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Orientation Contrast vs Orientation in Line-target Detection

DAVID H. FOSTER,* STEPHEN WESTLAND*

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This study concerns the roles of absolute and relative orientation in determining detectability of a line-element target in a background field of uniformly oriented line elements. Target detectability was determined as a function of background-field orientation, sampled at 5 deg intervals, for three levels of orientation contrast—the difference between target and background orientations—sampled at 10, 20 and 30 deg. Stimulus displays were presented briefly and followed by a mask. There were 10 observers, whose detection performance was quantified by the discrimination index *d′* from signal detection theory. Target detectability was found to depend both on absolute orientation, represented by background-field orientation, and on orientation contrast. At each level of orientation contrast, performance was best when the background field, not the target element, was vertical or horizontal. These data are difficult to explain by general models of orientation discrimination based on simple orientation opponency between local line-sensitive filter units; three other models specifically concerned with target detection are briefly considered.

Preattentive search Orientation contrast Symmetry Oblique effect Anisotropy

INTRODUCTION

The detectability of a line-element target differing in orientation from a background of otherwise identical line elements depends on the size of the angle between target and background elements, that is, on the relative orientation or orientation contrast. Performance can be quantified by the time taken to search for and find the target (e.g. Treisman, 1985; Sagi & Julesz, 1985; Marendaz, Stivalet & Genon, 1991; Wolfe, Friedman-Hill, Stewart & O'Connell, 1992; also Beck & Ambler, 1973); or by the proportion of correct detections or a derived threshold orientation contrast with a briefly presented display (e.g. Sagi & Julesz, 1987; Foster & Ward, 1991a; Nothdurft, 1991; also Beck & Ambler, 1972; Bergen & Julesz, 1983); or by some combination of these two measures (e.g. Javadnia & Ruddock, 1988; Meigen, Lagrèze & Bach, 1994).

For sufficiently large orientation contrasts, detection is fast, effortless, and accurate: the target is said to "pop out" (see Fig. 1). On the basis of results from a variety of experiments, performance is thought to be determined by the early (preattentive or distributed-attention) stages of vision (e.g. Beck & Ambler, 1972; Bergen & Julesz, 1983; Treisman, 1985; Sagi & Julesz, 1985; Javadnia & Ruddock, 1988; Nothdurft, 1992).

Data from some line-target search and detection tasks in which the orientations of the background line elements varied randomly, but over a smaller range than the differences in orientations of target and nearby background elements, led to the suggestion (Nothdurft, 1991, 1992) that pop-out was based on orientation contrast rather than on orientation itself. The fact that a sufficiently large local orientation contrast was both necessary and sufficient for fast visual search has been taken to argue against the special role of orientation features in preattentive vision (Nothdurft, 1992, p. 367).

Yet data from other line-target search and detection tasks have suggested that absolute orientation—characterized, for example, by background-field orientation—is also important. Thus search times obtained when the background elements are vertical (in the frontoparallel plane) and the target element is tilted are less than those obtained when the target element is vertical and the background elements are tilted, even though the difference in angle between target and background elements is the same (Treisman, 1985; Treisman & Gormican, 1988; Marendaz, Stivalet, Barraclough & Walkowiac, 1991; Meigen *et al.*, 1994). A similar search asymmetry exists for horizontal elements (Marendaz *et al.*, 1991). Previous measurements of orientation contrast at detection threshold (orientation increment threshold) as a function of background orientation have also shown marked anisotropies: increment thresholds were minimum for backgrounds in which the line elements were all vertical or all horizontal (Foster & Ward, 1991a). In search experiments with backgrounds containing more than one orientation, performance was found to be

*Department of Communication and Neuroscience, Keele University, Staffordshire ST5 5BG, England, [*Email*d.h.foster@keele.ac.uk].

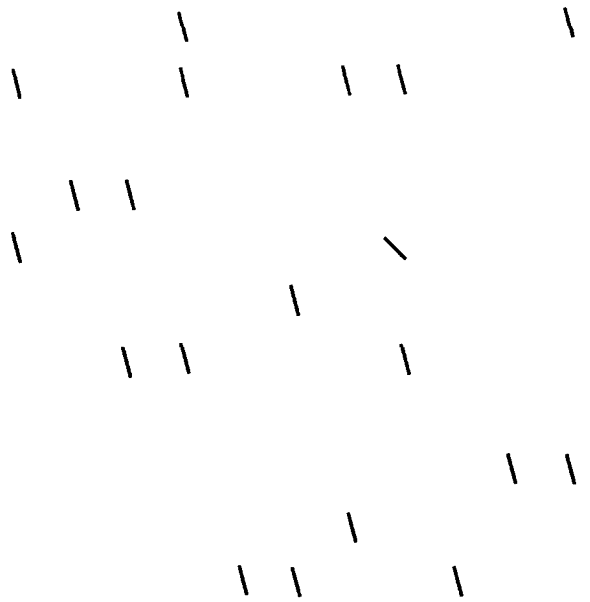

FIGURE 1. A typical stimulus display. The orientation of the background line elements is 15 deg and of the target line element 45 deg.

better when the target was the only line element that could be described as "steep", "shallow", or "tilted" (Wolfe *et al.*, 1992); conversely, when the target and some of the background line elements were symmetric about a vertical axis, performance was poorer (Wolfe & Friedman-Hill, 1992a).

The purpose of this study was to assess the contributions of absolute and relative line-element orientation to target detection. Measurements were made of the detectability of a line-element target as a function of background orientation sampled at 5 deg intervals for three levels of orientation contrast sampled at 10 deg intervals. Detection performance was found to depend significantly on both background orientation and orientation contrast. These data are considered in relation to several models of line-target detection.

NOTATION

In each stimulus display, let θ be the common orientation of the background elements and $\theta + \Delta\theta$ be the orientation of the target element, if present. All angles were measured anticlockwise from the vertical (0 deg in the frontoparallel plane). The *orientation contrast* is defined by $\Delta\theta$. (In some studies—but not this one—the term orientation contrast is used for the ratio of the angular difference $\Delta\theta$ between the orientations of the target and neighbouring background elements to the spatial distance Δs between them, i.e. $\Delta\theta/\Delta s$). The *absolute orientation* is defined here as the background orientation θ.

This parameterization of line-element orientations treats background and target line elements unevenly and it differs from that used in more traditional measurements of orientation acuity (e.g. Andrews, 1967; Regan & Beverley, 1985; Regan & Price, 1986), where the "absolute orientation" is naturally defined as the symmetry axis ϕ of the stimuli, i.e. $\phi = \theta + \Delta\theta/2$.

METHODS

Stimuli and apparatus

Each stimulus display consisted of 20 identical bright line elements distributed randomly over a field subtending 20 × 20 deg at the eye, as illustrated in Fig. 1 (the elements were placed on an imaginary matrix and then subjected to spatial jitter, but of limited extent to avoid elements' falling so closely together that they formed new features). Each line element subtended 1 deg, with width approx. 0.1 deg. All the line elements in the display had the same orientation, except for the target which was presented with probability 0.5 in each trial. (The "non-target" displays had the same number of elements as the target displays.) The orientations of the target and background elements were chosen randomly, as was the spatial location of the target, although it was constrained to fall within an imaginary annulus of radius 3–8 deg, to reduce the effects of retinal inhomogeneity (see e.g. Sagi & Julesz, 1987). The stimulus display was followed by a blank field [the duration of which defined the inter-stimulus interval (ISI)], and then a post-stimulus mask, which limited the time available for inspection of the afterimage. The mask consisted of 20 "patches" of four randomly oriented line elements, the arrangement of the elements differing from patch to patch.

Stimuli were presented on the screen of a CRT (Hewlett–Packard, Type 1317A, green P31 phosphor, measured 90%–10% decay time < 100 μsec, rise time less than decay time) controlled by a vector-graphics generator (Sigma Electronic Systems, QVEC 2150) and additional DACs, in turn controlled by a laboratory computer. 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 approx. 1 cm. Each patch was located with precision of 1 part in 4096 over the CRT screen. Orientation accuracy was differentially better than 0.2 deg and absolutely better than 0.5 deg. Because a vector-graphics system was used, aliasing artifacts, sometimes associated with raster-graphics displays, were absent. The screen was refreshed at intervals of 20 msec. (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 approx. 40 cd m^{-2}, on which the line-element stimuli appeared superimposed. Stimulus luminance was set by each subject at the beginning of each experimental session to ten times threshold on the uniform background (a 1-log-unit neutral-density filter was placed between the CRT screen and view-tunnel; the luminance of the line elements was set to threshold; and the neutral density filter was then removed).

On the basis of previous experiments (Foster & Ward, 1991a), the stimulus duration was fixed at 40 msec, the ISI at 60 msec, and the mask duration at 500 msec.

Procedure

Subjects initiated each trial and responded as to whether a target was present by using push-button switch-boxes connected to the computer. Fresh random displays (and masks) were generated in every trial. The orientation contrast $\Delta\theta$ was taken here from the range 10, 20 and 30 deg and orientation θ of the background field from the range 0, 5, . . . , 175 deg. In effect $\Delta\theta,\theta$ were sampled from a 3×36 matrix of orientations. The ordering of this sampling was chosen randomly and conditions (orientation contrasts and orientations) were not blocked.

Subjects

There were 10 subjects, each of whom had normal or corrected-to-normal vision (Snellen acuity 6/4–6/6 and optometrically verified astigmatism < 0.25 D). They were aged 19–30 yr, and, except for one subject (co-author SW), they were unaware of the purpose of the experiment and were paid for their participation.

Data analysis

Detection performance for each combination of target and background orientations was summarized by the discrimination index d' from signal detection theory (Green & Swets, 1966). Thus, let HR be the hit rate, i.e., the proportion of positive responses ("target present") with a target display (target orientation $\theta + \Delta\theta$, background orientation θ); let FAR be the false-alarm rate, i.e. the proportion of positive responses with the corresponding *non*-target display (background orientation θ); and let Φ^{-1} denote the inverse of the (cumulative) standardized normal distribution. Then the value of d' for this combination of orientations is given by

$$d' = \Phi^{-1}(\mathrm{HR}) - \Phi^{-1}(\mathrm{FAR}). \quad (1)$$

This function increases monotonically with increasing hit rate; zero corresponds to chance performance. Equation (1) may be treated simply as a device for linearizing and combining hit and false-alarm rates, but if certain assumptions are made about the underlying psychophysical mechanisms then d' serves also to minimize the effects of observer bias (Green & Swets, 1966).

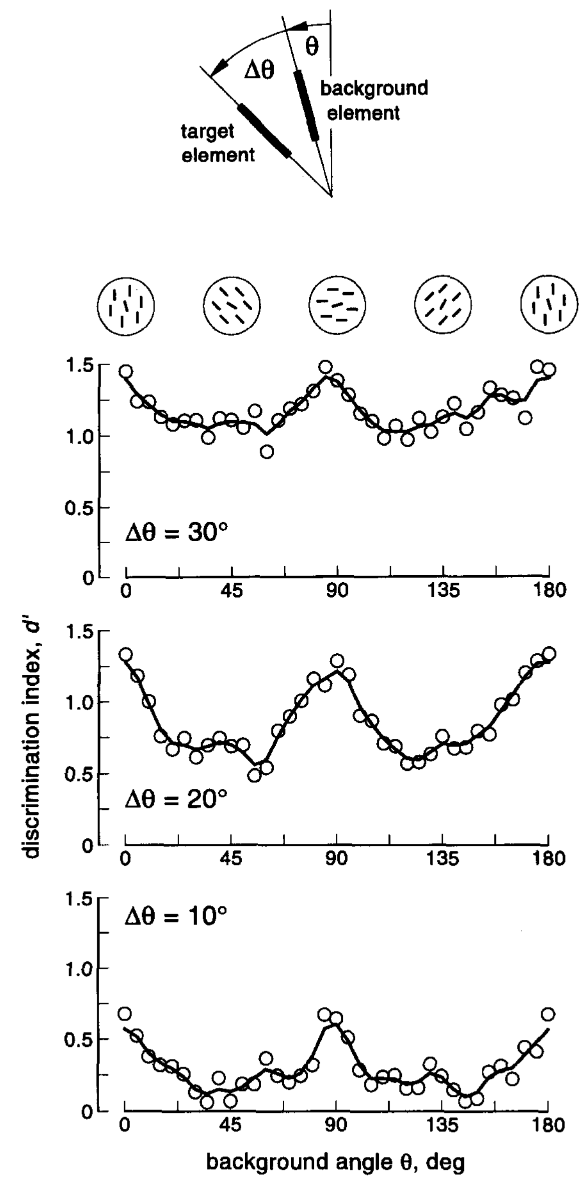

FIGURE 2. Detectability of a line-element target within a field of uniformly oriented line elements. Discrimination index d' is plotted against the orientation θ of the background elements (see diagram at top of figure), at three different levels of orientation contrast, $\Delta\theta = 10$, 20 and 30 deg. The bold solid line is the result of smoothing the data with a wrapped Gaussian function of orientation SD 4 deg. Each data point was based on approx. 250 target trials and approx. 250 non-target trials (for each target angle), pooled over 10 observers; the SDs of individual data points ranged from 0.09 to 0.14.

RESULTS

Figure 2 shows discrimination index d' for target detectability plotted against the orientation θ of the background field, at orientation contrasts $\Delta\theta$ of 10, 20 and 30 deg. Individual d' values, indicated by open circles, were each based on approx. 250 target trials and approx. 250 non-target trials (for each target angle), pooled over the 10 observers. The bold solid line is the result of smoothing the data by convolution with a wrapped Gaussian function (Mardia, 1972) with orientation standard deviation 4 deg (3 and 5 deg produced similar curves).

The results of a three-way analysis of variance with repeated measures showed only a weakly significant effect of overall orientation sense, i.e. whether background and target orientations, θ and $\theta + \Delta\theta$, were both positive or both negative [$F(1,9) = 6.60$, $P = 0.03$], and, for illustration only, the data shown in Fig. 2 were pooled over positive and negative values of the pair $\theta,\Delta\theta$.

As might be anticipated from the graphs, the analysis yielded highly significant effects of background-field orientation θ [$F(35,315) = 4.93$ $P \ll 0.0001$]; orientation contrast $\Delta\theta$ [$F(2,18) = 42.0$, $P \ll 0.0001$]; and interaction between θ and $\Delta\theta$ [$F(70,630) = 2.11$, $P < 0.0001$].

DISCUSSION

Both orientation contrast and absolute orientation—represented by background-field orientation—strongly affected line-target detection performance. As expected (Foster & Ward, 1991a; Nothdurft, 1991, 1992), detectability increased monotonically with orientation contrast, at least over the range of contrasts, 10–30 deg, considered here; of course, for sufficiently large values of $\Delta\theta$— less than 180 deg but not necessarily greater than 90 deg—detectability must decline, because of the equivalence of the orientation contrasts $\Delta\theta$ and $\Delta\theta + 180$ deg [in general, a cubic curve gives an adequate fit of d' to $\Delta\theta$, but its coefficients vary with background orientation θ (Foster & Ward, 1991a; Foster & Westland, 1995)].

In line-element displays more dense than those used here (only 20 line elements were distributed over the 20×20 deg field) absolute orientation may become less important, as line elements fall closer together and the possibility of local effects such as flow-field discontinuities become more important (e.g. Nothdurft, 1992). For sparse displays, with just five line elements distributed over a 20×20 deg field, the effects of absolute orientation are still detectable (Foster, Westland & Doherty, 1994).

The peaks in detectability occurred when the background field was either vertical or horizontal, within sampling error. This pattern of performance differs from that found in measurements of orientation acuity where the stimuli being discriminated are few (one or two at a time), are viewed for several hundred msec or continuously without a post-stimulus mask, and are symmetric (one exemplar of each) (e.g. Andrews, 1967; Regan & Price, 1986): in those measurements, peaks in orientation-discrimination performance were found when the symmetry axis was vertical or horizontal, although any evidence of asymmetry is difficult to detect because of the experimental design and the magnitude of the threshold orientation difference ($\Delta\theta$ here), which was of the order of 1 deg for short lines (Andrews, 1967) and 1 min arc for gratings (Regan & Price, 1986), as compared with the values 10–30 deg implied by the present data and previous search and detection experiments with complex and usually brief displays (e.g. Treisman & Gormican, 1988; Foster & Ward, 1991a; Nothdurft, 1992).

As in other studies of line-target search and detection, the discrimination performance shown in Fig. 2 is not symmetric with respect to stimulus orientation: interchanging θ and $\theta + \Delta\theta$ does not leave the discrimination function invariant. This asymmetry is difficult to explain by general models of orientation discrimination based on simple orientation opponency between local line-sensitive filter units (see e.g. Regan & Beverley, 1985; Regan, 1986; cf. Foster & Ward, 1991b). Anisotropies in traditional measurements of orientation acuity have been attributed to these filters having densities and orientation tuning widths varying with the filter's preferred orientation (e.g. Andrews, 1967; Bouma & Andriessen, 1968); but exchanging θ and $\theta + \Delta\theta$ should leave their responses, which depend only on the symmetry axis $\phi = \theta + \Delta\theta/2$ and the difference $\Delta\theta$, unaltered.

At least three models of orientation-dependent line-target search and detection have been proposed for early or preattentive vision. They may be summarized as follows in relation to the diagnostic task (Treisman & Souther, 1985) of detecting a tilted line element in a background of vertical line elements (as in Fig. 2 at $\theta = 0$ deg) and a vertical line element in a background of tilted line elements.

Model 1. Assume that a tilted line element is coded as a vertical line element with an additional feature marking the nature of the deviation (Treisman & Gormican, 1988, p. 41). Since vertical elements do not possess this additional feature, a tilted target element is distinguished by the additional activity it generates and so detection is easy. When target and background orientations are interchanged, no additional activity is generated by the vertical target element and detection is more difficult. A similar approach using filter normalization has been proposed for texture segmentation (Gurnsey & Browse, 1989).

Model 2. Assume that filter units responding to tilted line elements are more noisy than those responding to vertical line elements (Rubenstein & Sagi, 1990, p. 1633). When the target element is tilted and the background elements are vertical, detection is relatively easy. When target and background orientations are interchanged, the tilted line elements in the background generate more noise than when they are vertical, and, as a result, detectability of the vertical target element is more difficult. This model was tested on numerous pairs of texture displays and gave close correlations with human segmentation performance (Rubenstein & Sagi, 1990).

Model 3. Assume that two classes of broad-band filter units with axes close to the vertical and horizontal dominate detection performance, and that detection is determined by the class of filters with the best "signal-to-noise" ratio (Foster & Ward, 1991a, p. 79; Marendaz *et al.*, 1991). For either class, the noise arising from the background elements is least when their orientation is most different from the filters' preferred orientation; therefore, detection is easiest with the horizontal filters when the background elements are vertical and the target element is tilted. When target and background orientations are interchanged, both classes of filters respond to the tilted background elements and therefore detection is more difficult. A computational simulation of this performance in response to grey-level stimulus images has been reported elsewhere (Westland & Foster, 1995).

The orientation-tuning functions of the two classes of filters in Model 3 have been estimated analytically from orientation-discrimination data obtained from a much coarser orientation sampling than that used here (Foster & Ward, 1991a). A close and robust correspondence—in shape, position, and relative heights—was demonstrated (Baddeley & Hancock, 1991) between these tuning functions and the orientation sensitivities of two principal components derived in a neural-net analysis of real-world images (see also Craven, 1993). Although comparison of these tuning data with those from single-cell recordings from primate cortex is difficult, given the disparity in experimental conditions and variety of recorded responses, the half-height half-widths of about 30 deg obtained from that analysis (Foster & Ward, 1991a) are not unrepresentative (e.g. Schiller, Finlay & Volman, 1976; De Valois, Albrecht & Thorell, 1982a; De Valois, Yund & Hepler, 1982b), particularly since they were obtained with brief stimuli (see Snowden, 1992).

Independent of the particular explanatory model, the Cartesian frame associated with each may be the result of several factors. Visual-contextual factors have been revealed in target search performance: the performance asymmetry with tilted and vertical target and background elements (Treisman & Souther, 1985) is altered when a tilted rectangular frame is used instead of an upright rectangular one (Treisman, 1985); but a rectangular frame is not itself necessary for producing the asymmetry: it persists with a circular frame (Treisman & Gormican, 1988; Marendaz *et al.*, 1991).

Gravitational factors have been implicated in target search performed by observers standing upright, sitting immobilized, and supine (Marendaz *et al.*, 1993) and with observers seated in a non-pendular centrifuge (Stivalet, Marendaz, Barraclough & Mourareau, 1995). In supine viewing, where the gravitational axis cannot provide an orientational reference and balance dynamics are absent, the asymmetry is much reduced. The reduction is almost entirely due to an improvement in search times in the condition in which the target element is aligned with the retinal-body axis and the background is of tilted elements. For observers sitting immobilized, where the gravitational axis can provide a reference and balance dynamics are absent, the magnitude of the performance asymmetry was intermediate between that for unrestrained upright and supine viewing (Marendaz *et al.*, 1993).

The improved search times in supine viewing have been interpreted (Marendaz *et al.*, 1993) in terms of the notion that the centres of the estimated orientation-tuning functions in the two-filter Model 3 are subject to fluctuations when not stabilized by converging vestibular-somatosensory information. Differences in search times for vertical and horizontal targets with immobilized observers have been attributed (Marendaz *et al.*, 1993) to the estimated difference in sensitivity of the vertical and horizontal filters [a ratio of approx. 2.3:1 (Foster & Ward, 1991a)].

In addition to the proposed lability of these two classes of filters, it should be emphasized that they appear to represent only one, albeit dominant, component in the early stages of visual orientation analysis. Finer-grained measurements of orientation increment-threshold functions for target detection (Foster & Westland, 1995) have, when subjected to a detailed statistical periodogram analysis, revealed in individual observers significant responses at orientation periods of 90 deg, as expected, but also—and more weakly—at about 45 deg (cf. Regan & Price, 1986) and at 10–20 deg. There is some evidence in the data of Fig. 2 of subsidiary maxima at about 45 and 135 deg, although these are pooled performances, which may obscure individual differences.

In each application of the three models of line-target search and detection summarized earlier, the orientation of the background elements was assumed to be uniform: there was no conflict between local and global definitions of absolute orientation. In this study, any heterogeneity in the background elements was limited to spatial position: elements were distributed randomly over the field, but all had the same orientation (chance alignments were not excluded). It has been found that when background elements are distributed spatially so that they are maximally collinear, an improvement in target search times occurs for a tilted target element on a background of vertical elements (Meigen *et al.*, 1994). The effect may be attributable to a better specification of the structure of the background field (Meigen *et al.*, 1994), or, conversely, to a reduction in background-field heterogeneity. When heterogeneity is increased, by background elements being given more than one orientation as well as being positioned randomly, search performance declines (Alkhateeb, Morris, & Ruddock, 1990; Mannan, Ruddock & Wright, 1995; Wolfe & Friedman-Hill, 1992a; Wolfe *et al.*, 1992), but not in a way predictable simply by the increase in heterogeneity itself (Duncan & Humphreys, 1989; Wolfe & Friedman-Hill, 1992b).

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