Horizontal–vertical filters in early vision predict anomalous line-orientation identification frequencies

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SUMMARY

A characteristic of early visual processing is a reduction in the effective number of filter mechanisms acting in parallel over the visual field. In the detection of a line target differing in orientation from a background of lines, performance with brief displays appears to be determined by just two classes of orientation-sensitive filter, with preferred orientations close to the vertical and horizontal. An orientation signal represented as a linear combination of responses from such filters is shown to provide a quantitative prediction of the probability density function for identifying the perceived orientation of a target line. This prediction was confirmed in an orientation-matching experiment, which showed that the precision of orientation estimates was worst near the vertical and horizontal and best at about 30° each side of the vertical, a result that contrasts with the classical oblique effect in vision, when scrutiny of the image is allowed. A comparison of predicted and observed frequency distributions showed that the hypothesized orientation signal was formed as an opponent combination and horizontal and vertical filter responses.

1. INTRODUCTION

Visual performance in detecting an object in a crowded visual environment is thought to be largely determined by the early stages of visual processing, sometimes referred to as *preattentive* (Neisser 1967; Treisman *et al.* 1977; Julesz 1981) or as involving *distributed* attention (Beck 1972). The characteristics of the processes underlying early vision appear to be different from those that determine performance when more focused attention is possible. In effect, the number of filter mechanisms in early vision is reduced, leading to a performance based on discrete attributes (Foster 1983; Foster & Ferraro 1989).

The detection of a line-element 'target' differing in orientation from a field of line elements has been a commonly used task for exploring early visual processing of stationary monochromatic images. Provided that the orientation difference is sufficiently great, detection is fast and effortless (Beck & Ambler 1972; Sagi & Julesz 1985; Treisman 1985). Figure 1 illustrates a typical test stimulus. Measurements of the orientational limits on target-detection performance in brief displays of the kind shown in figure 1 have indicated a model of early line processing dominated by just two classes of orientation-sensitive filter (Foster & Ward 1991), as distinct from the continuum of orientation-sensitive filters inferred in traditional psychophysical experiments with simple, long-duration, and centrally fixated stimuli (Campbell & Kulikowski 1966; Blakemore & Nachmias 1971; Thomas & Gille 1979; Regan & Beverley 1985). The two classes of orientation-sensitive filter hypothesized in early vision have orientation-tuning functions that are approximately Gaussian in shape, with axes close to the vertical and horizontal and half-widths each of approximately 30° at half-height (Foster & Ward 1991). Similar values of orientation-tuning half-widths have been proposed by Alkhateeb *et al.* (1990) for possible filter mechanisms underlying search-time performance with single line-element targets in line-element backgrounds with two orientations (cf. figure 1).

Figure 1. Illustration of a display for testing line detection. The background lines are oriented vertically and the 'target' line is oriented at 15° to the vertical.

The outputs of these putative horizontal and vertical filters offer more than a cue for target detection. In principle, a local comparison of the signals from the two filters should allow an estimate to be made of the orientation of the detected line element. One of the simplest testable predictions that may be derived from such a calculation is the probability of a particular orientation identification being made in response to a target of given orientation. The present analysis shows that the variance in making orientation judgements should be greatest along the vertical and horizontal, in contradiction to what might be expected from the classical oblique effect (see, for example, Appelle 1972; Essock 1980) in which visual performance is best along these axes, providing that scrutiny is allowed. This prediction was confirmed quantitatively in an orientation-matching experiment, which also established the opponent nature of the signal for orientation identification in early vision.

2. ESTIMATION OF ORIENTATION-MATCH PROBABILITIES

Let $f_v(\theta)$ and $f_h(\theta)$ be the responses of vertical and horizontal filter units to an appropriately located line element of orientation θ. Thus $f_v(\theta)$ is maximum when $\theta = 0°$ (angles measured anticlockwise from the vertical) and $f_h(\theta)$ is maximum when $\theta = 90°$. No more detailed assumptions, other than the smoothness of the filter-response functions, need be made at this point. (Other factors determining the unit's response, such as element line length and intensity, are irrelevant here.) These filter units are assumed to be replicated over the visual field.

For an element of orientation θ, suppose that an orientation signal $s(\theta)$ is generated that consists of a linear combination of the responses of the two filters:

$$s(\theta) = a_v f_v(\theta) + a_h f_h(\theta), \tag{1}$$

where a_v, a_h are non-zero constants. No assumption is made about the signs of a_v, a_h. If such a signal occurs in an interval ω to $\omega + \delta\omega$, with $\delta\omega > 0$, it could be produced by any element whose orientation lies in the interval $s^{-1}(\omega)$ to $s^{-1}(\omega+\delta\omega)$ (s being locally one-to-one). The conditional probability $P(\theta)$ of then judging that the target orientation lies in the interval θ to $\theta + \delta\theta$, with $\delta\theta > 0°$, is given by the ratio

$$P(\theta) = \frac{\delta\theta}{|s^{-1}(\omega) - s^{-1}(\omega+\delta\omega)|}. \tag{2}$$

Make a Taylor's series expansion of $s^{-1}(\omega+\delta\omega)$ about ω. Provided that $\delta\omega$ is small relative to $|\omega|$, the denominator of equation 2 may be approximated by $|\mathrm{d}s^{-1}(\omega)/\mathrm{d}\omega| \cdot \delta\omega$. But, by the inverse function theorem,

$$\left|\frac{\mathrm{d}s^{-1}(\omega)}{\mathrm{d}\omega}\right| = \left|\frac{\mathrm{d}s(\theta)}{\mathrm{d}\theta}\right|^{-1}. \tag{3}$$

Hence, from equations 1, 2 and 3,

$$P(\theta) = \left| a_v \frac{\mathrm{d}f_v(\theta)}{\mathrm{d}\theta} + a_h \frac{\mathrm{d}f_h(\theta)}{\mathrm{d}\theta} \right|, \tag{4}$$

where the constant $\delta\theta/\delta\omega$ derived from equation 2 has been absorbed into a_v, a_h. If $P(\theta)$ is interpreted as an absolute probability density defined for all θ, then a_v, a_h are constrained by the requirement that $\int P(\theta)\, \mathrm{d}\theta = 1$.

The derivatives $\mathrm{d}f_v(\theta)/\mathrm{d}\theta, \mathrm{d}f_h(\theta)/\mathrm{d}\theta$ in equation 4 are minimum where the filter functions are maximum, that is at $\theta = 0°$ and 90°. Quantitative estimates of $P(\theta)$ may be obtained for various θ from simple detection experiments, the analyses of which yield estimates of $f_v(\theta)$ and $f_h(\theta)$ (Foster & Ward 1991). Contrary to what would be anticipated from the classical oblique effect, namely that the precision of orientation estimates and therefore $P(\theta)$ should be maximum at 0° and 90°, equation 4 implies that the probability of identifying a particular orientation θ is *minimum* at 0° and 90°, and maximum at or close to where f_v, f_h have points of inflexion, depending on the values of a_v and a_h.

3. IDENTIFYING ORIENTED LINE TARGETS

An experiment was performed to determine line-orientation identification frequencies. The experiment required first the detection of a target element in a multi-element field like that of figure 1 (in reverse contrast), and then an estimate of target orientation, obtained by a matching procedure. The stimulus display consisted of twenty identical white line elements distributed randomly over the 20° × 20° field. Each line subtended 1°, with width approximately 0.1°. All the line elements in the display had the same orientation except for the target, which was presented with probability of 0.5 in each trial. (The 'non-target' displays had the same number of elements as the target displays.) The orientation of the target and its spatial location within an annulus of radius 3°–8°, and the orientation of the background elements and their spatial locations were all chosen randomly (within minor constraints). The stimulus display was followed by an interstimulus interval (ISI) consisting of a blank field, and then a post-stimulus mask, which controlled the time available for inspection of the afterimage. The mask consisted of twenty patches of four randomly oriented lines, each patch covering one of the previously displayed line elements. If a positive detection response was made, subjects then made an estimate of the orientation of the target. Details of this procedure are described below.

Stimuli were presented with a CRT display (Hewlett-Packard, Type 1321A, white P4 sulfide phosphor) controlled by a vector-graphics generator (Sigma Electronic Systems, QVEC 2150) and additional DACs, in turn controlled by a 16-bit laboratory computer (details in Foster & Ferraro (1989)). This system produced very-high-resolution line-element displays in which individual line elements were defined with end-point (linear) resolutions of 1 part in 1024 over a square 'patch' of side approximately 1 cm. Each patch was located with a precision of 1 part in 4096 over the CRT screen. Because a vector-graphics system was employed, aliasing artifacts, sometimes associated with raster-graphics displays, were absent. The display was refreshed at intervals of 20 ms. (This temporal structure was not visually detectable.) Subjects viewed the display binocularly at 50 cm through a view-tunnel, which produced a uniformly illuminated, white background, luminance 50 cd m^{-2}, on which the stimuli appeared superimposed. Stimulus luminance was set by each subject at the beginning of each experimental session to 1 $\log_{10}$ unit above increment threshold.

On the basis of preliminary experiments, the stimulus duration was fixed at 40 ms, the ISI at 60 ms, and the mask duration at 500 ms. Subjects initiated each trial and signalled their response as to whether a target was present by using two push-button boxes connected to the computer. If a positive detection response was made (i.e. 'target present') subjects then made an estimate of the orientation of the target. A matching procedure was used in which copies of the target, oriented at $0°, 10°, ..., 170°$, were displayed simultaneously about the centre of the screen. Using the push-button boxes, subjects selected the line element that most closely coincided in perceived orientation with the detected target. The initial default selection of comparison line element varied randomly from trial to trial, and the display containing the comparison elements remained visible until a decision was made.

Fresh random displays were generated in every trial, and the ordering of target- and background-orientation combinations was chosen randomly (i.e. conditions were not blocked). Data were obtained from ten subjects. They each had normal or corrected-to-normal vision (Snellen acuity at least 6/6, without astigmatism) and were aged 19–27 years. All but two had participated in previous line-detection experiments (Foster & Ward 1991). In all they made approximately 4600 orientation matches.

Performance was expressed as a frequency distribution of reported matches for each target orientation. The means of the distributions corresponded closely to the target values ($r = 0.99$). Only identification frequencies were needed, and data were therefore pooled over all target orientations. No significant difference was found between computing frequencies from pooled counts at each reported orientation and as averages over frequencies for individual subjects ($\chi^2(18) = 15, p > 0.5$).

Figure 2 shows observed and predicted pooled orientation-identification frequency distributions, the latter obtained by evaluation of equation 4 with values of $f_v(\theta), f_h(\theta)$ taken from Foster & Ward (1991). Because line elements of orientation θ and $\theta + 180°$ are indistinguishable, plots are defined over a 180° range.

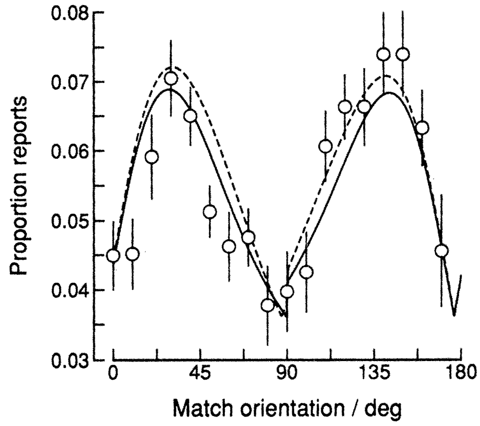

Figure 2. Orientation-identification frequency distributions. The symbols show the proportion of reports at each match orientation (0° vertical, positive anticlockwise). The continuous curve is the expected proportion $P(\theta)$ derived from equation 4 with a ratio of vertical to horizontal filter coefficients a_v/a_h of -2.818. Departures of the data from the model curve are not significant ($\chi^2(16) = 25, p > 0.05$). The broken curve is the expected proportion $P(\theta)$ when the coefficient a_h is doubled. (Vertical bars ± 1 s.e.m.; data from 10 subjects.)

The symbols show the mean proportion of responses made at each reported orientation and the continuous curve the expected proportion $P(\theta)$. The fitted curve had two degrees of freedom, and the two coefficients a_v, a_h of equation 4 were chosen to obtain the best fit to the data, subject to the constraint that $\Sigma_\theta P(\theta) = 1$. The optimum ratio of a_v to a_h was determined as -2.818, which, from equation 1, implies that the orientation signal $s(\theta)$ is formed as a *difference* in the responses of the vertical and horizontal filters. As a demonstration of the robustness of the calculation, the broken curve shows predicted performance when the coefficient a_h is doubled. The predicted values $P(\theta)$ accounted adequately for the observed frequencies ($\chi^2(16) = 25, p > 0.05$).

As anticipated, subjects identified matching orientations near 0° and 90° least often. But could a continuous distribution of narrowly tuned filter units of the kind proposed by Andrews (1967) and by Bouma & Andriessen (1968) (see Foster & Ward (1991) for formal descriptions of these models) also account for the observed frequency distribution? One possibility is that narrowly tuned filters with preferred orientations near 0° and 90° might signal responses less frequently because they are particularly vulnerable to sampling noise as a result of their small orientation-tuning halfwidths. But such an explanation is unsatisfactory, even allowing for the incompatibility of these models with line-detection data (Foster & Ward 1991). Although noise might effectively displace a stimulus oriented at 0° so that it was detected by filter units to either side of 0°, the total number of responses over, say, a 45° region centred at 0° should be the same as over a 45° region centred at 45° or at 135°. This is not the distribution shown in figure 2.

4. COMMENT

This study was based on a simple model of early line processing dominated by two classes of orientation-sensitive filter, with preferred orientations close to the vertical and horizontal, and orientation-tuning halfwidths each of approximately 30° at half-height. An orientation-identification frequency distribution was derived from an orientation signal represented as a linear combination of these filter responses. This estimated frequency distribution was shown to fit an observed distribution which had minima near 0° and 90°, in opposition to the classical oblique effect, and maxima at about 30° each side of the vertical. The orientation signal derived from the orientation-match data took the form of a difference in filter responses, an arrangement analogous to that in colour vision, where chromatic signals also receive an opponent coding. A similar opponent-coding hypothesis has been proposed (Westheimer *et al.* 1976; Regan & Beverley, 1985) to explain interference with high-acuity line-orientation sensitivity and orientation-dependent grating-adaptation effects.

The analysis of the present study was based on local computations in the visual field. Although a relation between detection and precision of identification emerged naturally from the analysis, it made no predictions of a global kind, relating detection and identification with target location performance, which has been considered elsewhere (Sagi & Julesz 1985; Atkinson & Braddick 1989).

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