element target differing sufficiently in orientation from a background of line elements can be performed rapidly, effortlessly, and without eye movements. There is, however, a response asymmetry: detection is better with an oblique target element in vertical or horizontal background elements than when these orientations are interchanged. If the underlying visual mechanisms also provide an input to the oculomotor system, then a similar asymmetry should be observed in eye-movement behaviour. To test this hypothesis, an experiment was undertaken in which eye movements were recorded while subjects searched for a line-element target in background of line elements; orientations were chosen from the range 0°, 30°, 60°, and 90° to the vertical. Data from three subjects showed that (1) latencies for the initial saccade, (2) angular errors in initial-saccade direction, and (3) manual response times depended similarly on the combination of target- and background-element orientations, performance being better for 30° or 60° targets in 0° or 90° backgrounds than vice-versa. The early orientation-selective mechanisms responsible for the rapid detection of oriented-line targets are probably the same as those providing signals for saccadic eye movements. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Saccadic eye movements; Search asymmetry; Orientation sensitivity; Target detection

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1. Introduction

Fig. 1 shows two line-element displays: in (a) the oblique ‘target’ element is more easily detected than in (b) where the orientations of target and background elements are interchanged. This asymmetry has been found both in the time taken to make a manual response (Sagi & Julesz, 1985; Treisman & Souther, 1985) and in the proportion of trials in which the target is detected (Foster & Ward, 1991; Poirier & Gurnsey, 1998). In general, searching for a target in a display like that of Fig. 1a can be done rapidly, effortlessly, and without eye movements; indeed reliable detection can be achieved with displays lasting no more than a few tenths of a second. Performance is thought to be determined by the early, preattentive or distributed-attention stages of visual processing (Beck, 1972; Julesz & Schumer, 1981; Treisman, 1985; Nothdurft, 1991). Because performance may depend little on the number of elements in the display, the underlying mechanisms are assumed to act in parallel over the visual field (Bergen & Julesz, 1983; Javadnia & Ruddock, 1988; Doherty & Foster, 1999).

Rapidly detected local features such as oriented lines and edges are commonly assumed to provide one of the visual cues for saccadic eye movements (Binello, Mannan & Ruddock, 1995; Schall, 1995; Zelinsky & Sheinberg, 1997; Scialfa & Joffe, 1998), although relatively little is known about the geometrical properties of individual local features relevant for eye movements. More is known about the detection of line targets in visual tasks where eye movements are unnecessary. Detailed measurements of orientation thresholds for target detection as a function of background-element orientation have led to estimates of the orientation-tun-

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ing characteristics of the underlying orientation-selective mechanisms (Alkhateeb, Morris & Ruddock, 1990; Foster & Ward, 1991; Foster & Westland, 1998). The asymmetry with respect to the interchange of target- and background-element orientations illustrated in Fig. 1 has been explained quantitatively in terms of the signals produced by these mechanisms (a brief account is given later in this report). If these mechanisms also provide signals to the oculomotor system, then it should be possible to find a similar orientation asymmetry in eye-movement behaviour. (This is not of course to deny the importance of cognitive factors in determining search efficiency; see e.g. Findlay, 1995.) A priori, it cannot be assumed that such asymmetries in eye-movement behaviour exist: line orientation has been found to be a poor cue in guiding saccades (Zelinsky, 1996; Motter & Belky, 1998), and even when saccades are successful, they need not be highly localized (e.g. Findlay, 1995).

To test the hypothesis that early orientation-selective mechanisms have an input to the oculomotor system, saccade latencies and angular errors in saccade direction were recorded for stimuli like those illustrated in Fig. 1 over a range of combinations of target- and background-element orientations. Only initial saccades were analysed, for with latencies of a few tenths of a second they should most directly reflect the activity of early visual processes (later saccades may also show greater inter-subject variance; Mannan, Ruddock & Wooding, 1997). Latencies were chosen as they provide an analogue of manual response times used as the dependent variable in search tasks, and directional errors as they provide an indicator of the precision of saccades. As a control, manual response times were also recorded to verify that the stimuli produced the expected asymmetries in search time. It was found that all three response measures depended similarly on the various combinations of target- and background-element orientations.

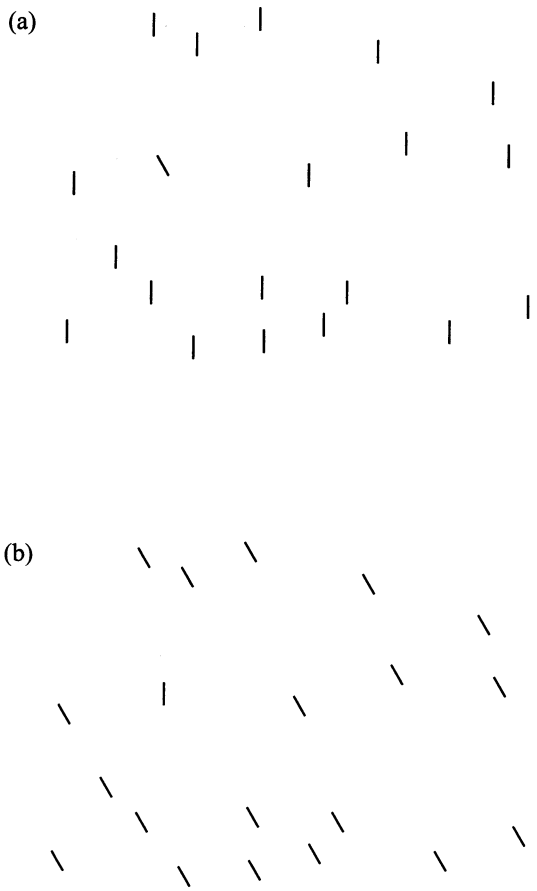

Fig. 1. Typical stimulus displays (in reverse contrast, subtending 25° × 20° at the eye in the experiment). In (a) the target element has orientation 30° to the vertical and the background elements have orientation 0°; in (b) the target element has orientation 0° and the background elements have orientation 30°.

2. Methods

2.1. Stimuli and apparatus

Each stimulus display consisted of 20 bright white line elements distributed randomly over a field subtending 25° × 20° at the eye, as illustrated in reverse contrast in Fig. 1. Each line element subtended 1°, with width approximately 0.04°. All the line elements in the display had the same orientation, except for the target, which was presented with probability 0.75 in each trial, this high proportion being chosen as eye movements with displays not containing a target were not informative here; the latter 'non-target' displays, containing background elements only, had the same number of elements as target displays. The orientations of the target and background elements were chosen randomly from the range 0°, 30°, 60°, and 90° (0° vertical, positive anticlockwise; orientations of 30° and 60° are subsequently termed 'oblique'). The spatial location of the target element was also chosen randomly. The luminous intensity of the line elements was approximately 0.5 mcd (equivalent to approximately 70 cd m^{-2}) and was independent of orientation. The field upon which the elements appeared was uniform and dark, with residual luminance less than 0.1 cd m^{-2}. Subjects did not report the presence of after-images.

Stimuli were presented on the screen of a 20-in. CRT (Hewlett-Packard, D1187A) controlled by a raster-graphics system (Texas Instruments, IGC20), in turn controlled by a laboratory computer. Screen resolution was 1280 × 1024 pixels; intensity resolution was 256 levels per gun. The subject viewed the CRT screen binocularly at 77 cm in a darkened room. Head position was stabilized with the aid of an adjustable chin-rest, forehead-rest, and two temple clamps.

Eye movements were recorded binocularly with an infrared computer-based imaging system (P_scan; Barbur, Thomson & Forsyth, 1987). Two arrays of infra-red LEDs, each covered with an infra-red glass filter, illuminated the subject's eyes. The reflected light was collected by two CCD cameras, working at video rates, although data from only one eye were used. The image of the left eye was analysed by a dedicated processor, which provided summary data comprising the x, y-co-ordinates of the boundaries of the pupil and iris in each video frame. The temporal resolution of the system was 20 ms; spatial resolution was at best 2 arcmin but somewhat lower in practice.

The system was calibrated before each experimental session by the subject fixating a flashing spot of light that moved along the vertical and horizontal meridians on the CRT screen. From these data, the centre of rotation of the eye was computed. To allow for small movements of the head during the course of an experimental session, the origin of the system's co-ordinate frame was reset before each experimental trial by the subject fixating a flashing spot of light at the centre of the screen.

2.2. Instructions and procedure

The task of the subject was to determine in each trial whether the display contained a target, that is, a line element whose orientation differed from that of all other line elements in the display. The instructions were to search for the target, to maintain fixation on it, and to respond manually whether there was a target present by pressing one of two push-button switches on a response box held in the dominant hand, after which the display disappeared. Responses were to be made as quickly as was consistent with accuracy.

Each trial started with the presentation of a fixation cross at the centre of the CRT screen. The subject then pressed a push-button switch on a response box held in the non-dominant hand, and the fixation cross disappeared after 500 ms. After a randomly selected delay of between 300 and 900 ms, the stimulus display was presented until the subject pressed one of the response buttons or the maximum display time of 2.5 s had elapsed.

Each experimental session, which lasted less than 30 min, comprised 10–20 blocks each of eight trials, in which six displays contained a target and two displays did not, in random order. In ten blocks, each combination of target- and background-element orientations occurred five times, also in random order. Each subject performed 1680 trials.

2.3. Subjects

There were three subjects, JS, SM (co-authors), and JB, who were aged 21–30 years and had binocular Snellen acuities of at least 6/6 and astigmatism of not more than 0.25D (for JS after correction with contact lenses). Subjects JS and SM were aware of the nature and purpose of the experiment; subject JB was not. Subject SM was well practised in the task; subjects JS and JB were not.

2.4. Data analysis

The eye-movement x, y-co-ordinate data were analysed off-line by a computer program that characterized saccades, fixations, and other features of the traces; see e.g. Binello et al. (1995). Saccades were generally characterized by a duration of <60 ms and amplitude $>0.3°$; fixations following a saccade were characterized by a duration of ≥ 60 ms during which the trace was localized to an area of diameter $<0.5°$. Traces including blinks were excluded from the analysis.

For each subject, the total number of trials discarded was less than 6%: of these, time-out trials (in which the subject failed to respond manually within the 2.5-s presentation time) comprised 0–6%; incorrect-response trials comprised 0.2–1.4%; and blink trials 0–5.3%. As only three subjects participated in the study, analyses were performed on individual rather than grouped data. Planned comparisons (Lindman, 1974) were used to test for effects of target- and background-element orientation. All tests were one-tailed, except where otherwise indicated.

3. Results

Fig. 2 shows summary data. The three columns of panels are for the three subjects JB, JS, SM; the three rows of panels are for the three measures of visual performance: (a–c) the angular error in the direction of the initial saccade to the target element (defined in the plane of the CRT screen by the magnitude of the angle between the initial-saccade direction and the direction of the target element with respect to the centre of the screen); (d–f) the latency of the initial saccade with respect to the onset of the stimulus; and (g–i) the manual response time, also with respect to the onset of the stimulus. Mean values of the measured variables are plotted against target-element orientation: oblique target (30° or 60°) on a vertical or horizontal background (0° or 90°) and vertical–horizontal target (0° or 90°) on an oblique background (30° or 60°). Vertical bars show ± 1 S.E.M., where sufficiently large. For each subject and each measure, ordinate scales were chosen to maximize the response range (Cleveland, 1994). The single graph (a′) at the right of the figure, a

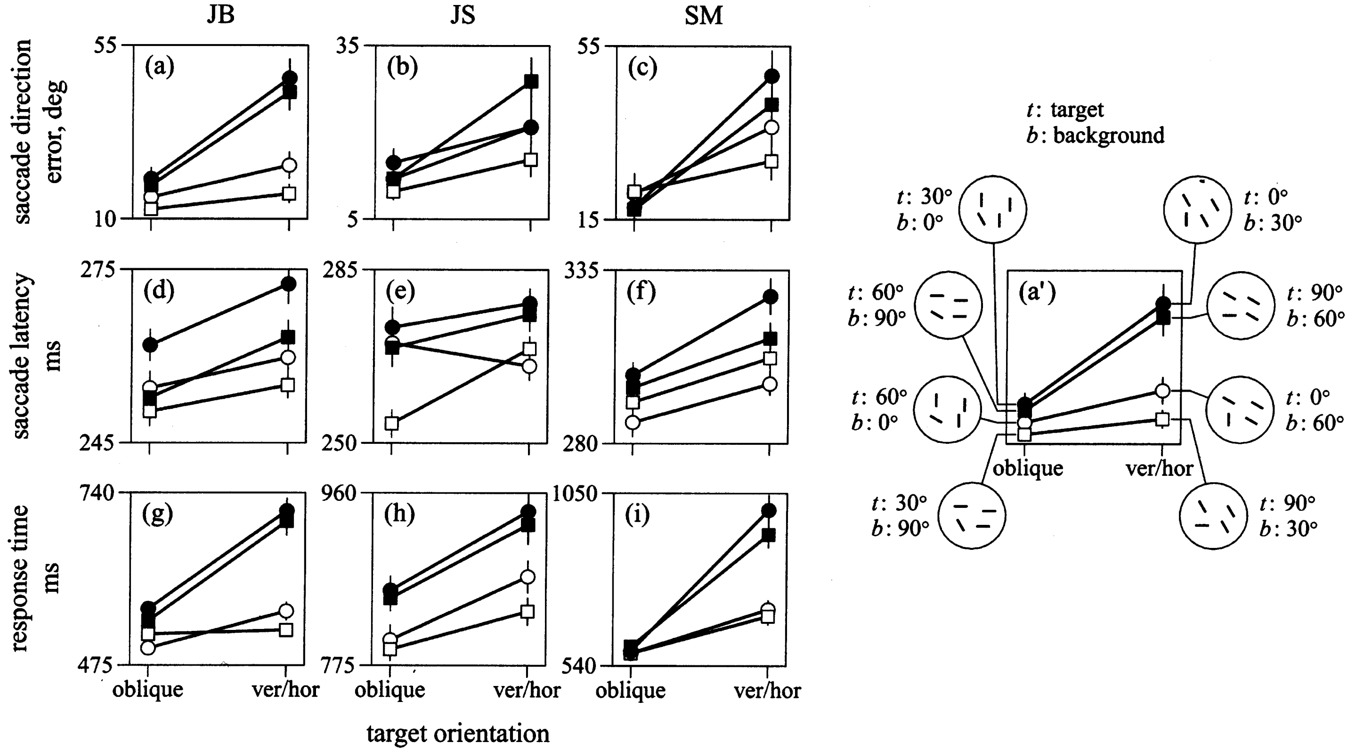

Fig. 2. Asymmetries in oculomotor behaviour and in manual response time with respect to interchange of target- and background-element orientations in visual search. Each panel shows a graph of mean response measure against target-element orientation: oblique target (30° or 60°) on a vertical or horizontal background (0° or 90°) and vertical–horizontal target (0° or 90°) on an oblique background (30° or 60°). Solid symbols are for an orientation difference between target and background elements of 30°; open symbols for an orientation difference of 60°. Vertical bars show ± 1 S.E.M., where sufficiently large. The three columns of panels are for three subjects JB, JS, SM; the three rows for three response measures: (a–c) the angular error in the direction of the initial saccade to the target element; (d–f) the latency of the initial saccade; and (g–i) the manual response time. Ordinate scales were chosen to maximize the range of each response. The single graph (a′) at the right of the figure shows which symbol corresponds to which combination of target- and background-element orientations. The line-element icons indicate only the orientations of target and background elements.

duplicate of (a), shows which symbol corresponds to which combination of target- and background-element orientations; the line-element icons in the circular 'windows' indicate only the orientations of the target and background elements, not their positions or number.

Errors in initial-saccade direction (Fig. 2, a–c) had a distribution with dominant mode at 14°–20° and a weaker secondary mode at 29°–38° (the error range was 0°–180°). Errors were smaller for oblique targets than for vertical or horizontal targets, and this effect was highly significant ($z \geq 4.5$; $P < 0.0001$) for all three subjects. The effect was numerically greater for all three subjects when the difference in orientations between target and background elements was 30° than when it was 60°, and it reached significance for two of the three subjects ($z \geq 2.6$; $P < 0.01$).

Latencies in initial saccades for all target displays (Fig. 2, d–f) were significantly shorter than for non-target displays (by 14–20 ms for all three subjects; $t > 5.0$; df > 532; $P < 0.0001$; two-tailed test). Latencies in initial saccade were shorter for oblique targets than for vertical or horizontal targets, and this effect was significant ($z \geq 2.3$; $P \leq 0.01$) for all three subjects. The effect was numerically greater for all three subjects when the difference in orientations between target and background elements was 30° than when it was 60°, but did not reach significance for any subject ($0.1 \leq z \leq 1.4$).

As expected, manual response times (Fig. 2, g–i) were shorter for oblique targets that for vertical or horizontal targets. This effect was highly significant ($z \geq 5.9$; $P < 0.0001$) for all three subjects. As with directional error and saccade latency, the effect was numerically greater for all three subjects when the difference in orientations between target and background elements was 30° than when it was 60°, and reached significance for two of the three subjects ($z \geq 6.3$; $P < 0.0001$).

The correlation between manual response times and saccadic latencies was high across combinations of target- and background-element orientations (for all three subjects, Pearson's product moment correlation coefficient 0.83–0.85, S.E. 0.04), but it was low within combinations of target- and background-element orientations (for all three subjects, 0.08–0.28, S.E. 0.03).

For a given difference in orientation between target and background elements, performance was generally better when either the target or background elements were horizontal than when either were vertical (29 out of 36 combinations over the three subjects, a result inconsistent with chance performance: $P < 0.0001$).

4. Discussion

Asymmetries in visual search performance with respect to interchange of target and background line-element orientations are clearly evident in oculomotor behaviour. The latency of the initial saccade to a target element and the directional error in that saccade were each smaller for an oblique target on a background of vertical or horizontal elements than for a vertical or horizontal target on a background of oblique elements. Manual response times showed the same asymmetry. The fact that saccadic latencies were correlated with manual response times across combinations of target- and background-element orientations but not within combinations suggests that saccades were not simply secondary to manual responses; rather, that they reflect responses to common neural activity elicited by the stimulus.

There have been several explanations of how this activity might account for orientation asymmetries, both qualitative (Treisman & Gormican, 1988) and quantitative (Rubenstein & Sagi, 1990; Foster & Ward, 1991; Westland & Foster, 1995). In one explanation (Foster & Ward, 1991), it was suggested that the rapid, early visual analysis of oriented lines is dominated by two classes of broadband orientation-selective mechanisms with tuning half-widths of 30° at half-height and preferred orientations close to the vertical and horizontal (other finer mechanisms may also be involved in rapid oriented line-target detection; see Foster & Westland, 1998). A close similarity has been noted between the orientation tuning of these mechanisms and certain principal components making up the spatial structure of natural scenes (Baddeley & Hancock, 1991; Craven, 1993; see also Coppola, Purves, McCoy & Purves, 1998). There is, however, some evidence that the preferred orientations of these mechanisms may depend on the direction of the gravitational field (Marendaz, Stivalet, Barraclough & Walkowiac, 1993; Stivalet, Marendaz, Barraclough & Mourareau, 1995), but also see Doherty and Foster (1998).

A simple analysis of the present data in terms of these mechanisms might proceed as follows. Consider the signal-to-noise ratio (SNR) in a class of mechanisms (with vertical or horizontal preferred orientations) to be the ratio of (1) the response to the target element to (2) the response to the background elements. Assume that the overall response is determined by the class of mechanisms with the higher SNR (the contribution of the class with the lower SNR being discounted). Then, when the target element is say 30° and the background elements are vertical, mechanisms with horizontal preferred orientations are activated moderately by the target element and only weakly, if at all, by the background elements; the SNR for these mechanisms is then high, and response time or detection threshold is therefore low. Conversely, when the target element is vertical and the background elements are 30°, mechanisms with vertical preferred orientations are activated strongly by both the target and the background elements; the SNR for these mechanisms is then low, and response time or detection threshold is therefore high.

If more specific assumptions are made about the orientation tuning functions and the comparison of signal and noise (see e.g. Foster & Ward, 1991; Westland & Foster, 1995), then this analysis can be extended to account for the asymmetries in responses being greater when the difference in orientations between target and background elements is 30° than when it is 60°.

Another explanation of the search asymmetry (Rubenstein & Sagi, 1990) has been founded on the assumption that orientation-selective mechanisms are more noisy along the 45° oblique axes. This assumption has also been made in some analyses of the classical oblique effect (although see Heeley, Buchanan-Smith, Cromwell & Wright, 1997). Under this assumption, the general level of noise would be greater when the background elements are oblique than when they are vertical or horizontal. But there should also then be little effect on target detection of changing background-element orientations from 30° to 60°, as they are symmetric with respect to the 45° axis; yet such an effect was evident here. Further discussion of this issue can be found elsewhere (Heeley et al., 1997; Foster & Westland, 1998).

Several previous studies have shown a general feature-based dependence of eye movements in visual search; for example, for oriented lines and squares (Binello et al. 1995), edge density (Mannan, Ruddock & Wooding, 1996; Mannan et al., 1997), luminance contrast (Scialfa & Joffe, 1998), and colour and simple geometric shape (Findlay, 1997). An asymmetry in eye movement responses has also been reported for ‘O’- and ‘Q’-like stimuli and coloured bars (Zelinsky & Sheinberg, 1997). The present study has shown a more specific correspondence between line-element properties providing cues for initial saccades and line-element properties providing cues for search and detection without eye movements. To summarize: saccadic latency, directional error, and manual response time are each affected in the same way by (1) the interchange of target and background-element orientations, (2) the magnitude of the difference in target and background-element orientations, and (3) the presence of horizontal rather than vertical elements in the stimulus display. The most parsimonious interpretation of this correspondence is that the early orientation-selective mechanisms underlying rapid visual detection of an oriented line-element target are the same as those providing signals for saccadic eye movements.

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References

Alkhateeb, W. F., Morris, R. J., & Ruddock, K. H. (1990). Effects of stimulus complexity on simple spatial discriminations. *Spatial Vision*, *5*, 129–141.

Baddeley, R. J., & Hancock, P. J. B. (1991). A statistical analysis of natural images matches psychophysically derived orientation tuning curves. *Proceedings of the Royal Society of London Series B*, *246*, 219–223.

Barbur, J. L., Thomson, W. D., & Forsyth, P. M. (1987). A new system for the simultaneous measurement of pupil size and two-dimensional eye movements. *Clinical Vision Sciences*, *2*, 131–142.

Beck, J. (1972). Similarity grouping and peripheral discriminability under uncertainty. *American Journal of Psychology*, *85*, 1–19.

Bergen, J. R., & Julesz, B. (1983). Parallel versus serial processing in rapid pattern discrimination. *Nature* (*London*), *303*, 696–698.

Binello, A., Mannan, S., & Ruddock, K. H. (1995). The characteristics of eye movements made during visual search with multi-element stimuli. *Spatial Vision*, *9*, 343–362.

Cleveland, W. S. (1994). *The elements of graphing data*. Summit, NJ: Hobart Press, Sect. 2.5.

Coppola, D. M., Purves, H. R., McCoy, A. N., & Purves, D. (1998). The distribution of oriented contours in the real world. *Proceedings of the National Academy of Sciences USA*, *95*, 4002–4006.

Craven, B. J. (1993). Orientation dependence of human line-length judgements matches statistical structure in real-world scenes. *Proceedings of the Royal Society of London Series B*, *253*, 101–106.

Doherty, L. M., & Foster, D. H. (1998). Orientational anisotropy in line-target detection with and without a gravitational reference for orientation. *Perception* (*Suppl.*), *28*, 54.

Doherty, L. M., & Foster, D. H. (1999). Limitations of rapid parallel processing in the detection of long and short oriented line targets. *Spatial Vision*, *12*, 485–497.

Findlay, J. M. (1995). Visual search: eye-movements and peripheral vision. *Optometry and Vision Science*, *72*, 461–466.

Findlay, J. M. (1997). Saccade target selection during visual search. *Vision Research*, *37*, 617–631.

Foster, D. H., & Ward, P. A. (1991). Asymmetries in oriented-line detection indicate two orthogonal filters in early vision. *Proceedings of the Royal Society of London Series B*, *243*, 75–81.

Foster, D. H., & Westland, S. (1998). Multiple groups of orientation-selective visual mechanisms underlying rapid orientated-line detection. *Proceedings of the Royal Society of London Series B*, *265*, 1605–1613.

Heeley, D. W., Buchanan-Smith, H. M., Cromwell, J. A., & Wright, J. S. (1997). The oblique effect in orientation acuity. *Vision Research*, *37*, 235–242.

Javadnia, A., & Ruddock, K. H. (1988). The limits of parallel processing in the visual discrimination of orientation and magnification. *Spatial Vision*, *3*, 97–114.

Julesz, B., & Schumer, R. A. (1981). Early visual perception. *Annual Review of Psychology*, *32*, 575–627.

Lindman, H. R. (1974). *Analysis of variance in complex experimental designs*. San Francisco: W.H. Freeman.

Mannan, S. K., Ruddock, K. H., & Wooding, D. S. (1996). The relationship between the locations of spatial features and those of fixations made during visual examination of briefly presented images. *Spatial Vision*, *10*, 165–188.

Mannan, S. K., Ruddock, K. H., & Wooding, D. S. (1997). Fixation patterns made during brief examination of two-dimensional images. *Perception*, *26*, 1059–1072.

Marendaz, C., Stivalet, P., Barraclough, L., & Walkowiac, P. (1993). Effect of gravitational cues on visual search for orientation. *Journal of Experimental Psychology*: *Human Perception and Performance*, *19*, 1266–1277.

Motter, B. C., & Belky, E. J. (1998). The guidance of eye movements during active visual search. *Vision Research*, *38*, 1805–1815.

Nothdurft, H. C. (1991). Texture segmentation and pop-out from orientation contrast. *Vision Research*, *31*, 1073–1078.

Poirier, F. J. A. M., & Gurnsey, R. (1998). The effects of eccentricity and spatial frequency on the orientation discrimination asymmetry. *Spatial Vision*, *11*, 349–366.

Rubenstein, B. S., & Sagi, D. (1990). Spatial variability as a limiting factor in texture-discrimination tasks: implications for performance asymmetries. *Journal of the Optical Society of America A*, *7*, 1632–1643.

Sagi, D., & Julesz, B. (1985). 'Where' and 'what' in vision. *Science* (*New York*), *228*, 1217–1219.

Schall, J. D. (1995). Neural basis of saccade target selection. *Reviews in the Neurosciences*, *6*, 63–85.

Scialfa, C. T., & Joffe, K. M. (1998). Response times and eye movements in feature and conjunction search as a function of target eccentricity. *Perception & Psychophysics*, *60*, 1067–1082.

Stivalet, P., Marendaz, C., Barraclough, L., & Mourareau, C. (1995). Effect of gravito-inertial cues on the coding of orientation in pre-attentive vision. *Journal of Vestibular Research*, *5*, 125–135.

Treisman, A. (1985). Preattentive processing in vision. *Computer Vision*, *Graphics and Image Processing*, *31*, 156–177.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: evidence from search asymmetries. *Psychological Review*, *95*, 15–48.

Treisman, A., & Souther, J. (1985). Search asymmetry: a diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology*: *General*, *114*, 285–310.

Westland, S., & Foster, D. H. (1995). Optimized model of oriented-line-target detection using vertical and horizontal filters. *Journal of the Optical Society of America A*, *12*, 1617–1622.

Zelinsky, G. J. (1996). Using eye saccades to assess the selectivity of search movements. *Vision Research*, *36*, 2177–2187.

Zelinsky, G. J., & Sheinberg, D. L. (1997). Eye movements during parallel-serial visual search. *Journal of Experimental Psychology*: *Human Perception and Performance*, *23*, 244–262.