“Weber’s Law” for Position: the Role of Spatial Frequency and Contrast

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We used Gabor bars to measure the effects of spatial bandwidth, spatial scale, contrast and separation on three-line spatial interval discrimination (bisection). In the first experiment, we used stimuli that were well above threshold. Our results show that at all spatial scales, spatial interval discrimination (three-line bisection) thresholds are proportional to the separation of the Gabor patches (i.e. Weber’s law) when the separation exceeds approximately 2.5 times the standard deviation (σ) of the Gaussian envelope. The optimal threshold occurs when the separation is approx. 2–2.5σ, and for separations larger than the optimal, bisection thresholds are equal to a more or less constant Weber fraction (ΔS/S) of approx. 0.02–0.04. These results are consistent with a number of previous studies. In the second experiment, we examined the effect of contrast. Our results show an interaction between separation and stimulus visibility. Reducing the stimulus contrast has a marked effect on spatial interval thresholds at small separations (e.g. separations less than about 3σ), and much less effect at larger separations. Thus, the Weber’s law relationship appears to depend on the visibility of the stimuli, but does not depend on the spatial frequency or bandwidth of the stimuli. These results can be predicted by an ideal observer model of spatial interval discrimination.

Psychophysics Spatial interval discrimination Bisection Hyperactivity Gabor stimuli Weber’s law Spatial vision

INTRODUCTION

A striking aspect of position acuity is that for a wide variety of tasks and conditions, the position thresholds are approximately proportional to the separation between the features defining the stimulus. This proportionality between separation and the position threshold is “Weber’s law” for position (Weber, 1834), and it is found for alignment and vernier acuity (Sullivan, Oatley & Sutherland, 1972; Andrews, Butler & Buckley, 1973; Westheimer & McKee, 1977; Beck & Schwartz, 1979; Beck & Halloran, 1985; Klein & Levi, 1987; Levi & Klein, 1990a), and for spatial interval discrimination and bisection (Foehner, 1860; Volkman, 1863; Westheimer & McKee, 1977; Hirsch & Hylton, 1982; Watt, 1984; Klein & Levi, 1987; Levi & Klein, 1990a), even under scotopic conditions (Yap, Levi & Klein, 1989). Weber’s law also holds for Gaussian blurred stimuli, provided the separation is more than about 2.5 times the Gaussian standard deviation (Toet, van Eekhout, Simons & Koenderink, 1987b; Levi & Klein, 1990b; Levi, Jiang & Klein, 1990).

While Weber’s law for position seems to be ubiquitous in human spatial vision, it can fail when the stimuli are placed on an iso-eccentric arc, and the separation is greater than about a third of the eccentricity (Levi, Klein & Yap, 1988; Levi & Klein, 1990a; Burbeck & Yap, 1990). Under these conditions, position thresholds are approximately proportional to the target eccentricity, suggesting that the stimulus eccentricity may provide one fundamental limit to the precision of spatial vision. Recently, Hayes and Hess (1992) measured spatial alignment and bisection thresholds with two-dimensional Gabor patches of very low visibility (~4dB above the pattern detection threshold). They report that under their stimulus conditions, they “find no evidence for Weber’s law”. They argue thresholds are mainly dependent on the carrier spatial frequency of the Gabor patch. This result is both surprising, and potentially very important to our understanding of the mechanisms underlying Weber’s law for position. One reason that it is surprising is that previous studies of positional acuity using widely separated Gabor patches have led to the conclusion that the stimulus spatial frequency, orientation and color are irrelevant, and that the precision of localization is determined by the standard deviation of the Gaussian envelope and by the stimulus separation (Burbeck, 1987; Toet, 1987; Toet & Koenderink, 1988; Kooi, DeVloois & DeVloois, 1991). The results of Hayes and Hess are also potentially very important because, in general, they place strong constraints upon the classes of models which can be used to explain Weber’s law for position.

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We have independently been performing experiments similar to those of Hayes and Hess, and our results suggest that a Weber relationship can occur with spatially bandlimited stimuli. Our results, consistent with previous studies (Burbeck, 1987; Toet, 1987; Toet & Koenderink, 1988; Kooi et al., 1991), show that spatial interval discrimination is independent of stimulus spatial frequency and bandwidth. However, we find a strong interaction between stimulus visibility and stimulus separation. We will argue that the failure of Hayes and Hess to find a Weber relationship may be a consequence of the low visibility of their stimuli, rather than the fact that they are narrow-band in spatial frequency.

METHODS AND PROCEDURES

Stimuli

The stimuli were three horizontal bars each of whose orthoaxial luminance profile was a Gaussian modulated cosine grating (i.e. a Gabor bar) according to:

\[
G(x) = \exp\left(-\frac{x^2}{2\sigma^2}\right)\cos(2\pi Nx/\sigma + \phi)
\]  

where \(\sigma\) is the standard deviation of the Gaussian envelope, \(N\) is the number of cycles per standard deviation, and \(\phi\) is the phase. The stimulus full bandwidth at half maximum is \(0.55/N\) octaves. In our experiments, \(\phi\) was always 0.

Figure 1 shows examples of our stimuli. Each panel of our 3 bar stimulus shows a different value of \(N\). From top to bottom \(N = 0\) (the Gaussian envelope), \(N = 1, 2, 3,\) and 4. Each stimulus in Fig. 1 has the same separation (equal to \(6\sigma\)) between the bisection point and the outer "reference" bars.

Note that our stimuli differed from Hayes and Hess (1992) in two important respects. First, Hayes and Hess’s stimuli were two-dimensional Gabor patches, i.e. their stimuli were patches of sinusoidal gratings which were multiplied in both the \(x\)- and \(y\)-dimensions by a circularly symmetric Gaussian envelope. Our stimuli were horizontal Gabor bars, i.e. they were cosine gratings which were multiplied by a Gaussian in only the \(y\)-dimension. The bars were elongated, and the length was truncated by a black mask. The Hayes and Hess stimuli were in sinewave phase (\(\phi = \pi/2\)) and had a bandwidth corresponding to \(N = 1/\sqrt{2}\). Figure 2 illustrates how our bandwidths compare with those of Hayes and Hess (1992) by plotting the tuning curves for our stimuli (\(N = 1\) to \(N = 4\), shown by the dotted lines) and that of Hayes and Hess (shown by the solid line). The tuning curves are given by the Fourier transform of equation (1) with the carrier frequency normalized to \(f_{\text{carrier}} = N/\sigma = 1:\n
\[
\tilde{G}(f) = \exp\left(-[(f - 1)2\pi N]^2/2\right).
\]

The second difference is that because our stimulus bars were elongated, they had much lower contrast detection thresholds than an equivalent two-dimensional patch. This difference made it easy to obtain contrast levels
FIGURE 2. Shows the spatial frequency tuning of our stimuli ($N = 1-4$ shown by the dotted lines). Note that the $N = 4$ has the narrowest spatial frequency tuning, and $N = 1$ has the broadest of our stimuli. Also shown are the stimuli of Hayes and Hess (1992) shown by the solid line. Note that Hayes and Hess stimuli had broader bandwidths than all of our Gabor stimuli.

which are well above threshold over a wide range of spatial scales. Moreover, since the spatial interval task (bisection) is one-dimensional, the stimulus remains narrow-band in the dimension of interest (i.e. in the “cue” or offset dimension).

The stimuli were generated by a programmable arbitrary function generator under computer control, and were presented on a Joyce CRT with a white, P4 phosphor, and a mean luminance of 115 cd/m$^2$. The function generator was synchronized to the fast sweep of the Joyce, and two programmable attenuators in series provided excellent control of stimulus contrast and timing. The screen was masked by a black rectangle, 23 cm high by 12 cm wide. In order to minimize temporal transients, the stimuli were ramped on over 300 msec, remained at a plateau for 600 msec, and were ramped off over 300 msec. We used a long stimulus duration, because spatial interval thresholds are best with long viewing duration (Yap, Levi & Klein, 1987).

The peak contrast of each Gabor bar was either set to 33% or to a fixed multiple of the detection threshold as will be indicated; however, in order to minimize contrast cues to separation, we introduced a contrast jitter of $\pm 15\%$ from trial to trial. Detection thresholds for our Gabor stimuli were measured over the full range of conditions using a signal detection methodology (Levi & Klein, 1990b), and in some experiments the contrast of the Gabor bars were set to a fixed multiple of the detection threshold (8 or 10 times the detection threshold for that stimulus $\pm$ a contrast jitter of 15% from trial to trial). Note that detection thresholds were measured for single Gabor bars, which were directly viewed (the consequences of this will be discussed later). In the spatial interval discrimination experiments, absolute position cues were eliminated by jittering the position of the entire stimulus. In order to achieve a wide range of line separations and standard deviations, we fixed the Gaussian standard deviation at 20 pixels, and varied the separation of the lines on the screen from 50 to 200 pixels (note that we specify separation from the bisection point to the center of one reference line). The standard deviation was varied by changing the viewing distance from 0.5 m ($\sigma = 30\%$) to 2 m ($\sigma = 7.5\%$). This strategy varied the bar length and the screen size in proportion to $\sigma$. At 2 m the lines were approx. 3.4 deg long, and the vertical extent of the screen was approx. 6.5 deg. For stimuli viewed from closer distances, all dimensions were scaled proportionally. Variations in bandwidth ($N$) were achieved by holding $\sigma$ constant and varying spatial frequency.

**Psychophysical methods**

Thresholds for three-line spatial interval discrimination (bisection) were measured using a self-paced rating-scale method of constant stimuli. An experimental run consisted of 125 trials (preceded by 10–20 practice trials). On each trial the middle test line was presented in one of three randomly chosen vertical positions, equally spaced about, and including the bisection point. The size of the offset was determined by pilot experiments in order to obtain $d'$ values close to unity. The observer's task was to judge the position of the test line relative to the bisection point by giving integers from $-1$ to $+1$. This self-paced method of constant stimuli with multiple responses is a multiple-criterion probit analysis and has been described elsewhere (Levi & Klein, 1983). Between runs we varied the separation, $N$ (the bandwidth), and the viewing distance (the spatial frequency). Thresholds for *spatial interval discrimination* were obtained by calculating a maximum-likelihood estimate of the $d'$ values for each stimulus and interpolating to $d' = 1$, equivalent to the 84% correct level. To compare the present thresholds to those specified at 75% correct (e.g. Westheimer & McKee, 1977), our thresholds should be multiplied by 0.675. The thresholds reported are the geometric mean of 2–4 runs, weighted by the inverse variance, and the error bars reflect both within and between run variance (Klein, 1992).

**Observers and conditions**

Two highly practiced observers participated in the experiments. CN and DN are students well practiced in psychophysics, but were naive as to the purpose of the experiments. Both observers had normal binocular vision and corrected-to-normal visual acuity in each eye. Viewing was binocular and with natural pupils. All of the main observations were also replicated by author DL.

**Calibration**

Stimulus luminance and contrast (Michelson), were calibrated using a Pritchard SpectraPhotometer.
RESULTS

Fixed contrast targets: effect of bandwidth and spatial frequency

Figures 3 and 4 show data of the two naive observers obtained at a fixed contrast level (33%). In these figures each panel represents a particular bandwidth \((N)\), with \(N = 1\) at the top, and \(N = 4\) at the bottom. Each panel contains several data sets. Each data set was obtained using identical stimuli on the screen, but viewed from a different distance. Thus, the data connected by different lines are scaled replicas of each other. Each stimulus has the same bandwidth, but the spatial frequency (in c/deg), standard deviation \((\sigma\) in min), and the range of separations (in min) varies. In all of the figures, the symbol size is proportional to the spatial scale (i.e. \(\sigma\) and spatial period) of the stimuli. Consider the data of CN with \(N = 1\) (top panel in Fig. 3). The smallest symbols show data with a standard deviation of \(\sigma = 7.5\). These data follow the familiar V-shaped function of separation seen with lines (Klein & Levi, 1985), dots (Yap et al., 1987) and Gaussian bars (Levi et al., 1990), with thresholds first decreasing, and then increasing as target separation increases. Note that this pattern is seen for each of the three curves in the top panel of Fig. 3. However, as \(\sigma\) increases, the bottom of the V occurs at progressively wider separations, and the optimal thresholds increase. For both observers, with \(N = 1\), spatial frequency = 8 c/deg and \(\sigma = 7.5\), optimal thresholds are close to 6 arc sec (0.1 min). This is equal to a Weber fraction \((\Delta s/s)\) of \(\approx 1/190\) at the optimal separation of 19'. Each panel and both observers show similar trends, although the sharp upturn at small separations is not always evident. Note that the optimal thresholds increase with increasing \(N\). This latter point may be due to the lower visibility of the stimuli as \(N\) increases (and bandwidth decreases). The critical point is that even with rather narrow band stimuli, over a wide range of spatial frequencies and Gaussian standard deviations, there is a range of separations where thresholds increase with separation, following the familiar Weber's law relationship (indicated by the unity slope of the dashed line in each panel) or increase even more steeply. This “supra-Weberian” regime (where thresholds increase more steeply than predicted by Weber’s law) is likely a consequence of facilitation at separations near the optimum, and will be discussed in the section titled “Limiting Factors in Positional Coding” (see Discussion).

Fixed contrast targets: effect of spatial scale

The data of Figs 3 and 4 are replotted in Figs 5 and 6, however, now both the ordinate and the abscissa have been divided by \(\sigma\) (the Gaussian standard deviation). As occurs with Gaussian bars \((N = 0;\) Levi et al., 1990), the functions obtained with self-similar stimuli collapse into a more-or-less unitary V-shaped function with thresholds showing an optimum at a separation about 2–3 times the standard deviation of the stimulus. At both smaller separations and larger separations, thresholds
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FIGURE 4. Same as Fig. 3 but for observer DN.

FIGURE 5. The data of Fig. 3 (observer CN) are replotted here; however, now both the ordinate and the abscissa have been divided by $\sigma$ (the Gaussian standard deviation). See text for further details.
increase. At small separations this increase is due to overlap of the stimuli, at large separations it is a consequence of Weber's law. Note that of the twenty curves represented in these two figures, only one (CN with $N = 3$ at 24 c/deg) shows less than proportionality between threshold and spatial interval (i.e. a slope markedly less than unity). As noted above, this is probably a consequence of the low visibility of this high spatial frequency stimulus. Note too that when scaled in this way the results become "scale invariant", i.e. they are similar at each spatial scale. More importantly, the present results suggest that bisection thresholds are highly dependent on the stimulus spatial interval; however, spatial frequency appears to have little if any significant effect on bisection thresholds.

**Fixed visibility targets: effect of spatial scale**

Figure 7 shows data of CN obtained with stimuli whose contrast was fixed at 10 times the detection threshold. The physical contrasts actually ranged from approx. 5% ($N = 1$, 2 c/deg, $\sigma = 30'$) to 47% ($N = 4$, 16 c/deg, $\sigma = 15'$). In Fig. 7 the thresholds and spatial intervals are plotted in sigma ($\sigma$) units (i.e. as in Figs 5 and 6 both axes have been divided by the Gaussian standard deviation). The results are similar to those of Fig. 5, with the curves at each bandwidth collapsing to a single V-shaped function, with an optimum at about 2.5$\sigma$. For spatial intervals larger than the optimum, thresholds increase more or less in proportion to the spatial interval, or, as noted earlier, even more steeply.

**Fixed visibility targets: effect of bandwidth**

Figure 8 shows that for widely separated stimuli (separation = 6$\sigma$) neither spatial frequency nor standard deviation strongly influence the threshold; rather, thresholds are proportional to the target separation, i.e. they are a constant Weber fraction. The thresholds from Fig. 7 expressed as a Weber fraction ($\Delta s/s$) are plotted as a function of $N$ (the number of cycles per standard deviation). Note that as $N$ increases, spatial frequency increases and the bandwidth becomes narrower. Each curve represents data obtained at a different viewing distance, so that the separation, standard deviation and range of spatial frequencies expressed in units of visual angle are different for each of the three curves; however the separation is always 6$\sigma$, and the stimuli are again scaled replicas of each other. Stimulus contrast was always 10 times the target detection threshold. Note that thresholds when expressed as a Weber fraction are approximately constant despite the 4-fold range of standard deviations and separations, and the wide range of spatial frequencies (from 2 c/deg at $N = 1$ and $\sigma = 30'$, to 12 c/deg at $N = 3$ and $\sigma = 15'$), suggesting that thresholds for stimuli whose separation is large relative to their spread ($\sigma$) obey Weber's law. The left-most datum of each curve represents $N = 0$ (the low pass Gaussian), and it is interesting to note that thresholds for band-limited Gabor bars are similar to those obtained with equally visible Gaussian bars (Burbeck, 1987; Toet, 1987; Toet & Koenderink, 1988). The only
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![Graphs showing Weber's Law for Position](image_url)

**Effect of target visibility**

Here we take up the question of why the present results differ so markedly from those of Hayes and Hess (1992). Hayes and Hess used two-dimensional Gabor patches which were 4 dB (0.2 log units or a factor of 1.6) above threshold to measure both alignment and spatial interval thresholds. Their conclusion was "we find no evidence for Weber's law with such stimuli". Rather, they find thresholds are proportional to the spatial scale as defined by the cycle size ($\sigma/N$). They argued that the Weber relationship can only occur with broadband stimuli because it is a consequence of switching scales as the eccentricity of the targets increases. The present results show that Weber's law can occur with stimuli which were as narrow or narrower in bandwidth than those of Hayes and Hess (1992). While there are a number of important differences between the stimuli and methods employed in the two studies (e.g. one vs two-dimensional patterns), we argue below that the failure of Weber's Law in the Hayes and Hess studies is not due to their use of bandlimited stimuli, but rather that it is a consequence of the very low visibility level that they used.

Figure 9 provides some evidence that the visibility of the stimulus rather than its spatial frequency content plays an important role in limiting position discrimination. Shown in Fig. 9(A) are spatial interval discrimination thresholds for DL (in min) plotted against spatial interval (in min). The open symbols are for Gabor bars with $\sigma = 15'$ and $N = 2$ (corresponding to 8 c/deg—large circles) and $N = 3$ (corresponding to 12 c/deg—small circles). Both data sets were obtained with stimulus contrast set to 8 times the foveal detection threshold.

**Figure 8.** Threshold expressed as a Weber fraction ($\Delta/\sigma$) is plotted as a function of $N$ (i.e. the number of cycles per standard deviation of the Gabor patch). See text for further details.
threshold, and the two separations correspond to 2.5 and 6 times \( \sigma \). Note, that as shown for the other observers, neither spatial frequency nor bandwidth significantly effect the thresholds for these equally visible stimuli, and more importantly, thresholds increase with increasing spatial interval with a slope near unity [as illustrated by the \( \frac{1}{4} \) Weber's Law line], or steeper. The solid symbols show data at approximately 2 times the detection threshold for Gabor bars with \( N = 3 \) (12 c/deg) and \( \sigma = 15' \). Note that thresholds are elevated at both separations; however, lowering the contrast has a much greater effect at the small than at the large separation, resulting in a loss of the Weber's law relationship. A similar effect can be seen in the data of DL with Gaussian bars (Levi et al., 1990—see Figs 7 and 9). Figure 9(C) shows similar results for observer CN with Gabor bars with \( N = 1 \) and \( \sigma = 15 \) or 30'. The stimuli are scaled replicas of each other viewed at two different distances. Note that for this observer, when the stimulus visibility is high (10 times threshold—open circles), the

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**FIGURE 9.** (A) Spatial interval discrimination thresholds for DL are plotted against spatial interval. The open symbols are for Gabor bars with \( \sigma = 15' \) and \( N = 2 \) (corresponding to 8 c/deg—large circles) and \( N = 3 \) (corresponding to 12 c/deg—small circles). The solid symbols show data at approximately 2 times the detection threshold for Gabor bars with \( N = 3 \) (12 c/deg) and \( \sigma = 15' \). Note that thresholds are elevated at both separations; however, lowering the contrast has a much greater effect at the small than at the large separation, resulting in a loss of the Weber's law relationship. (B) Data of (A) replotted with both the thresholds and separations plotted in \( \sigma \) units (as in Fig. 7). The horizontal dotted line shows the predictions of an ideal observer model which suggests that at low visibility levels, performance is limited by a "floor" which is independent of separation. (C) Similar results for observer CN with Gabor bars with \( N = 1 \) and \( \sigma = 15 \) or 30'. The stimuli are scaled replicas of each other viewed at two different distances. Note that for this observer, when the stimulus visibility is high (10 times threshold—open circles), the optimal data fall close to the \( \frac{1}{4} \) Weber's law line. At 3 times threshold, for both \( \sigma \), thresholds are markedly elevated at the small separation but not at the large separation, resulting in a loss of the Weber relationship. (D) Data of (C) replotted with both the thresholds and separations plotted in \( \sigma \) units (as in Fig. 7). The horizontal dotted line shows the predictions of an ideal observer model which suggests that at low visibility levels, performance is limited by a "floor" which is independent of separation.
data fall close to the Weber line showing the near proportionality between threshold and separation. Note that in Fig. 9(C) the Weber's law line is drawn at a Weber fraction of $\frac{\sigma}{M_0}(0.01)$. At three times threshold, for both $\sigma$, thresholds are markedly elevated at the small separation but not at the large separation, resulting in a loss of the Weber relationship. Figure 9(B, D), replot the data of Fig. 9(A, C), with both the thresholds and separations plotted in $\sigma$ units (as in Fig. 7). Figure 9(D) reveals the scale invariance of the results. At high target visibility levels (e.g. 10 times threshold—open circles), spatial interval thresholds are a V-shaped function of separation. For separations greater than about $2.5\sigma$, thresholds rise more or less in proportion to target separation. This is the familiar Weber's law relationship. At low target visibility (e.g. 2 or 3 times threshold—solid circles), spatial interval thresholds are more or less independent of the target separation (at least between 2.5 and $6\sigma$). Thus it seems likely that the failure of Hayes and Hess (1992) to find Weber's law was most likely a consequence of their low stimulus visibility (<2 times threshold) rather than their use of stimuli which were restricted in spatial scale. The horizontal dotted lines in Fig. 9(B, D) show the predictions of an ideal observer model (to be discussed below) which suggests that at low visibility levels, performance is limited by a "floor" which is independent of separation.

To check this notion further, an additional experiment was conducted. In this experiment, the stimuli were again one-dimensional Gabor patches with $\sigma = 30'$ and $N = 1$ (peak spatial frequency = 2 c/deg, and just slightly narrower in bandwidth than Hayes and Hess' stimuli). To make the stimuli more similar to those of Hayes and Hess, the length was truncated at $4\tau$ (corresponding to 2 deg). Detection thresholds were measured for single Gabor stimuli presented at the eccentricity corresponding to the separation (or eccentricity) of the "reference" bars for two separations (1.25 and 3 deg, corresponding to separations of 2.5 and $6\sigma$). Spatial interval discrimination thresholds were then measured at the two separations at contrasts of the reference bars set to either 2 times or 20 times threshold. At 20 times threshold, spatial interval thresholds showed the usual Weber dependence on separation (similar to Fig. 9). Lowering the contrast to twice the detection threshold resulted in about an 18 fold increase in threshold at a separation of $2.5\sigma$; but only a $40\%$ increase in thresholds at the larger separation ($6\sigma$), with a consequent loss of the Weber relationship. This extreme effect of contrast at small separations is partly due to the supra-Weberian dependence at small separations and high contrasts. Thus we conclude that low stimulus visibility rather than the use of stimuli which were restricted in spatial scale led to the failure of Hayes and Hess (1992) to find Weber's law.

**DISCUSSION**

**Role of Spatial Frequency and Bandwidth**

Our results suggest that the Weber relationship for position obtains with spatially bandlimited stimuli. Under both fixed contrast (Figs 3 and 4) and fixed visibility (Fig. 7) conditions, thresholds increase more or less in proportion to the separation of the features. Moreover, the present results, in conjunction with those of Burbeck (1987), Toet (1987), Toet and Koenderink (1988), and Kooi et al. (1991) suggest that neither the orientation, the spatial frequency, nor the bandwidth of the patterns influence the positional thresholds. Rather, spatial interval discrimination thresholds are proportional to the spatial interval of the stimuli. Weber's law has important implications for size perception. As viewing distance changes, the angular distance between objects in the environment varies, as does the angular size and retinal eccentricity of the objects. Weber's law implies that a just noticeable change in position or size will be just noticeable at any viewing distance. Figure 8 shows that this is indeed the case. The three curves in Fig. 8 represent a 4-fold variation in viewing distance (and hence angular separation), and it is clear that there is little variation in the Weber fraction over this range of distances or over the large range of spatial frequencies or bandwidths tested.

**Role of stimulus visibility**

Most studies of Weber's law for position have used highly visible stimuli (e.g. Fechner, 1860; Volkman, 1863; Westheimer & McKee, 1977; Hirsch & Hylton, 1982; Watt, 1984; Klein & Levi, 1987; Levi & Klein, 1990a). However, several studies suggest that there may be an interaction between target contrast and separation. Morgan (1986) first reported experiments in which the effects of feature separation interacted with target contrast. More recently Waugh and Levi (1993) measured vernier alignment thresholds for line targets over a wide range of separations and contrasts. In that experiment, the observer foveally fixated a "reference" line, and as the separation increased, the eccentricity of the "test" line also increased. Since the targets were thin lines, their spatial frequency content was "broadband". Thus, according to the Hayes and Hess model, under these stimulus conditions, Weber's law should hold. Waugh and Levi found that abutting vernier thresholds improve with stimulus contrast up to at least 30 times the detection threshold. With widely separated targets (> about 5") vernier thresholds improve with increasing stimulus contrast up to about 3-4 times the detection threshold for the eccentric test line, and then saturate. Their results show the usual strong dependence of thresholds on separation for targets with high visibility; however, for targets whose visibility level is near the detection threshold (like those of Hayes and Hess), vernier thresholds increased less than a factor of 2 as separation increased from 5 to 90 min. Weber's law predicts that thresholds should increase 18-fold in proportion to the 18-fold increase in separation. Thus, we believe that the absence of Weber's law is a consequence of the low target visibility. At face value this explanation may seem at odds with the notion of a local sign mechanism, since the position label should be more or less contrast independent. However, Waugh and Levi
argued that many mechanisms probably contribute to the detection threshold (through probability summation), thus, near threshold, the local sign mechanism would provide ambiguous information, because it would be uncertain as to precisely which position label was being stimulated. Thus some suprathreshold level of contrast is needed to enable the observer to "know" which position label to read.

To be clear, we are postulating that the failure of Weber's law at low target visibility occurs because at small separations (< about 5') position thresholds are strongly dependent upon the visibility of the stimulus over a wide range of stimulus strengths. For example, abutting vernier acuity thresholds improve as a power function of contrast up to at least 30 times the target detection threshold (Bradley & Skottun, 1987; Wehrhahn & Westheimer, 1990; Klein, Casson & Carney, 1990; Levi & Klein, 1992; Waugh & Levi, 1993). Similarly, spatial interval discrimination thresholds also depend strongly on the target visibility for small separations (Carney & Klein, 1989). On the other hand, for well separated targets, the contrast dependence vanishes above about 3-4 times the target detection threshold for both vernier acuity (Waugh & Levi, 1993) and spatial interval discrimination (Carney & Klein, 1989; Morgan & Regan, 1987), although it seems likely that the transition may occur at different separations for vernier and spatial interval discrimination (Morgan & Regan, 1987; Waugh & Levi, 1993). Thus, a consequence of using low contrast (or low visibility) targets, is that thresholds may be elevated more at small separations than at large separations. Thus the failure of Weber's law is due to a selective effect of low visibility at small separations, and it should be, and in fact is, evident in other studies. For example, Klein and Levi (1985) found that shortening the lines of their bisection targets (below about 10'; see Klein & Levi, 1985, Fig. 3) dramatically increased bisection thresholds for a separation of 1.3 arc min, but had much less effect at a separation of 3 min. Thus, between 1.3 and 3 min, a constant Weber fraction is only found with lines longer than about 10 min. Similarly, Klein and Levi (1985, Fig. 4) found that at high line luminance levels (e.g. 0.079 cd/m), bisection thresholds conform to Weber's Law, whereas at lower line luminances, they do not. Decreasing the line luminance from 0.079 to 0.0031 cd/m had a pronounced effect on bisection thresholds at the smallest separations, and little effect at a separation of 4.2'. Other examples of a failure of a precise Weber relationship are also evident in the spatial interval data of Yap et al. (1987) (with small dots and brief durations), and in the vernier acuity data of Waugh and Levi (1993) at low target visibility.

With blurred stimuli, it is clearly not the separation in minutes that defines large vs small separations, but rather the separation in standard deviation (σ) units. This is evident with Gaussian blurred stimuli (Toet et al., 1987a; Levi & Klein, 1990b; Levi et al., 1990), and with Gabor stimuli as shown in the present study. It is interesting to note that Burbeck (1987) compared the effect of contrast on spatial interval discrimination with rectangular bars (broadband) and Gabor (high spatial frequency) bars separated by 175 min. Her results, in agreement with the present study, show that for these

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**FIGURE 10.** Schematic illustration of three classes of models to account for Weber's law for position. For simplicity, we consider spatial interval discrimination with just two lines. The top row illustrates two different spatial intervals. The leftmost column depicts the "simple" single size-tuned filter model. As the spatial interval increases, progressively larger filters will be optimally sensitive to the change in separation (i.e. the filter of optimal size will have a center size approximately equal to the spatial interval). As filter size increases, the slope of the filter weighting function becomes shallower, so a proportionally greater change in separation is needed to give a criterion change in filter response. Thus, Weber's law for position is a natural consequence of such a scheme. The middle column illustrates a "two-filter" model. The notion here is that the position of each line is elaborated by a separate filter, and the positions are compared at a second stage. Weber's law occurs because the position of the features becomes increasingly uncertain as their separation and hence their eccentricity increases. The rightmost panel illustrates a variation of the two-filter model. It shows each line viewed by an "eclectic unit" (after Morgan et al., 1990). These are "second-stage" units which derive their inputs from lower order neurons of diverse types. As illustrated here, the lower order neurons have a wide range of sizes, orientations, polarities and positions. The eclectic units have fairly large receptive fields, and pool the positional signals of the underlying units. In this model, as in the two-filter model described above, Weber's law would be a consequence of increasing uncertainty of the unit's position label with increasing separation (and hence eccentricity) of the target lines.
widely separated targets, (i) spatial interval thresholds improve with contrast only up to about 5 times threshold, and more importantly, (ii) the Weber fractions for spatial interval discrimination were essentially identical for the broadband and high pass stimuli when equated for visibility. If our hypothesis is correct, that the absence of Weber's law at low stimulus visibility is due to a selective effect of visibility at small separations, then at very wide separations Weber's law should occur even at low visibility levels. With this view, it is interesting to note that the spatial interval data of RFH [Hayes & Hess, 1992, Fig. 3(B)] with the lowest spatial frequency (5 c/deg) at the two largest separations appear to approach a constant Weber fraction (i.e. they fall along a line with a slope of 1).

**Models for Weber's Law**

There are several classes of models to account for Weber's law for position. Figure 10 illustrates three such models schematically. For simplicity, we consider spatial interval discrimination with just two lines. The two rows in Fig. 10 illustrate two different spatial intervals. The leftmost column depicts the "simple" single size-tuned filter model. A number of investigators have suggested that models of this general class can account for hyper-acuity thresholds at small separations, and also the Weber's law dependence of threshold on spatial interval (e.g. Carlson & Klopfenstein, 1985; Klein & Levi, 1985; Wilson, 1986). The key notion is that there is a range of size-tuned filters in the visual system, and as depicted in Fig. 10, as the spatial interval increases, progressively larger filters will be optimally sensitive to the change in separation (i.e. the optimal sized filter will have a center size approximately equal to the spatial interval). As filter size increases, the slope of the filter weighting function becomes shallower, so a proportionally greater change in separation is needed to give a criterion change in filter response. Thus, Weber's law for position is a natural consequence of such a scheme. However, while the simple single filter model apparently works rather well at small separations, it encounters several difficulties at large separations. First, Weber's law holds over very large separations (at least 10 deg), and it is unclear whether the visual system has sufficiently large filters (e.g. Wilson, 1986, 1991); moreover, the single filter model predictions fail at large separations (Wilson, 1986; Klein & Levi, 1987). A second difficulty lies in the absence of perturbation by nearby distractors when the target separation is large (Levi & Westheimer, 1987; Morgan, Ward & Hole, 1990). For example, Levi and Westheimer (1987) found that a randomly presented bright perturbing line had no effect upon spatial interval discrimination when the line separation was greater than about 5 min. Similarly, Morgan, Hole and Glennerster (1990) found that for both vernier acuity and spatial interval discrimination, a "supernumerary" square randomly positioned between the targets had a marked effect upon thresholds at small target separations, but no effect on thresholds at large separations.

A simple single filter model like the one illustrated here will show a strong contrast dependence. A shift of the lines will produce a change in the filter signal which is proportional to the contrast of the line times the shift. In the viewpoint model (Klein & Levi, 1985) the differential response to the line shift is based upon the detection of a luminance cue. This differential response is a product of the spatial shift times the contrast. At the detection threshold the differential response is a constant, so the spatial interval threshold will be inversely proportional to contrast. For other filter models (e.g. Wilson, 1986) the threshold will vary in inverse proportion to the square root of the stimulus contrast (see Browne, 1990 for a discussion of this). While spatial interval discrimination does indeed vary with target contrast for Gaussian blurred stimuli with separations of less than about $5\sigma$ (Levi et al., 1990), at large separations, once contrast exceeds about 3 times the detection threshold, contrast has very little effect upon spatial interval discrimination thresholds (Morgan & Regan, 1987; Carney & Klein, 1989; Levi et al., 1990). One additional difficulty for simple filter models is that they are based upon linear filters. However, the evidence (Toet, 1987; Toet & Koenderink, 1988; Burbeck, 1987, and the current data) suggests that for spatial interval discrimination, thresholds for Gabor patches are based upon localization of the Gaussian envelopes, and it is unclear how this would be achieved without adding an early nonlinearity. Thus, it appears that while a single filter model might provide a reasonable explanation for spatial interval discrimination at small separations, where both lines fall within a single size-tuned filter, it is unlikely to account for spatial interval discrimination at larger spatial intervals or with Gabor stimuli.

The essence of filter models of interval judgments is that the filter must span the interval to be measured. Thus if the features are separated by 10 min, a mechanism whose zero crossings are about 10 min apart would be used. Hayes and Hess, on the other hand, argue that the relevant mechanisms are those tuned to the Gabor carrier spatial frequency. It is difficult to see how such a mechanism could work since the stimuli are separated by many times the cycle size.

A second approach is to consider a "two filter" model such as that shown in Fig. 10 (middle column). The notion here is that the position of each line is elaborated by a separate filter, and the positions are compared at a second stage (Klein & Levi, 1987; Levi et al., 1988; Morgan & Regan, 1987; Burbeck & Yap, 1990; Levi & Klein, 1990; Wilson, 1991; Morgan, 1991). This sort of model has sometimes been referred to as a "local sign" model (Lotze, 1885; Koenderink, 1984; Toet, Blok & Koenderink, 1987a; Levi & Klein, 1990a; White, Levi & Aiisahamo, 1992). One advantage of such a model is that it would be robust to perturbing stimuli between the target lines; moreover, if spatial interval discrimination is limited by the precision with which the brain knows the position labels of the filters, then thresholds would be independent of target polarity, and robust to variations in target contrast (Morgan & Ward, 1985). In
such a model Weber’s law could be accounted for in several ways. First, as the separation between the target lines increases, the eccentricity of the target necessarily increases too. Thus, Weber’s law could be explained as an eccentricity effect. With increasing eccentricity, the spacing of retinal cones and ganglion cells increases (Wassle, Grunert, Rohrenbeck & Boycott, 1989; Curcio & Allen, 1990) and the cones become less ordered (Hirsch & Miller, 1987; Hirsch & Curcio, 1989; Wilson, 1991). Moreover, these alterations in the retina are also evident in the cortex where both the receptive field size and separation increase with eccentricity, and $M^{-1}$ (the number of deg of visual angle per mm of cortex) increases more or less linearly with eccentricity (Dow, Snyder, Vautin & Bauer, 1981; Tootell, Silverman, Switkes & DeValois, 1982; Tootell, Silverman, Switkes & Hamilton, 1988; Van Essen, Newsome & Maunsell, 1984; Tolhurst & Ling, 1988; Wassle et al., 1989). Thus, Weber’s law would occur because the position of the features becomes increasingly uncertain as their separation and hence their eccentricity increases. One line of evidence for such an explanation comes from measuring spatial interval thresholds on iso-eccentric arcs, where separation can be varied while holding eccentricity constant. Under such conditions, when the feature separation is large relative to the target eccentricity, thresholds are proportional to eccentricity and more or less independent of separation (Levi et al., 1988; Levi & Klein, 1990a; Burbeck & Yap, 1990). So one plausible explanation for Weber’s law at large separations is that the position labels of the filters becomes increasingly uncertain as separation, and thus eccentricity increases.

Note that in the bottom row, middle column of Fig. 10, the rightmost filter is shown as larger than the leftmost filter. Imagine that the left line is foveally fixated. As separation (and thus eccentricity) increases, the right-hand line would fall more eccentrically. The enlarged filter illustrates the suggestion that with increasing eccentricity, increasingly coarser scales (i.e. larger filters) will be engaged if the stimuli are broadband such as the lines illustrated here. Hayes and Hess suggest that Weber’s law is a direct consequence of this increase in spatial scale with increasing eccentricity. To state this another way, Hayes and Hess suggest that it is the size of the receptive field that determines the threshold. Hayes and Hess’ suggestions leads to two predictions: (i) spatial interval discrimination thresholds measured with bandlimited stimuli should not vary with separation, since the same size mechanisms will be engaged at all separations (to the extent that these same size mechanisms are present over the range of separations/ eccentricities studied), and (ii) spatial interval discrimination thresholds at a fixed separation, should vary with the spatial frequency of the bandlimited targets. Hayes and Hess report a failure of the Weber relationship with their bandlimited Gabor patches; however, under the conditions of our experiments, neither of these predictions is correct (below we will discuss possible reasons for the discrepancies in the two studies). Moreover, in an experiment involving the alignment of two Gabor patches, Kooi et al. (1991) found that lowering the spatial frequency of one patch by a factor of 3 so that one patch was 6 c/deg while the other was 2.1 c/deg resulted in the same thresholds as when both patches were either 6 or 2.1 c/deg. While it is clear that receptive fields increase in size and coverage with increasing eccentricity, it seems unlikely that it is the spatial frequency of the stimulus that determines the threshold for large scale spatial interval discrimination (Burbeck, 1987; Toet, 1987; Toet & Koenderink, 1988; Kooi et al., 1991).

The rightmost panel of Fig. 10 illustrates an appealing variation of the two-filter model. It shows each line viewed by an “eclectic unit” (after Morgan et al., 1990). These are “second-stage” units which derive their inputs from lower order neurons of diverse types. As illustrated here, the lower order neurons have a wide range of sizes, orientations, polarities and positions. The eclectic units have fairly large receptive fields, and pool the positional signals of the underlying units. Morgan and his colleagues (Morgan & Hotopf, 1989; Morgan et al., 1990) have argued that units of this sort are ideal for extracting the position of simple features such as line terminators. Units of this sort would be insensitive to the spatial frequency, color, polarity and orientation of the targets, and because they are inherently nonlinear, they would be able to localize the Gaussian envelope of a Gabor patch. In this model, as in the local sign model described above, Weber’s law would be a consequence of increasing uncertainty of the unit’s position label with increasing separation (and hence eccentricity) of the target lines. Our hypothesis, based upon the present experiments and our previous iso-eccentric experiments, is that at least two mechanisms are involved in limiting positional discrimination: at very small separations, thresholds are determined by a size-tuned filter type of model (although it most likely involves pooling of information across more than one filter), while at larger separations, the positions of each element are elaborated separately (by “eclectic” units), and a measurement or comparison is made. Recent work suggests that both the separation and the stimulus contrast (or visibility) may play an important role in which mechanism is selected (Waugh & Levi, 1993).

Limiting Factors in Positional Coding

In this section we consider the factors which may place limits on our positional coding. Specifically, this section presents a simple model that can account for the broad features of the present data. The model is based upon several “floors” which could limit performance in the spatial interval task, and account for the present results.

High contrast floors

The most extensive data on bisection of blurred stimuli at high contrast is in the Levi et al. (1990) paper for the $N = 0$ case. A portion of this data is shown as the stippled region of Fig. 11(A, B) for observers CN and DL and it is shown here to facilitate comparison between
The high contrast data can be divided into three regimes:

1. **Weber regime for separations above \( \sigma \)**: This is the regime in which the bisection threshold is about \( \frac{1}{4\sigma} \) of the separation. In Fig. 12 this regime is shown as the line with a positive slope that has a Weber fraction of \( \frac{1}{4\sigma} \). As discussed above, the Weber regime is further subdivided into the filter and the local sign regimes. The filter regime is strongly dependent on stimulus contrast, and is most sensitive at small separations, whereas the local sign regime is essentially independent of the target details, and is most sensitive at large separations. Because of the large values of \( \sigma \) that were used in the present study, and hence the large separations, it is likely that much of our data fall in the local sign regime. In that case the similarity of \( N = 0 \) to \( N > 0 \) is not that surprising.

2. **Facilitation regime for separations near \( 2\sigma \)**: One of the surprising features seen especially in our \( N = 0 \) and \( N = 1 \) data is the sharp "V" shape of the data that occurs when the separation is close to \( 2\sigma \). The separation of \( 2\sigma \) is special in that it corresponds to the "Sparrow" condition, i.e. where the center of the luminance distribution has a vanishing second derivative (Sparrow, 1916). When two Gaussians are separated by more than \( 2\sigma \) the sum of the Gaussians has a dip at the midpoint. When the separation equals \( 2\sigma \) the dip goes away (the second derivative of the sum become zero). At this point

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**Figure 11.** (A) The symbols show spatial interval thresholds plotted as a function of separation in standard deviation units for observer CN with Gabor bars with \( N = 1 \), and \( \sigma = 7.5' \) (small circles) 15' (medium circles) or 30' (large symbols) at 10 times threshold. The stippled region shows the range of results obtained for the same observer with Gaussian bars \( (N = 0) \), from that data of Levi et al. (1990). (B) The symbols show spatial interval thresholds plotted as a function of separation in standard deviation units for observer DL with Gabor bars with \( \sigma = 15' \) and \( N = 1 \) (large circles), 2 (medium circles) and 3 (large circles), and spatial frequency = 4, 8 and 12 c/deg respectively. Contrast was 33%. The stippled region shows the range of results obtained for the same observer with Gaussian bars \( (N = 0) \) from Levi et al. (1990).

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**Figure 12.** A simple model illustrating several "floors" which could limit performance. (i) High contrast floors: at high contrasts there is a Weber's law floor, illustrated by the line with a positive slope, and a resolution floor, illustrated by the line with the negative slope. Also illustrated (dotted line) is the facilitation when the separation is close to \( 2\sigma \), corresponding to the Sparrow condition (see text). (ii) Low contrast floors: The horizontal lines show ideal observer model predictions for three different visibility levels, 1.6, 3 and 10 times the target detection threshold. Note that the presence of these floors implies that performance cannot be better than these limits. According to this analysis, at high contrast levels, thresholds at small separations \( (< 2\sigma) \) are limited by the resolution floor; and at larger separations \( (> about 2\sigma) \), are limited by Weber's law. On the other hand, at low contrast levels, the low contrast limits are set by the ideal observer. Thus, at very low contrast levels \( (e.g. < 3 times the target detection threshold) \), there would be essentially no effect of separation for separations between 1 and 10\( \sigma \), while at higher contrast levels \( (e.g. 10 times threshold) \), Weber's law would be evident.
the luminance profile of the sum of three Gaussians will be very flat. The slightest shift of the middle Gaussian will produce a luminance change that can be detected. The task becomes one of comparing a slight increment on one side of the pattern to a slight decrement on the other side. In Fig. 12 this regime is shown as the dotted V. This cue leads to a positive slope greater than unity. A similar steep, supra-Weberian slope is evident in much V. This cue leads to a positive slope greater than unity. The task becomes one of comparing a slight increment

well-known result that resolution thresholds are about distribution. The sharp degradation of threshold as the Gaussian bars. Rather the decision must be based on the locations (the first moments) of its decision based on the Gaussian data of Levi et al. (1990) as can be seen in Fig. 11. Optimal thresholds can be as low as $\frac{a}{b}$ (e.g. Fig. 3).

3. Resolution regime for separation below $2\sigma$. As the separations get smaller than $2\sigma$ the task for $N = 0$ becomes one of resolution and thresholds must rise. An ideal observer (Geisler, 1984, 1989) can no longer make its decision based on the locations (the first moments) of the Gaussian bars. Rather the decision must be based on the shape (higher moments) of the intensity distribution. The sharp degradation of threshold as the separation becomes smaller than $\sigma$ corresponds to the well-known result that resolution thresholds are about 10 times worse than hyperacuity thresholds.

In Fig. 12 the resolution branch of the curve has been drawn as a straight line that is defined by the following two points: (1) For a separation of $2\sigma$, the threshold shift is at the hyperacuity level of $\frac{a}{b}$ of the separation, which equals $\frac{a}{b}$. (2) At a separation of $0.5\sigma$ we have taken the shift threshold to be $0.5\sigma$. This was done because we expect the three-line bisection task to be twice as good as the two-line resolution task. We know that for a two-line resolution task a pair of lines with zero separation can be just discriminated from a pair with a separation equal to $\sigma$ (Levi & Klein, 1990b). This resolution point is plotted at an abscissa value of $0.5\sigma$ since that falls halfway between the separation of the two stimuli being discriminated.

Low contrast floors

At low contrasts the visibility of the stimuli play an important role. A new floor comes into play. The easiest way to understand the low contrast floor is to consider what the stimulus-known-exactly ideal observer must do to detect the shift of a Gaussian bar (e.g. Geisler, 1984, 1989). We model the data using a Gaussian bar corresponding to $N = 0$ because this case is simpler to examine; however, as we have shown (e.g. Fig. 11) the Gabor data with $N > 0$ is similar to the low pass $N = 0$ case. The ideal observer will form a template that is the difference between the original Gaussian and the shifted Gaussian. Thus we must ask how visible is the stimulus pattern consisting of the difference between a Gaussian and a shifted Gaussian. The pattern can be written as:

$$D(x) = G(x + \delta/2) - G(x - \delta/2)$$

where

$$G(x) = c \exp(-x^2/2\sigma^2)$$

and $c$ is the contrast of the Gaussian. When the shift, $\delta$, is small, equation (2) can be approximated using a Taylor’s expansion:

$$D(x) \approx x \delta^2 G(x)$$

Equation (4) has a peak at $x = \sigma$. The contrast of $D(x)$ at the peak is

$$\text{peak contrast} = 0.606 \frac{c \delta}{\sigma}$$

since $\exp(-0.5) = 0.606$. We now assume that the visibility of both $G(x)$ and $D(x)$ is based on the peak-to-trough contrast. For $D(x)$, the peak-to-trough contrast is twice the Michelson contrast. An ideal observer would use a template that is sensitive to the full peak-to-trough distance. Let us call $Th$ the threshold visibility. In that case the shifted Gaussian is at threshold when:

$$0.606 (2c) \delta/\sigma = Th$$

or

$$\delta/\sigma = 0.825 Th/c.$$

The Taylor’s series approximation that was made in obtaining equation (4) is quite good. For $\delta/\sigma = 0.6$ and 1.0 the exact peak contrasts are 0.35 $c$ and 0.56 $c$ whereas the contrasts from the approximation given by equation (5) are 0.36$c$ and 0.61$c$. If the contrast of the Gaussian stimulus is 3 times the Gaussian's detection threshold, then from equation (7), the just visible displacement is:

$$\delta/\sigma = 0.825/3 = 0.275.$$

In Fig. 12, the expected thresholds for the low contrast region take the form of the floors indicated by the horizontal lines. The prediction from equation (7) for Gaussian contrasts of 1.6, 3 and 10 times threshold are shown. The value of 1.6 was chosen to agree with the contrast used by Hayes and Hess (1992). In making the predictions for the horizontal lines in Fig. 12, it was assumed that the visibility of the difference function was based on the peak-to-trough contrast difference. If, however, detection is based on the peak to mean luminance then the shifted Gaussians would be half as visible and a double sized shift would be needed in order to detect the displacement. The data of Fig. 9 are closer to the ideal observer prediction shown in Fig. 12 than to the doubled prediction. The ideal observer predictions are shown as the stippled horizontal lines in Fig. 9(B, D).

Note that based upon the above analysis, at high contrast levels, thresholds at small separations ($< 2\sigma$) are limited by the resolution floor; and at larger separations ($> 2\sigma$), are limited by Weber's law. On the other hand, at low contrast levels, the low contrast limits are set by the ideal observer. Thus, at very low contrast levels (e.g. $< 3$ times the target detection threshold), there would be essentially no effect of separation for separations between 1 and 10$\sigma$. Thus, the ideal observer predictions are consistent with the data of Hayes and Hess (1992) and the present data at low contrast levels (e.g. Fig. 9) in showing a failure of Weber's law. It is of particular interest to note that at higher contrast levels (e.g. 10 times threshold), Weber's law would be evident. It is also of some interest to note that the ideal observer model sets floors (that is it predicts that performance could not be better than the level shown) thus an ideal
observer model based upon the information at the retinal receptors (Geisler, 1984, 1989) does not predict Weber's law. Rather, Weber's law must be a consequence of information loss at a higher level of neural processing, and the section on models for Weber's law suggests several possible mechanisms for this loss of information.

SUMMARY AND CONCLUSIONS

We used Gabor bars to measure the effects of spatial bandwidth, spatial scale and contrast on three-line spatial interval discrimination. For stimuli that are well above detection threshold, at all spatial scales, spatial interval discrimination (three-line bisection) thresholds are approximately proportional to the separation of the Gabor bars (i.e. Weber's law) when the separation exceeds approximately 2.5 times the standard deviation ($\sigma$) of the Gaussian envelope. The optimal threshold occurs when the separation is approx. 2–2.5$\sigma$, and for separations larger than the optimal, bisection thresholds are equal to a more or less constant Weber fraction ($\Delta$/$\sigma$) of approx. 0.02–0.04. These results, in conjunction with those of Burbeck (1987), Toet (1987), Toet and Koenderink (1988), Morgan et al. (1990) and Koo et al. (1991), suggest that for separations greater than about 3$\sigma$ the stimulus features (spatial frequency, bandwidth color and orientation) are largely irrelevant. The novel result of this study, is that there is a strong interaction between stimulus separation and stimulus visibility, so that at low target visibility, Weber's law is not evident. Reducing the stimulus contrast has a marked effect on spatial interval thresholds at small separations (e.g. separations less than about 3$\sigma$), and much less effect at larger separations. Thus, the Weber's law relationship appears to depend on the visibility of the stimuli, but does not depend on the spatial frequency or bandwidth of the stimuli. These results can be predicted by an ideal observer model of spatial interval discrimination.

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