Visibility and Vernier Acuity for Separated Targets

SARAH J. WAUGH,*† DENNIS M. LEVI*‡

Received 20 March 1992; in revised form 10 July 1992

The purpose of this study was to investigate the roles of the putative “spatial filter” and “local sign” mechanisms in determining line vernier thresholds for a range of target separations, using stimulus contrast or visibility as a tool. In Expt 1, the effects of varying target contrast and exposure duration on vernier thresholds for lines separated by 90 min arc, where the reference line was fixed, were measured. Contrast thresholds for the nonfixed test line were also measured, so that the role of its visibility in limiting vernier thresholds could be assessed. Vernier thresholds decreased almost proportionally with increasing contrast only until the visibility of the test line reached about 3 times the contrast detection threshold, regardless of exposure duration. At higher visibility levels, vernier thresholds were virtually independent of target contrast. In Expt 2, the effects of varying target contrast on vernier thresholds for a range of target separations (2–90 min arc) were measured using a 250 msec exposure duration. Vernier thresholds for abutting lines and for those separated by 2 min arc, decreased with target contrast until about 30 times the test line’s contrast detection threshold. However, for lines separated by 4 min arc or more, they were only weakly dependent on target contrast at much lower visibility levels. We propose that for very close separations vernier thresholds are limited by the contrast response properties of spatial filters. For separations of 4 min arc or more, thresholds appear to be limited by the positional uncertainty of the test line, which increases with eccentricity.

Spatial filter models are not able to predict the virtual contrast independence of other relative position thresholds such as spatial interval discrimination for widely separated targets (Morgan & Regan, 1987; Levi, Jiang & Klein, 1990), spatial frequency discrimination (Regan, Bartol, Murray & Beverley, 1982; Thomas, 1983; Skottun, Bradly, Sclar, Ohzawa & Freeman, 1987; Bowne, 1990), and orientation discrimination (Regan & Beverley, 1985; Skottun et al., 1987; Bowne, 1990). Nor do they predict the approximately Weber’s law dependence of spatial interval discrimination thresholds (and presumably vernier thresholds) on target separation for separations greater than about 10 min arc (Wilson, 1986, 1991; Klein & Levi, 1987). In addition, the ability to localize widely separated targets is robust to other changes in target visibility which would cause predictable changes in the output of spatial filters, e.g. changes in target blur (Stigmar, 1971; Williams, Enoch & Essock, 1984; Toet, van Eckhout, Simons & Koenderink, 1987), exposure duration (Leibowitz, Myers & Grant, 1955; Burbeck, 1986), and luminance (Leibowitz et al., 1955; Bedell, Johnson & Barceto, 1985; Klein & Levi, 1985; Bedell, 1987; Yap, Levi & Klein, 1989). For these types of tasks a second strategy must be proposed such as one where the absolute position labels or local signs (Lotze, 1885) associated with the critical target features are compared, to obtain relative position information. These relative position thresholds would not be limited by target accuracy.

INTRODUCTION

The human visual system is exquisitely precise at judging the relative position of two objects in space. Under optimal conditions, judgments an order of magnitude finer than the diameter of a single photoreceptor, or the spacing between photoreceptors, are possible. Optimal conditions for the vernier acuity task using line targets include foveal viewing (Westheimer, 1982; Levi, Klein & Aitsebaomo, 1985), highly visible lines (Morgan & Aiba, 1985; Wilson, 1986; Klein, Casson & Carney, 1990; Banton & Levi, 1991; Waugh & Levi, 1993a) which are abutting or very close together (Berry, 1948; Sullivan, Oatley & Sutherland, 1972; Westheimer & McKee, 1977; Watt, 1984), and synchronous presentation (Westheimer & Hauske, 1975). In previous work, it has been demonstrated that for abutting targets, vernier thresholds are dependent on target visibility (Krauskopf & Farell, 1991; Waugh & Levi, 1993a, b, c). Such results are consistent with the idea that these vernier thresholds are mediated by the differential contrast responses of spatially localized filters (Klein & Levi, 1985; Wilson, 1986). However,
visibility but by other factors such as the positional uncertainties of the absolute position labels themselves (Beck & Halloran, 1985; Levi & Klein, 1985; Klein & Levi, 1987; Levi, Klein & Yap, 1987; Bowne, 1990; Wilson, 1991), or by the comparison process between them (Morgan, Ward & Hole, 1990; Morgan, 1991; White, Levi & Aitsebaomo, 1992).

Both the contrast dependent and contrast independent strategies mentioned above may independently contribute to relative position thresholds depending on the characteristics of the target features, the separation between them, and the task itself. For example, although spatial interval discrimination thresholds for line targets separated by <5 min arc under foveal viewing conditions are dependent on target contrast, for larger separations once the targets are visible, they are virtually contrast or polarity independent (Levi & Westheimer, 1987; Morgan & Regan, 1987). Also, vernier acuity for opposite polarity lines is degraded, only for separations less than about 5–10 min arc (O’Shea & Mitchell, 1990; Morgan, 1991). However, the dependence of vernier thresholds and spatial interval discrimination thresholds on contrast, for Gaussian bar stimuli (space constant of 1 min arc) separated by 6 min arc, have been suggested to be inherently different (Morgan & Regan, 1987). In addition, the actual separation at which different sources of noise might limit relative position thresholds probably depends on the blur characteristics of the stimuli (Stigmar, 1971; Williams et al., 1984; Toet et al., 1987; Levi et al., 1990; Whitaker & MacVeigh, 1991).

The purpose of the present study was to investigate the roles of the putative “spatial filter” and “local sign” mechanisms in determining line vernier thresholds for a range of target separations, using stimulus contrast or visibility as a tool. It is assumed that relative position thresholds which are limited by the differential contrast response of spatial filters, will necessarily improve with stimulus contrast. However thresholds which are limited by the uncertainty of absolute position labels or by a comparison process between them, will be virtually independent of target contrast. In previous work we present results to suggest that foveal vernier thresholds for abutting targets are dependent on target visibility at least until about 30 times the contrast detection threshold (Waugh & Levi, 1993a). In the first experiment to be described, we investigate the effects of target visibility on vernier thresholds for line targets separated by 90 min arc, by varying both target contrast and exposure duration. The second experiment measures the effects of varying target visibility on vernier thresholds for line targets separated by between 2 and 90 min arc. Our results are reasonably well accounted for by assuming that vernier thresholds are limited by at least two independent processes. For separations less than about 4 min arc, the contrast dependency of vernier thresholds is consistent with an hypothesis for which relative position information is derived from the differential contrast responses of spatial filters. However, for wider separations once the targets are significantly above the contrast detection threshold, vernier thresholds are only weakly dependent on contrast, and may result from a process where the absolute position labels for each vernier line are compared.

**GENERAL METHODS**

The methods are described in detail elsewhere (Waugh & Levi, 1993a). Briefly dark line stimuli were presented on a Tektronix 608 oscilloscope screen with a P3 phosphor at a mean luminance of 123.5 cd/m² using a VENUS stimulus generator.

**The stimuli**

To produce the vernier stimulus, two horizontal lines of equal contrast, each 30 min arc in length and separated by between 2–90 min arc, were offset vertically with respect to one another [see Fig. 1(a)]. A 30 min arc line length was chosen to ensure a wide range of target visibilities. From pilot experiments with our widest separation, we found that this line length was outside the zone where line exposure could be obtained (Su 1977).

Observing target line judgment did the fi could als (the test judgment cues avai rounding screen w magnitudes the line d length w screen [f the fixati dimensio moving t measurec duration.

**Psychophysics**

The s stimuli w estimates those des threshold of 1, i.e. co indicated ation wa threshold slope of t specified.

The counterbal exposure during e mean of variance, the large Curve fi uses a minimize the mod.

**Observer**

Three participa normal low deg For all c which ce an artific ing eye, therefore
zone where contrast thresholds increase proportionally with line length, for both a 15 and 1000 msec exposure duration. It is also longer than that required to obtain optimal vernier thresholds for all separations used (Sullivan et al., 1972; Westheimer & McKee, 1977).

Observers were instructed to always fixate the leftmost target line (the reference line) while making vernier judgments. Using this experimental strategy, not only did the fixation line act like a high fidelity ruler, but we could also test how the visibility of the nonfixated line (the test line) limited the ability to make a vernier judgment. To preclude the use of any unwanted position cues available from the circular aperture, or from surrounding objects, the position of the reference line on the screen was randomly jittered (by an amount about the magnitude of the largest offset) from trial to trial. For the line detection task, one horizontal line (30 min arc in length) was always presented at the same position on the screen [Fig. 1(b)]. The separation between this line and the fixation target, a dark horizontal line similar in dimensions to the vernier reference line, was varied by moving the fixation line. Line detection thresholds were measured for each separation condition and exposure duration used in the vernier experiments.

Psychophysical method and analysis

The self-paced rating scale method of constant stimuli with auditory feedback used to obtain threshold estimates, and signal detection analysis are identical to those described in Waugh and Levi (1993a). The vernier thresholds represent the offset corresponding to a $d'$ of 1, i.e. corresponding to 84% correct. Unless otherwise indicated (e.g. in the experiment where exposure duration was varied for a 90 min separation), the detection thresholds reported were calculated by constraining the slope of the psychometric function to be 1.5, and are also specified at $d' = 1$.

The data for all experiments were collected in counterbalanced order, where the separation and exposure duration were fixed and contrast was varied during each session. The thresholds reported are the mean of at least four runs weighted by the inverse variance, and the error bars represent $±1$ SE, reflecting the larger of the within run and between run variance. Curve fitting was accomplished using Igor™, which uses a Levenberg–Marquardt iterative algorithm to minimize the error between the experimental data and the model fit.

Observers

Three observers, one author and two naive observers, participated in the experiments. All observers had normal or were corrected to normal vision: two had low degrees of myopia, and one was emmetropic. For all experiments observers wore light tight goggles, which carried any refractive correction and introduced an artificial pupil (diameter of 2.5 mm) before the viewing eye. Retinal illuminance for these observers was therefore about 650 td. The observer's head was supported by both a chin and a forehead rest, which helped to stabilize head position and minimize head tilt. All observers were very well practiced at making these psychophysical judgments before experimental data collection began.

EXPERIMENTAL METHODS

Experiment 1: the effect of varying target visibility on vernier thresholds for widely separated target lines

Vernier thresholds were measured for different line contrasts ($≈40–85\%$) and exposure durations (15–1000 msec) where the target lines were separated by 90 min arc. To obtain this target separation a viewing distance of 2 m was used. However to obtain test target visibilities above threshold for short durations, the width of the target lines was varied from 1.24 min arc (2 pixels) to 4.34 min arc (7 pixels) for the 15 and 23 msec durations. Since the line widths were always within Rico's dimension (where visibility is equal to the product of line contrast and line width) this provided a greater range of suprathreshold line visibilities.

To test whether the ability to perform the vernier task was limited by the visibility of the test line at 90 min arc, detection thresholds for a single line target placed 90 min arc from the fixation line were measured for the same exposure durations as vernier thresholds. In this way, the effect of target visibility (in contrast threshold units) on vernier thresholds could be assessed. Visibility of the test line was varied from near the line detection threshold to about 20 times threshold by varying both its contrast and its width. Control experiments were performed at this separation to ensure that these line widths were within Rico's dimension for all exposure durations. Because a systematic steepening of the psychometric function slope was found as the exposure duration decreased, for durations of 50 msec or less, a psychometric function exponent of 2 was used to obtain contrast thresholds, however for all other conditions an exponent of 1.5 was used.

Experiment 2: the effect of target visibility on vernier thresholds for targets separated by 2–90 min arc

Vernier thresholds were measured for line targets separated by between 2 and 90 min arc, for a single exposure duration of 250 msec. For each separation condition, the visibility of the vernier lines was varied. Vernier stimuli for the 2, 4, 6, 15 and 30 min arc gap conditions were viewed from a 3 m viewing distance, whereas the vernier lines separated by 90 min arc were viewed from 2 m. Again the width of the test line was restricted to be within Rico's dimension, where the line width for separations from 2 to 30 min arc was mostly 2 pixels or 0.82 min arc, and the maximum line width used was 3 pixels or 1.24 min arc. For all separations, a 250 msec duration lay beyond the region where there is perfect reciprocity between contrast and time, thus allowing for a high range of target visibilities for the same physical contrast. This exposure duration also served to minimize scanning eye movements between the targets.
The vernier thresholds obtained in this way were compared with those found for abutting line targets using a 250 msec exposure duration in experiments performed just prior to, and concurrently with, the experiments reported here. Results of experiments where vernier thresholds for abutting targets were measured for a range of contrasts and exposure durations, have been reported elsewhere (Waugh & Levi, 1993a), and were obtained at a viewing distance of 4 m where the lines subtended 40 min arc in length and 0.62 min arc (2 pixels) in width.

Line detection thresholds were measured for a line placed at the same separations from the fixation line, as the vernier test line was from the reference line. To assess the effect of target visibility on vernier acuity for different target separations, vernier target contrasts were normalized by these line detection thresholds.

**Control experiment: the effect of controlled fixation**

To be able to measure more accurately the effect of varying the visibility of the test line on vernier thresholds, it was necessary to provide a fixation target for both detection and vernier acuity tasks. In the current experiments, observers were instructed to fixate the vernier reference line, or a fixation line placed at the same separation from the detection target line. If fixation were accurate, this paradigm would place the vernier and detection test lines at progressively greater retinal eccentricities with increasing separation. To gain additional insight into the role of eccentricity in determining vernier thresholds for separated targets, vernier thresholds were measured under two fixation conditions for targets separated by between 6 and 90 min arc and an exposure duration of 250 msec. In the controlled fixation condition as for all other experiments, observers fixated the reference line. In the free fixation condition, observers were instructed to use any fixation strategy in order to do as well as possible. High contrast vernier targets were chosen so that optimal thresholds could be obtained for each separation condition. Data for between three and five runs per condition were collected for two observers.

**RESULTS**

**Experiment 1: the effect of varying target visibility on vernier thresholds for widely separated target lines**

The circles and triangles in Fig. 2 show the effects of target visibility on vernier thresholds for targets separated by 90 min arc for a range of target exposure durations, for observers TN and SJW, respectively. The abscissa is specified in contrast detection threshold units (Waugh & Levi, 1993a). The data plotted in this way collapse down to a narrow, two branched curve, where there appears to be no systematic effect of exposure duration. For all exposure durations, the data are well described by two power functions, which appear as two lines on log-log axes, given by:

\[
th = \theta_i (V_i/V)^{\text{slope}_1} \quad \text{for} \quad V < V_i
\]

and

\[
th = \theta_i (V_i/V)^{\text{slope}_2} \quad \text{for} \quad V \geq V_i
\]

where \(V_i\), the independent variable, is the target visibility in contrast threshold units; \(\text{slope}_1\) and \(\text{slope}_2\) are exponents representing the slopes of the initial and final rates of change of vernier threshold, with changes in target visibility; \(V_i\) is the visibility level (contrast threshold units) where these two slopes intersect; and \(\theta_i\) is the vernier threshold (sec arc) associated with \(V_i\). These functions were combined and simultaneously fit to the data, where each datum was weighted by the inverse of its standard error. The data for each exposure duration and each observer were fit separately and estimates of the parameters, where all were fit to vary, are given in Table 1. In general, there appears to be no systematic effect of exposure duration on any of the curve fitting parameters. The visibility level at the inflection point \(V_i\) between the two slopes varies from 2.54 to 4.42 contrast threshold units with a mean of 3.10 ± 0.52 and 3.42 ± 0.78 for TN and SJW, respectively. In addition, a
TABLE 1. Effect of target visibility on line vernier for separation of 90 min arc

<table>
<thead>
<tr>
<th>Time (msec)</th>
<th>Visibility (ctu)</th>
<th>Vernier threshold (arc sec)</th>
<th>Slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slope1</td>
</tr>
<tr>
<td>TN</td>
<td></td>
<td></td>
<td>-0.90 ± 0.32</td>
</tr>
<tr>
<td>1000</td>
<td>2.76 ± 0.31</td>
<td>98.18 ± 7.54</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>2.72 ± 0.22</td>
<td>115.51 ± 3.76</td>
<td>-0.90 ± 0.44</td>
</tr>
<tr>
<td>100</td>
<td>4.00 ± 0.36</td>
<td>93.59 ± 3.67</td>
<td>-0.60 ± 0.15</td>
</tr>
<tr>
<td>50</td>
<td>2.95 ± 0.57</td>
<td>108.04 ± 10.46</td>
<td>-0.72 ± 0.38</td>
</tr>
<tr>
<td>23</td>
<td>3.05 ± 0.41</td>
<td>103.72 ± 7.41</td>
<td>-0.75 ± 0.15</td>
</tr>
<tr>
<td>Average</td>
<td>3.10 ± 0.52</td>
<td>103.81 ± 8.53</td>
<td>-0.77 ± 0.13</td>
</tr>
<tr>
<td>SJW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>2.54 ± 0.36</td>
<td>75.44 ± 4.45</td>
<td>-0.83 ± 0.31</td>
</tr>
<tr>
<td>250</td>
<td>4.42 ± 0.46</td>
<td>67.67 ± 4.54</td>
<td>-0.89 ± 0.10</td>
</tr>
<tr>
<td>50</td>
<td>3.54 ± 0.65</td>
<td>74.28 ± 1.77</td>
<td>-0.96 ± 0.34</td>
</tr>
<tr>
<td>15</td>
<td>3.18 ± 0.16</td>
<td>82.49 ± 2.73</td>
<td>-0.95 ± 0.33</td>
</tr>
<tr>
<td>Average</td>
<td>3.42 ± 0.78</td>
<td>74.97 ± 6.07</td>
<td>-0.91 ± 0.06</td>
</tr>
</tbody>
</table>

similar fit to the data for a third observer (FR) in Expt 2 where a 250 msec exposure duration was used, produced a $V_r$ of 2.92 ± 0.22 contrast threshold units. Vernier thresholds improve initially with increasing target visibility as a power function with an exponent averaging -0.77 ± 0.13 for TN, and -0.91 ± 0.06 for SJW. However once the visibility of the test line is greater than about 3 times the line detection threshold, vernier thresholds are virtually independent of target visibility, i.e. average exponents are -0.07 ± 0.05 for TN and -0.05 ± 0.02 for SJW. The presence of individual variability is revealed by the difference in the very repeatable asymptotic vernier thresholds found for each observer, both of whom were highly practiced at this task.

Also included for comparison in Fig. 2 (double-triangles) are the data obtained for the same observers in another series of experiments, where the effects of target visibility on vernier thresholds for abutting line targets were investigated (Waugh & Levi, 1993a). These data represent vernier thresholds for a range of target line contrasts and exposure durations (23–1000 msec) again normalized by the line detection thresholds. The exponents of the single power functions fit to these data are -1.00 and -0.93 for TN and SJW, respectively. These slopes are comparable with those found previously for thin line stimuli (Morgan & Aiba, 1985; Wilson, 1986; Klei et al., 1990; Banton & Levi, 1991; Waugh & Levi, 1993a), or for high contrast gratings (Bradley & Skottum, 1987). In contrast to the data obtained for vernier lines separated by 90 min arc, abutting vernier thresholds continue to decrease at a similar rate with increasing target visibility, until at least 30 times the line detection threshold (Waugh & Levi, 1993a).

Experiment 2: the effect of target visibility on vernier thresholds for targets separated by 2–90 min arc

The effects of varying target line visibility on vernier thresholds for targets separated by between 0 and 90 min arc are shown for each of three observers in Fig. 3. For these thin line targets, visibility is dependent on the product of line contrast (%) and line width (min arc) (Klein et al., 1990), therefore, vernier thresholds are plotted against “line visibility” in units of %min. This allows direct comparison of the data for all separations despite the different viewing distances and line widths used to obtain visible stimuli. It also enables the line detection thresholds, i.e. detection thresholds for a line separated from a fixation line by the same distance that existed between the two vernier lines, to be plotted in the same units (%min) along the abscissas of Fig. 3. The effects of varying target line visibility (in contrast threshold units) on vernier thresholds for line targets are shown for the same observers in Fig. 4. As in Expt 1, contrast threshold units were obtained by dividing the target line visibility (in %min) by the line’s detection threshold (in %min), this time for each separation condition.

Inspection of both Figs 3 and 4 reveals that for abutting lines, and for lines separated by 2 min arc
TABLE 2. Effect of target visibility on line vernier (time = 250 msec), actual fitting parameter estimates to data in Fig. 3

<table>
<thead>
<tr>
<th>Separation (arc min)</th>
<th>Visibility (c/s)</th>
<th>Vernier threshold (sec arc)</th>
<th>Slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>2.92 ± 0.22</td>
<td>75.49 ± 4.62</td>
<td>1.30 ± 0.23, -1.06 ± 0.5</td>
</tr>
<tr>
<td>60</td>
<td>3.91 ± 0.39</td>
<td>26.41 ± 1.47</td>
<td>1.35 ± 0.01, -0.12 ± 0.6</td>
</tr>
<tr>
<td>30</td>
<td>6.22 ± 0.56</td>
<td>22.81 ± 1.49</td>
<td>1.57 ± 0.33, -0.24 ± 0.6</td>
</tr>
<tr>
<td>15</td>
<td>5.08 ± 0.28</td>
<td>20.44 ± 1.16</td>
<td>1.73 ± 0.43, -0.19 ± 0.6</td>
</tr>
<tr>
<td>0</td>
<td>30 (approx.)  4.68 (approx.)</td>
<td>-0.77 ± 0.04</td>
<td>-1.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SJW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>4.42 ± 0.46</td>
<td>67.67 ± 4.54</td>
<td>0.89 ± 0.10, -0.07 ± 0.07</td>
</tr>
<tr>
<td>60</td>
<td>7.20 ± 0.74</td>
<td>23.52 ± 1.93</td>
<td>0.80 ± 0.17, 0.06 ± 0.10</td>
</tr>
<tr>
<td>30</td>
<td>6.06 ± 0.97</td>
<td>17.30 ± 1.08</td>
<td>0.81 ± 0.14, -0.16 ± 0.08</td>
</tr>
<tr>
<td>15</td>
<td>9.69 ± 0.79</td>
<td>13.81 ± 0.85</td>
<td>-1.02 ± 0.11, -0.03 ± 0.10</td>
</tr>
<tr>
<td>0</td>
<td>30 (approx.)  5.02 (approx.)</td>
<td>-0.84 ± 0.05</td>
<td>-0.01 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>2.72 ± 0.22</td>
<td>98.18 ± 5.74</td>
<td>-0.90 ± 0.22, -0.02 ± 0.06</td>
</tr>
<tr>
<td>8.55 ± 0.84</td>
<td>18.96 ± 1.12</td>
<td>1.19 ± 0.21, -0.20 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>30 (approx.)  4.62 (approx.)</td>
<td>-0.92 ± 0.03</td>
<td>-0.87 ± 0.03</td>
</tr>
</tbody>
</table>

TABLE 3. Separation (arc min)

<table>
<thead>
<tr>
<th>Separation (arc min)</th>
<th>Visibility (c/s)</th>
<th>Vernier threshold (sec arc)</th>
<th>Slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>2.92 ± 0.22</td>
<td>75.49 ± 4.62</td>
<td>1.30 ± 0.23, -1.06 ± 0.5</td>
</tr>
<tr>
<td>30</td>
<td>3.91 ± 0.39</td>
<td>26.41 ± 1.47</td>
<td>1.35 ± 0.01, -0.12 ± 0.6</td>
</tr>
<tr>
<td>15</td>
<td>6.22 ± 0.56</td>
<td>22.81 ± 1.49</td>
<td>1.57 ± 0.33, -0.24 ± 0.6</td>
</tr>
<tr>
<td>0</td>
<td>5.08 ± 0.28</td>
<td>20.44 ± 1.16</td>
<td>1.73 ± 0.43, -0.19 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>30 (approx.)  4.68 (approx.)</td>
<td>-0.77 ± 0.04</td>
<td>-1.2 ± 0.3</td>
</tr>
</tbody>
</table>

FIGURE 4. Vernier thresholds (arcsec) for different line separations vs target visibility in line contrast threshold units. The functions fit to the data are as follows. For abutting targets and targets separated by 2 min arc, a single power function with an exponent of -1 was used. For separations of 4-90 min arc, double power functions with the average parameters obtained for this range of separations for each observer (given in Table 2) were fit to the data.

(VR and SJW), vernier thresholds continue to decrease at a similar rate over the whole range of line contrasts available. Also, vernier thresholds at each target line contrast are lowest for abutting line targets, such that the introduction of any separation degrades performance. For lines separated by 4 min arc or more, the effect of increasing line contrast on vernier threshold changes. For low line contrasts, vernier thresholds are initially almost proportionally dependent on line contrast. However after some point, they become only weakly dependent on line contrast. Therefore at any particular contrast level, vernier thresholds increase with increasing separation between the target lines, this increase being more substantial at high line contrast levels.

The data of Fig. 3 were fit using either a single power function or a double power function of the form described by equation (1). Estimates of the fitting parameters obtained using these functions are given in Table 2. For targets separated by 4-90 min arc, the exponent of the first slope found when the visibility of the test line was low, is on average -1.16 ± 0.33. However the effect of increasing target contrast is much stronger for observer FR (average slope of -1.49 ± 0.20), than for either SJW (average slope of -0.88 ± 0.10), or TN (average slope of -1.05 ± 0.21). For abutting targets, or those separated by only 2 min arc, the average slopes obtained over the whole range of target visibility levels were -0.95 ± 0.25, -0.93 ± 0.12 and -0.92 ± 0.03 for FR, SJW and TN, respectively. For two observers (SJW and TN), the dependency of vernier thresholds on line visibility appears to be similar for all separations at low visibility levels. However for FR, vernier thresholds for targets separated by 4 min arc or more, appear to depend more strongly on visibility than they do for closely separated or abutting targets. This effect is more likely due to this observer's response to low target visibility levels rather than to the effect of separating the targets. That is, the slope of the function fit to FR's data for visibility levels <4 times the contrast threshold of the test line using abutting targets as for separated targets, is steeper at -1.58 ± 0.28; and for visibility levels <7 times the contrast threshold it is -1.33 ± 0.08. Another interesting trend is that for all observers the visibility level at which the vernier threshold becomes essentially independent of target visibility generally decreases as the separation between the vernier lines increases. To obtain the lines superimposed on the data in Fig. 4, values for the two slope parameters obtained for separations from 4-90 min arc were averaged across separation for each observer, and constrained to reflect the data. The exponents for the slopes fit to the 0 and 2 min arc separations were constrained to be -1.

The data of Figs 3 and 4 show that vernier thresholds for targets separated by less than about 4 min arc...
TABLE 3. Single and double power exponent estimates for transition zone (exposure duration = 250 msec)

<table>
<thead>
<tr>
<th>Separation</th>
<th>Single power fit</th>
<th>Double power fit</th>
<th>Reduced ( Z^2 ) (q^2/d.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope1</td>
<td>Slope1</td>
<td>Slope2</td>
</tr>
<tr>
<td>FR</td>
<td>6</td>
<td>-1.57 ± 0.33</td>
<td>-0.24 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-1.73 ± 0.43</td>
<td>-0.19 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-1.05 ± 0.14</td>
<td>-0.66 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-1.12 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>SJW</td>
<td>6</td>
<td>-0.81 ± 0.14</td>
<td>-0.16 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-1.02 ± 0.11</td>
<td>-0.03 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.94 ± 0.11</td>
<td>-0.60 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-1.01 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>4</td>
<td>-1.19 ± 0.21</td>
<td>-0.20 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-0.47 ± 0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-0.92 ± 0.03</td>
<td></td>
</tr>
</tbody>
</table>

*Used for subsequent analysis.

The decrease approximately proportionally with increasing target visibility suggesting that these vernier thresholds are limited by a single factor, i.e. contrast or visibility, over the range of contrast levels studied. However for separations of 4 min arc or more, the dependence of vernier thresholds on target visibility is nonmonotonic. This finding suggests that these thresholds are limited by at least two factors, one which is contrast dependent, and one which is essentially contrast independent. That the transition from one to two different dependencies of vernier thresholds on target visibility occurs for target separations between 2 and 4 min arc, is supported by examining the slope and reduced chi-square values, for single and double power functions fit to the data for small separations (see Table 3). Although on occasion, a double power function fit to the data produced a slightly smaller reduced chi-square than a single power function (e.g. 2 min arc separation), the two slope estimates are both quite steep and fall within the range of values obtained for the visibility dependent limitation, i.e. -0.60 to -1.73. The slope of the weakly visibility dependent function is much flatter, i.e. +0.06 to -0.24.

Another interesting way to view the data, is to plot vernier thresholds against target separation. Because we measured vernier thresholds for a range of target visibilities at each separation condition, we are able to add a second dimension to previous findings where the effect of target separation on vernier thresholds has been assessed, usually for bright, highly visible targets (Westheimer & McKee, 1977; Beck & Schwartz, 1979; Klein & Levi, 1987; Levi & Klein, 1990). Using the equations of the functions fit to the data in Fig. 3, vernier thresholds were interpolated for specific visibility levels for each observer at each separation. These interpolated values are represented as data in Fig. 5. This figure shows that vernier thresholds increase quite rapidly for small separations, and then less rapidly for separations greater than about 4 min arc. The curves fit to these data are derived from a simple model which will now be described.

The increase in vernier thresholds with increasing target separation is often described as following Weber's law where threshold is proportional to separation (e.g. Sullivan et al., 1972; Beck & Schwartz, 1979; Klein & Levi, 1987; Toet, 1987; Levi & Klein, 1990). Because for most relative position tasks where separation is varied, eccentricity is also varied, the role of each of these two factors in contributing to Weber's law has recently been placed in question (Klein & Levi, 1987; Toet, 1987; Levi & Klein, 1988; Levi & Klein, 1989, 1990; Morgan & Watt, 1989; Burbeck & Yap, 1990). One hypothesis is that Weber's law represents the

FIGURE 5. Using the equations fit to the data of Fig. 3 (parameters given in Table 2), vernier threshold predictions were made for different target visibility levels (see legend) at each target separation. Thus this figure shows interpolated vernier thresholds (log axis) vs target separation (linear axis). Since the reference line was fixated, the test line moved more eccentrically with increasing separation. The curves fit to these data were generated using a simple model where the more sensitive of a separation dependent (spatial filter) and an eccentricity dependent (local sign) mechanism is revealed (see text). Note that for FR, the exponent assigned to the local sign mechanism was 0.15, rather than 0.10 which was used for SJW and TN.

The 2. For effect of either SJW or TN, the decay appears in the 35 ± 0.25, 0.06 ± 0.10, 0.16 ± 0.08, 0.03 ± 0.10, or 0.02 ± 0.06 and 0.20 ± 0.08 at times greater than 4 g abutting deeper area, and in the other interactivity levels.
envelope of contributions by the more sensitive of two mechanisms. One of these mechanisms has been referred to as separation dependent (Levi et al., 1988; Levi & Klein, 1989, 1990; Burbeck & Yap, 1990), and has been attributed to the contrast response properties of spatial filters (Klein & Levi, 1987; Morgan, 1991; Wilson, 1991). The other mechanism has been referred to as eccentricity dependent (Levi et al., 1988; Levi & Klein, 1989, 1990; Burbeck & Yap, 1990), and has been suggested to result from a type of cortical measurement process (Klein & Levi, 1987; Levi et al., 1988; Wilson, 1991). With this dual mechanism approach in mind we have fit our data with a model where the more sensitive of two mechanisms, a separation dependent (spatial filter) mechanism which is strongly contrast dependent, and an eccentricity dependent (local sign) mechanism which is weakly contrast dependent, determines the vernier threshold. The data predictions for target visibilities of 5–30 contrast threshold units were simultaneously fit with the minimum of the following two functions:

spatial filter (separation dependent) mechanism

\[ th = [k_{sep} \, (sep + 1) \, (30/cfu)] \, 60 \tag{2a} \]

local sign (eccentricity dependent) mechanism

\[ th = [k_{ecc} \, (ecc + E_s) \, (30/cfu)] \, 60 \tag{2b} \]

where \( th \) is the vernier threshold (sec arc), \( k_{sep} \) is a fraction of the target separation (or Weber fraction), \( k_{ecc} \) is a fraction of the “effective eccentricity” (ecc + \( E_s \)) of the nonfixed vernier line, \( sep \) is the target separation (min arc), \( ecc \) is the eccentricity of the nonfixed target line and in these experiments is equivalent to the target separation, \( E_s \) is a constant representing the eccentricity at which the foveal threshold doubles (Levi et al., 1985), and \( cfu \) is the test line visibility level from 5 to 30 contrast threshold units. Vernier thresholds limited by the spatial filter mechanism are proposed to decrease proportionally with target visibility (exponent of 1), whereas those limited by the local sign mechanism are proposed to be only weakly dependent on target visibility (exponent of 0.1). This model assumes that vernier thresholds for line targets cease to improve at about 30 times the line detection threshold. Although we have no firm experimental evidence to support this assumption, it seems reasonable since the thresholds predicted for abutting target lines at this visibility level are close to the best ever reported at around 3 sec arc. Vernier thresholds for target visibilities of 1 and 3 contrast threshold units were simultaneously fit again using equations (2a) and (2b), however the local sign mechanism for these low visibility levels was also assumed to be contrast dependent, i.e. exponent of 1, assuming that accurate local sign information may depend to a degree on the signal to noise properties of spatial filters.

*Note that in equation (2a) threshold depends on separation + 1. This assumes that thresholds obtained with abutting line targets are equivalent to those obtained with lines separated by 1 min arc due to the blur function of the eye and ensures that this term is nonzero for abutting stimuli.*

![Figure 6](image-url)  
**FIGURE 6.** Schematic illustrating predictions using the model described in text. The top panel shows the predictions for the “spatial filter” or separation dependent mechanism. These curves were generated using a \( k_{sep} \) of 0.05 (5%), and assumes that thresholds at each separation decrease proportionally (exponent of -1) with increasing target contrast. On log-log axes, these predictions would appear as a series of nearly straight, parallel lines with a slope of 1, i.e. Weber's law for position. The middle panel shows the predictions for the “local sign” or eccentricity dependent mechanism. For target visibilities of 10 and 30 contrast threshold units, these curves were generated using a \( k_{ecc} \) of 0.009 (0.9%) and an \( E_s \) of 0.4 deg, where thresholds at each separation are only weakly dependent on line visibility (exponent of -0.1). For target visibilities of 1 and 3 contrast threshold units, these curves were generated using a \( k_{ecc} \) of 0.009 and an \( E_s \) of 1.3 deg. On linear-linear axes, these predictions would appear as lines which intersect the abscissa at a value defined by \( E_s \) (Levi et al., 1985). These functions also approach Weber's law at large separations. The bottom panel reveals which of these two mechanisms is more sensitive for different visibility levels and separations. For small separations the “spatial filter” mechanism is more sensitive. However for separations larger than about 4 min arc (at least for target visibilities of 30 cfu or less) the “local sign” mechanism is the more sensitive mechanism.
TABLE 4. Estimates of parameters from model fit and comparison across studies

<table>
<thead>
<tr>
<th>Task</th>
<th>Observer</th>
<th>$k_{gap}$</th>
<th>$k_{res}$ (deg)</th>
<th>$E_0$</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vernier</td>
<td>SJW</td>
<td>0.042 (0.002)*</td>
<td>0.0075 (0.0005)</td>
<td>0.44</td>
<td>Present</td>
</tr>
<tr>
<td>30 ctw</td>
<td>FR</td>
<td>0.051 (0.005)</td>
<td>0.0079 (0.0006)</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>0.076 (0.007)</td>
<td>0.0136 (0.0009)</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Vernier</td>
<td>SJW</td>
<td>0.056 (0.004)</td>
<td>0.0088 (0.0004)</td>
<td>1.17</td>
<td>Present</td>
</tr>
<tr>
<td>1 ctw</td>
<td>FR</td>
<td>0.074 (0.007)</td>
<td>0.0057 (0.0003)</td>
<td>2.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>0.077 (0.029)</td>
<td>0.0128 (0.0017)</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>Vernier</td>
<td>SK</td>
<td>0.005</td>
<td>0.27</td>
<td></td>
<td>Klein and Levi</td>
</tr>
<tr>
<td>3 dot</td>
<td>WS</td>
<td>0.010</td>
<td>0.21</td>
<td></td>
<td>(1987)</td>
</tr>
<tr>
<td></td>
<td>DL</td>
<td>0.010</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vernier</td>
<td>JT</td>
<td>0.031</td>
<td>0.007</td>
<td>0.45†</td>
<td>Levi and Klein</td>
</tr>
<tr>
<td>3 dot</td>
<td>KH</td>
<td>0.031</td>
<td>0.009</td>
<td></td>
<td>(1990)</td>
</tr>
<tr>
<td>Isoeccentric</td>
<td>JW</td>
<td>0.008</td>
<td>0.43</td>
<td></td>
<td>White et al.</td>
</tr>
<tr>
<td>(no references)</td>
<td>DL</td>
<td>0.012</td>
<td>0.35</td>
<td></td>
<td>(1992)</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>0.010</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Values in parentheses are standard errors of the estimates.
†Average value reported includes analysis of 3 dot alignment and 3 dot spatial interval discrimination thresholds combined.

Figure 6 schematically illustrates how the proposed spatial filter and local sign mechanisms independently affect vernier thresholds as the separation between the targets is increased. Assuming that the optimal vernier threshold for abutting targets is 3 sec arc, the spatial filter or separation dependent mechanism (top panel) predicts that vernier thresholds increase proportionally with increasing target separation (Weber's law), and decreasing target contrast. On log–log axes, each of these functions would appear as close to a straight line described by a power function with an exponent of 1. The local sign or eccentricity dependent mechanism (middle panel) predicts that vernier thresholds increase with increasing target separation, because the positional uncertainty of the nonfixed vernier line increases with eccentricity. On linear–linear axes, these functions would appear as straight lines which intersect the x-axis at a value defined by $E_0$. This function also exhibits Weber's law behavior at large eccentricities. The bottom panel represents the thresholds predicted by the more sensitive of the spatial filter and local sign mechanisms. Representative values for each of the parameters obtained by fitting the data of Fig. 5 were used to create these predictions (see legend of Fig. 6 for details).

As can be seen from Fig. 5, such a model does reasonably well at describing the effect of target separation and target visibility on vernier thresholds. The resulting envelope suggests that the contrast response properties of spatial filters limit vernier thresholds for a very limited range of target separations, and that the local sign mechanism limits vernier thresholds for line target separations of about 4 min arc. Estimates of the parameters obtained from fitting the model just described are given in Table 4, and compare well with those found in previous studies at least for highly visible targets. However the model in its present form has some difficulty in describing the trend from one regime to the other for intermediate visibility levels. This is seen by the model's poor fit to the data predicted for targets at 5 times the visibility level in Fig. 5, particularly for small separations. That is, the model predictions are lower than the measured thresholds.

Control experiment

The effect of controlled fixation. The effects of controlled vs uncontrolled fixation on vernier thresholds for line targets separated by between 6 and 90 min arc are

FIGURE 7. Histograms where vernier thresholds in sec arc (linear axis) are plotted against the separation condition (categories) for two observers, where the position of fixation was either directed at the vernier reference line (controlled fixation) or directed at the vernier lines (free fixation). These experimental results are represented by the hashed bars (see legend). Predictions based on a Pythagorean comparison process, where vernier thresholds are calculated by combining the positional uncertainties (or local signs "ls") associated with each target line ($ls_1^2 + ls_2^2$), for each fixation condition are shown as the solid bars. To make predictions for the "free fixation" condition, observers were assumed to fixate exactly in between the target lines.
shown in Fig. 7 for two observers (see hatched bars). When fixation was free to vary, both observers found the task easiest to perform, if they attempted to fixate in the region between the vernier lines. Similarly steady fixation was preferred, since if scanning eye movements were made between the target lines, their relative position appeared to vary. The results for two observers show that for highly visible targets, the position of fixation did not appear to affect vernier thresholds except for the 90 min arc separation, although the effect here is not statistically significant ($t = 3.87, d.f. = 1; P > 0.05$). These results are not incompatible with a process whereby the absolute position labels associated with each target line are compared to obtain relative position information. The local sign model that we described earlier predicts that for highly visible targets, such as those used in this experiment, vernier thresholds are limited by the uncertainty of the absolute position label or local sign associated with the nonfixed vernier test line. Positional uncertainty in turn is assumed to increase with retinal eccentricity at a rate described by $E_c$. Using the parameters estimated from our model for each observer (see Table 4), the positional uncertainty associated with the fovea is given by $k_{sec} \times (ecc + E_c)$ where ecc the eccentricity at the fovea, is 0. Thus estimates of the precision of the foveal local sign are about 12, 15, and 15 sec arc for SJW, TN, and FR respectively. These values are slightly lower than those estimated previously under different experimental conditions, i.e. between 14 and 30 sec arc (Zeeki & Mangoubi, 1984; White et al., 1992). If a simple Pythagorean comparison process between absolute position labels associated with the vernier lines is assumed, then relative position threshold predictions under both fixation conditions compare fairly well with the data obtained (see solid bars in Fig. 7). These findings support the suggestion that eccentricity, or the comparison process between the position labels whose uncertainties are determined by eccentricity, limit vernier thresholds for separated targets.

**DISCUSSION**

It is clear from the results of these experiments that the contrast dependence of vernier acuity depends on the separation between the vernier features. This finding is in agreement with an earlier report by Morgan (1986), and a recent report by Levi and Klein (1992). The present study shows that for abutting or very closely separated vernier lines viewed foveally, vernier thresholds continue to decrease with increasing contrast, until about 30 times the contrast detection threshold for a line target. However, once the separation between the lines is 4 min arc or more, although initially dependent on target visibility, vernier thresholds become only weakly dependent on target contrast at a much lower visibility level. The results of Exp 1 suggest that as with abutting vernier targets (Waugh & Levi, 1993a), increasing exposure duration has little effect on vernier thresholds for separated targets, independent of its contribution to increasing target visibility. Overall, the results of Expts 1 and 2 are consistent with the suggestion that whereas vernier thresholds for very close, or abutting line targets may be limited by the contrast response properties of spatial mechanisms, for more widely separated targets, they are limited by different factors such as the absolute positional uncertainties associated with each vernier line or perhaps the comparison process required to obtain relative position information. The present experiments cannot conclusively distinguish between limitations based on a separation dependent comparison process vs eccentricity per se. However, taken together, the present experiments and previous studies in which the stimuli were presented on an isoeccentric arc (Levi et al., 1988; Levi & Klein, 1990; Burbeck & Yap, 1990), or in isolation (i.e. with no reference, White et al., 1992) are consistent with the hypothesis that the eccentricity rather than the separation or distance between the lines limits performance at large separations.

**Sources of noise limiting vernier thresholds**

**Orientalational noise.** In our experiments, the effects of head tilt were minimized by supporting the head in chin and forehead rests. Nonetheless, one factor which may add noise to vernier thresholds, is angular noise produced by variations in head tilt and torsional eye movements. Although the relative position threshold for separated targets increases with separation, the vernier threshold in angular terms is smaller for large separations than for small separations. This can be seen by comparing the values obtained for the Weber fractions for the small separation and large separation regimes, i.e. $k_{sec}$ and $k_{ecc}$ for small separations (up to about 4 min arc), a Weber fraction ($k_{sec}$) of 0.05 (5%) represents a constant orientation threshold of 2.9 deg (about 172 min arc). However for large separations, the eccentricity Weber fraction ($k_{ecc}$) of 0.01 (1%) represents a constant orientation threshold of about 0.57 deg (about 34 min arc).

For prolonged monocular fixation where the head is held as still as possible, the standard deviation of torsional eye movements is reported to average about $\pm 17$ min arc in angular terms, but can be as high as $\pm 30$ min arc in some observers (Ferman, Collewijn, Jansen & Van der Berg, 1987). For targets separated by 90 min arc, angular noise due to such torsional eye movements, produces a relative position error of $\pm 27$–47 sec arc. Although under our experimental conditions where the head was supported, angular noise due to torsional head and eye movements is estimated to be less than the vernier thresholds obtained for this separation, it is a factor which should be considered in these types of studies. The effects of stabilizing retinal image motion due to eye movements on vernier thresholds have been assessed and found to have no effect (Keesey, 1960); however abutting line targets were used, where the effect of torsional eye movements is predicted to be least.

One advantage of using line stimuli in contrast to point or dot stimuli, is that the lines have internal orientation information, and may therefore be less susceptible to orientational noise.
The contrast response properties of spatial filters. Several models have attempted to account for vernier acuity on the basis of local changes in the pattern of illumination at the photoreceptors (e.g., Hartridge, 1922; Geisler, 1989; Morgan & Aiba, 1985; Morgan, 1986; Klein et al., 1990). None of these models can simply account for the increase in vernier thresholds with increasing separation, i.e. Weber's law, since the pattern of local retinal information is not altered by adding a gap. Recently, several investigators have suggested that vernier thresholds for abutting targets may be limited by the differential contrast response properties of the localized spatial filters in the cortex that represent the basic contrast detection mechanisms of vision (Klein & Levi, 1985; Wilson, 1986; Morgan, 1986). This notion is supported by the result that vernier thresholds for targets kept equally visible (in terms of contrast detectability), remain close to constant despite wide variations in target chromatic content, blur, exposure duration and retinal illumination level (Krauskopf & Farell, 1991; Waugh & Levi, 1992a,b). The increase in vernier and separation discrimination thresholds with increasing target separation has also been successfully modeled using a spatial filter approach, at least for separations up to 10 min arc under foveal viewing conditions (Klein & Levi, 1985; Wilson, 1986). That is, it is assumed that as separation increases, these thresholds are mediated by the contrast response properties of successively larger, or lower spatial frequency filters which have proportionally lower localization acuity. Our results do not argue against this possibility, however they suggest that this type of mechanism is not the most sensitive one for extracting vernier thresholds once the separation between the target lines is increased by more than about 4 min arc (under foveal viewing conditions and for target contrasts less than about 30 times the detection threshold). If vernier thresholds for separated targets are limited by the contrast response properties of successively larger spatial filters, a Weber's law dependence of vernier threshold on separation would continue to hold, a result described by the curves in Fig. 6 (top). The contrast dependency of spatial filter responses also predicts that all spatial discrimination thresholds that are limited by these responses will decrease with increasing contrast, at least up to the point of saturation (Morgan, 1986).

For targets separated by 90 min arc, where a single filter large enough to encompass both target lines is unlikely to be mediating vernier thresholds (the largest receptive field in Wilson's line element model have excitatory regions about 30 min arc wide), vernier thresholds are dependent on target visibility only until about 3 times the contrast detection threshold. For smaller separations however, vernier thresholds are in general contrast dependent over a wider range of visibility levels (see Table 2). This trend may be the result of either the contrast response properties of spatial filters which encompass both vernier lines limiting vernier thresholds until the local sign mechanism becomes more sensitive, or that for close separations because of the wider available range of spatial filters at the fovea, the local sign mechanism requires more contrast to locate with certainty the optimally responding spatial filter. Our results do not distinguish between these two alternatives.

Absolute positional uncertainty. Our model suggests that the local sign mechanism is more sensitive than the spatial filter mechanism for separations greater than about 4 min arc, for target contrasts less than about 30 times threshold. However, to account for the increase in vernier thresholds with increasing separation, this mechanism assumes that the positional uncertainty of the local sign increases at a rate linearly proportional to retinal eccentricity. This increase in positional uncertainty with eccentricity has been suggested to arise from a decrease in the precision of retino-cortical mapping (Morgan, 1977; Klein & Levi, 1987; Levi & Klein, 1990), and from increases in the spatial irregularity of the retinal mosaic (Wilson, 1991). However there are a number of changes which occur at all levels of the visual pathway as retinal eccentricity increases, so that the physiological origin of the positional uncertainty which may limit relative position thresholds remains unclear. Whatever the origin, a useful parameter to describe the rate of change in vernier thresholds with increasing eccentricity is described by $E_\text{f}$, i.e. the eccentricity (usually expressed in deg) at which the foveal threshold doubles (Levi et al., 1985).

Inspection of Figs 4 and 5 reveals that the rate of change in threshold with separation/ eccentricity, i.e. $E_\text{f}$, varies systematically with target visibility level from an $E_\text{f}$ of about 0.1-1. However it is important to remember that this rate of falloff reflects the envelope of two mechanisms one which is separation dependent ($E_\text{f} \approx 0$) and the other which is eccentricity dependent. Our model allows us to estimate the values for $E_\text{f}$ for the eccentricity dependent mechanism by itself. The model estimates for highly visible stimuli (Table 4) are between 0.3 and 0.5 deg. These values are similar, to those reported previously (0.4-0.9 deg) for the decline of optimal position acuity with eccentricity (Westheimer, 1982; Levi et al., 1985; Yap, Levi & Klein, 1987). However they are even more similar to those found using a similar paradigm to ours, in which a relative position judgment is made between an eccentrically placed test line, and a foveally fixated reference line (Klein & Levi, 1987; Levi & Klein, 1990), or between the test line and a remembered foveal reference line (White et al., 1992). For these tasks, the value of $E_\text{f}$ appears to be slightly smaller (0.10-0.67), indicating a more rapid variation in threshold with eccentricity (see Table 4). Interestingly Wilson (1991), has suggested that the increase in separation discrimination thresholds with eccentricity can be modeled reasonably well by cumulating the standard deviations of cone position at different eccentricities. Wilson's predictions for cumulative cone positional uncertainty are superimposed (dot-dashed line) on the data of Fig. 8.

For targets at very low visibility levels, our model suggests that relative position thresholds increase at a lower rate with increasing target separation than they do for highly visible targets (Table 4). Assuming that the
local sign mechanism does require contrast to increase certainty as to which position label is being stimulated, and that the range of spatial filters available to signal absolute position is largest at the fovea, this finding is not too surprising. For example, at the line detection threshold the position of the target lines may be registered by a range of spatial filters which vary widely in size and orientation, especially at the fovea. Thus our threshold predictions for closely separated targets at the fovea at low visibility levels are raised relative to those for widely separated targets as a result of at least two factors: (1) the range of spatial filters available to signal the position of the test line is larger at the fovea so that with decreases in target visibility the relative decrease in positional certainty, afforded by smaller spatial filters, is greatest at the fovea; and (2) for close separations the visibility of both vernier lines is at a similar low level perhaps limiting the positional labeling process for both lines, whereas for large separations it is likely that vernier thresholds are limited by the visibility of the more peripheral test line only.

Comparison with previous studies

In Fig. 8, our data predictions for test targets at 30 times the line detection threshold are plotted along with vernier data from previous studies where relatively long (8 min arc or more), highly visible lines were used over a similar range of target separations. Superimposed on the data are our model predictions for the spatial filter and local sign mechanisms, also predicted for targets at 30 times the line detection threshold. On the whole, these data appear to follow a similar trend, which follows our model predictions fairly well. Note that with short target lines (4 min arc or less) (Sullivan et al., 1972; Westheimer & McKee, 1977; Levi et al., 1985; Levi & Klein, 1990), thresholds increase as a result of blurring at separations less than about 2–4 min arc. Our results, obtained for long lines at contrasts below 30 times the detection threshold reveal an increase in vernier threshold when a separation of 2 min arc or more is introduced between the lines. This result would be expected if the same spatial filters, which are optimally stimulated by long abutting lines, are also employed for these small separations. Thus a small separation would be processed similarly to a small loss in effective contrast.

Effect of blur

Watt and Morgan (1983) used blurred edges (standard deviation of 2.5 min) separated by 6 min arc, and found that vernier acuity improved with contrast with a slope of \(\approx -0.5 \) over a substantial contrast range. Similar slopes have been confirmed by other investigators using abutting targets with an extended light distribution (Krauskopf & Farell, 1991; Klein et al., 1990; Wehrhahn & Westheimer, 1990; Watt & Morgan, 1984). While these results seem at odds with the present results, one possible interpretation is that localization of an extended light distribution is affected by contrast for the informational reasons discussed by Watt and Morgan (1983); however, the localization error for a thin line is relatively small, and is overwhelmed by the Weber error when separation increases (Morgan, personal communication). If correct this implies a three-way interaction between blur, contrast and separation, as has been shown for spatial interval discrimination with Gaussian blurred bars (Levi et al., 1990) and Gabor patches (Levi & Klein, 1992). Thus, the actual separation at which different sources of noise might limit relative position thresholds may depend on the blur characteristics of the stimuli (Stigmar, 1971; Williams et al., 1984; Toet et al., 1987; Levi et al., 1990; Whitaker & MacVeigh, 1991).

Effect of task

Morgan and Regan (1987) reported a greater effect of contrast on vernier thresholds than on spatial interval discrimination thresholds for Gaussian blurred targets separated by the same amount. This raises the possibility that the transition from contrast dependent to virtually contrast independent regions, may occur at different separations for the two tasks. This is a reasonable suggestion since the relative position judgments for these two tasks are orthogonal.

Conclusion

In summary, our results show that the contrast dependence of vernier acuity varies, depending on the separation between the vernier features. For foveally viewed target lines which are abutting or separated by 2 min arc or less, vernier thresholds decrease...
approximately proportionally with increasing contrast at least until the contrast of the test line reaches about 30 times the line detection threshold. For targets separated by approximately 4 min arc or more, vernier thresholds become only weakly dependent on target contrast at much lower visibility levels. Our results are reasonably well accounted for by a model where the more sensitive of two mechanisms limits vernier thresholds. In agreement with earlier studies, we suggest that for small separations, vernier thresholds are limited by the differential contrast response properties of spatial mechanisms. As the separation between the vernier lines increases, thresholds become only weakly contrast dependent and appear to be limited by the positional uncertainty of the test line which increases with the increasing separation or eccentricity.

REFERENCES


**Acknowledgements**—We thank Thom Carney for his help in setting up the experiments. We also thank Harold Bedell, Nancy Coletta, Stan Klein, Michael Morgan, Earl Smith and an anonymous referee for helpful comments on an earlier version of the manuscript. This research was supported by grant ROI/EY01728 from the National Eye Institute, and a Sigma Xi Grant in Aid of Research.