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RESEARCH NOTE

ORIENTATION DISCRIMINATION DEPENDS ON SPATIAL FREQUENCY

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Abstract—Thresholds were measured for discriminating the orientation of sinusoidal gratings of varying spatial frequency, and found to decrease monotonically with increasing spatial frequency. For discrimination of high-contrast (10 times threshold) near-vertical gratings, thresholds ranged from about 1 deg at 0.04 c/deg to 0.5 deg at 0.2 c/deg, after which there was little improvement. At lower contrasts and for discriminations around a mean of 45 deg, thresholds varied more so, and continued to improve until 1 c/deg. The variation of orientation discrimination thresholds with spatial frequency follows a similar trend to the variation in orientation bandwidth of visual units over the same range of spatial frequencies. Thus the present results are consistent with recent "opponent-process" models of orientation discrimination, that predict that thresholds to be limited (at least in part) by the maximum slope of orientation selectivity of visual detectors. That thresholds for high contrast vertical gratings did not improve for frequencies higher than 0.2 c/deg implies that orientation bandwidth and noisiness of oriented detectors may not be the sole factor limiting orientation discrimination, and suggests the existence of more central noise sources.

INTRODUCTION

Human observers are particularly sensitive to small variations in stimulus orientation, and are able to discriminate differences as small as 0.3 deg reliably (Andrews, 1965, 1967; Burbeck & Regan, 1983; Regan & Price, 1986). For short lines the discrimination is a "hyper-acuity" (Westheimer, Shimanura & McKee, 1976), as the ends of the lines are displaced by less than the inter-cone spacing.

Orientation discrimination thresholds are considerably lower than most estimates of orientation tuning bandwidth of individual detectors: 0.2–0.5 deg, compared with 12–18 deg bandwidth (e.g. Blakemore & Campbell, 1969). To explain this difference, Westheimer et al. (1976) proposed that orientation discrimination is achieved by comparing the *relative* activity of two broadly tuned mechanisms, similar to the opponent process theory of colour discrimination (where hue discrimination is considerably finer than cone spectral bandwidth). This idea has been framed in two specific models, as an opponent-process (Regan & Beverley, 1985) and a line-element model (Wilson & Gelb, 1984; Wilson & Regan, 1984). The two formulations share the features that orientation discrimination is limited by the maximal slope of the orientation tuning curves, and the intrinsic noisiness of the detectors. Both formulations have demonstrated considerable success in predicting quantitatively experimental discrimination thresholds. However, Bowne (1990) has recently suggested, with good supporting evidence, that detection is limited not only by the noisiness of the oriented detectors, but also by a noise source added after comparison of detector output.

Visual detectors do not all have the same orientation bandwidth. Figure 1 replots data from Phillips and Wilson (1984) and Anderson and Burr (1991) which show how orientation bandwidth varies considerably with spatial frequency, from 30 deg at 12 c/deg to 100 deg at 0.1 c/deg. These results are in general agreement with physiological measures of orientation bandwidth in macaque monkey (DeValois, Yund & Hepler, 1982). Although the bandwidth varies with stimulus conditions, the general form of the tuning curves remain constant (Phillips & Wilson, 1984; Anderson & Burr, 1985, 1991). Thus the maximum slope of the tuning curves should scale with bandwidth, and

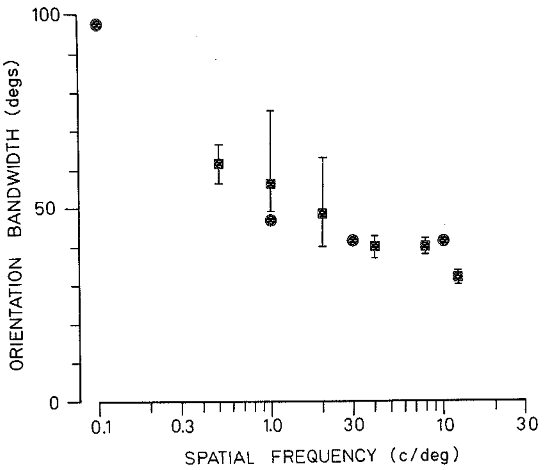

Fig. 1. Orientation bandwidth (full width at half height) as a function of spatial frequency. The squares represent the mean bandwidth of Phillips and Wilson's (1984) four subjects (with bars indicating range), and the circles the bandwidth of Anderson and Burr's (1991) observer. Phillips and Wilson's data were collected with briefly flashed gratings and Anderson and Burr's with drifting gratings (probing so-called "transient" visual mechanisms). The two studies are in reasonable agreement, showing that orientation bandwidth varies dramatically with spatial frequency, from 30 deg at 12 c/deg to 100 deg at 0.1 c/deg.

therefore vary monotonically with spatial frequency. If orientation discrimination depends on the steepness of the orientation selectivity curves, discrimination thresholds should also vary with spatial frequency. This study was designed to test this assertion by measuring orientation discrimination for sinusoidal gratings of various spatial frequencies.

METHODS

The stimuli for all experiments were sinusoidal gratings displayed on the face of an electrostatic oscilloscope (HP1311A), using standard raster techniques (100 frames/sec, 1000 lines/frame). Sinusoidal waveforms were generated by microcomputer and attenuated through a computer controlled digital attenuator. The oscilloscope was slightly modified to allow orientation to be varied under computer control, by applying a voltage to the mechanism that aligns orientation. This was calibrated and found to be linear up to 5 deg either side of vertical.

The oscilloscope face was masked to a circle of 20 cm diameter by a 100 × 100 cm white card floodlit to the same mean luminance as the oscilloscope screen (12 cd/m^2). Four cycles of grating were always displayed, and spatial frequency was adjusted by varying viewing distance from 9 to 570 cm, using inverted binoculars (Zeiss × 10) for the larger distances.

Thresholds were measured with a two-alternative forced-choice technique guided by the QUEST program of Watson and Pelli (1983). For each trial, a grating was briefly presented twice for 50 msec, separated by a 1 sec pause. On one presentation the grating was slanted clockwise, on the other anti-clockwise. Observers were required to indicate the slant of the first presentation by pressing an appropriate button. After such response, the program revised its estimate of discrimination threshold (by applying simple Bayesian statistics rules), and set the orientation for the next trial near that estimate. In estimating thresholds, QUEST assumes that the probability of correct response is fit reasonably well by the *Weibull* function (Weibull, 1951):

$$P(\alpha) = 1 - \tfrac{1}{2}\exp\left[-\left(\frac{\alpha}{\alpha_T}\right)^{\beta}\right] \qquad (1)$$

where α is the orientation of the stimuli, α_T the threshold for orientation discrimination, and $p(\alpha)$ the probability of correctly discriminating orientation α. β is a parameter that determines the steepness of the psychometric function. Preliminary experiments showed that the Weibull function provided a quite good fit to the data, and predicted β to be about 3 for all observers.

Before measuring orientation discrimination, contrast sensitivity for briefly flashed sinusoidal gratings was first measured as a function of spatial frequency. As with the orientation discrimination experiments, the stimuli were 4 cycles of vertical sinusoidal gratings, briefly flashed for 50 msec. Contrast sensitivity was found to be fairly constant with spatial frequency up to 1 c/deg, and declined thereafter (agreeing with Burr, Holt, Johnstone & Ross, 1982). These results were used to set the contrast for the orientation discrimination tasks at 3 times and 10 times detection thresholds.

Three young observers were used for the study, all with vision corrected to 6/6.

RESULTS

Figure 2 shows orientation discrimination thresholds as a function of spatial frequency at contrasts of either 10 or 3-times detection threshold. In practice all stimuli below 1 c/deg had the same contrast. For all observers, discrimination thresholds decreased with spatial

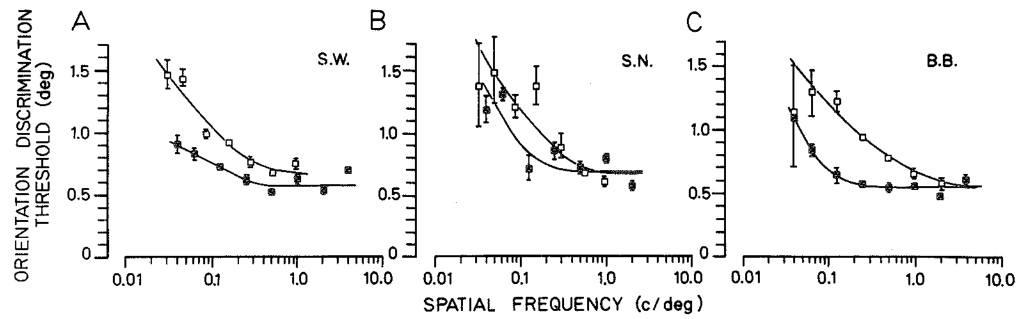

Fig. 2. Thresholds for discriminating orientation of vertical gratings of contrast either 3-times detection threshold (open symbols) or 10-times threshold (solid symbols). For all three observers, thresholds decreased monotonically with increasing spatial frequency. For the higher contrast there was a tendency to asymptote at around 0.5 deg after around 0.3 c/deg.

frequency. For the higher contrast of 10-times threshold (solid symbols), discrimination thresholds decreased from over 1 deg at 0.04 c/deg to about 0.5 at 0.2 c/deg, and remained relatively constant thereafter. At the lower contrast of 3-times threshold (open symbols), the variation with spatial frequency was even greater: from 1.5 deg at 0.4 c/deg to just over 0.5 deg at 2 c/deg. The major difference between the two conditions is that at the higher contrast, the curves asymptote at around 0.2 c/deg for all observers, whereas at the lower contrast discrimination thresholds improved with spatial frequency up until 2 c/deg.

Thresholds were also measured for discriminating orientations around a mean of 45 deg. The procedure was identical to the previous condition, except that the oscilloscope was tilted 45 deg. The results are shown in Fig. 3, for stimulus contrasts 10-times threshold. Again, orientation thresholds varied monotonically with spatial frequency, from around 2 deg at 0.04 c/deg to around 0.7 deg at 3 c/deg. Unlike the vertical condition, thresholds did not asymptote but continued to improve until the highest frequencies tested.

DISCUSSION

The results of this study show that thresholds for orientation discrimination decrease with increasing spatial frequency by a factor of 2–3 over 2 log units of spatial frequency. Orientation bandwidths also decrease over that range, by a similar amount (Phillips & Wilson, 1984; Anderson & Burr, 1985, 1991). As the shape of orientation tuning curves remains constant with spatial frequency, a variation in bandwidth will cause a commensurate variation in slope of the function; and if orientation discrimination is determined at least in part by the maximum slope of the orientation tuning function (Regan & Beverley, 1985; Wilson & Regan, 1984), then the decrease in slope with decreasing spatial frequency would account for the decrease in orientation sensitivity.

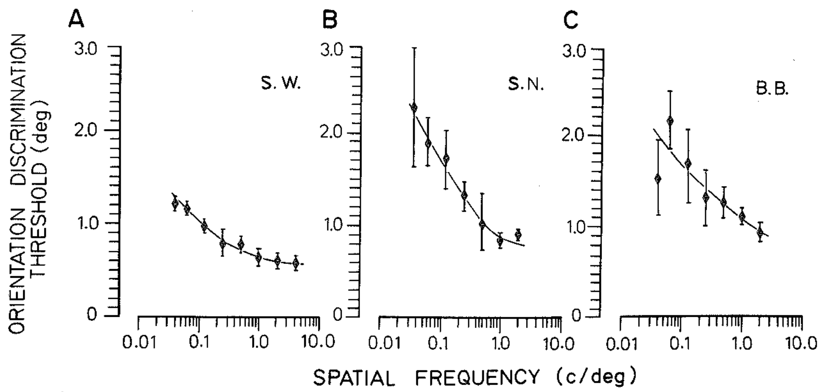

Fig. 3. Thresholds for discriminating the orientation of gratings around a mean orientation of 45 deg. Contrast was 10-times detection threshold. Thresholds were higher than for vertical gratings (Fig. 2), but still decreased monotonically with contrast.

The measurements with high contrast gratings around the vertical were slightly different than the others, in that they tended to asymptote around 0.5 deg after 0.1 c/deg. Figure 1 shows that orientation bandwidths decrease quite rapidly until 1 c/deg, and more shallowly thereafter until at least 12 c/deg. This result is consistent with the recent suggestion by Bowne (1990) that orientation (and other) discriminations are limited not only by the bandwidth and noisiness of oriented detectors, but also by more central noise sources. This central noise source could impose an effective absolute threshold of about 0.5 deg, that could not be surpassed under any circumstances.

Another possible explanation for the asymptotic performance of orientation discrimination (and for Bowne's results) could be that the form of the orientation tuning curves changes at high contrasts, possibly as a result of processes such as cross-orientation inhibition (Morrone et al., 1982; Burr & Morrone, 1987). However, this possibility would require further testing with more appropriate conditions (such as superimposed orthogonal masks) before it can be given too much credence.

Ideally, one would like to test quantitatively the predictions of models such as those of Wilson and Regan against the data reported here. However, as the estimates of bandwidth were collected under quite different conditions, a rigorous test is not possible. For the present it is sufficient to say that the data provide general support for the notion that the orientation selective mechanisms revealed by masking studies are instrumental in orientation discrimination tasks.

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