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Sensitivity to Orientation Modulation in Micropattern-based Textures

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We have measured the sensitivity of the human visual system to sinusoidal modulations of orientation in micropattern-based textured stimuli. The result is the orientation modulation function, or OMF, which describes this sensitivity as a function of the spatial frequency of orientation modulation. We found that the OMF was bandpass with peak sensitivity at spatial frequencies ranging between 0.06 and 0.2 c/deg, depending on the size of the micropatterns. The OMF was found to be scale invariant, that is its position on the spatial frequency axis did not change with viewing distance when spatial frequency was measured in object rather than retinal units. This scale invariance was shown to result from the visual system taking into account the scale rather than the density of the micropatterns as viewing distance was changed. It has been argued by Bergen [(1991) *Vision and visual dysfunction* (Vol. 10B) New York: Macmillan] that scale invariance in textures is a consequence of the coupling of mechanisms which detect textural features with those which detect local luminance contrasts. We reasoned that Gabor micropattern textures might therefore show narrower OMFs compared to line micropattern textures. However we found no difference in OMF bandwidth between the Gabor and line micropattern textures, suggesting that the line micropatterns were acting as selectively as the Gabor micropatterns for the spatial scale of the mechanisms which detected the orientation modulation. Evidence is presented which suggests that the mechanisms which detected the orientation modulation in our stimuli are non-linear. Finally we showed similar OMFs for sine-wave and square-wave modulations of micropattern orientation, and similar OMFs for modulations of micropattern with orientation about the horizontal and about the vertical, the direction of modulation in both cases being horizontal. The implications of these findings for the mechanisms involved in orientation-defined texture processing is discussed.

Texture Orientation Scale invariance

INTRODUCTION

The issue of how the visual system segregates image regions on the basis of texture differences is important because texture is often a defining feature of surfaces. The consensus is that broadly speaking texture segregation involves two main stages. The first stage filters the stimulus with spatial filters tuned to various orientations and spatial frequencies (such as simple and complex cells) while the second stage processes the global properties of the texture, for example the spatial variations in orientation or element density (Zucker, 1985; Bergen & Adelson, 1988; Link & Zucker, 1987; Malik & Perona, 1990; Landy & Bergen, 1991; Sutter, Beck & Graham, 1989; Graham, Beck & Sutter, 1992). One function of the second stage is to detect texture discontinuities in order to segregate the stimulus into regions. A common finding in studies of texture segregation is that the tendency of texture regions to segregate depends only weakly on viewing distance (Nothdurft, 1985; Landy & Bergen, 1991; Bergen, 1991). Bergen (1991) has suggested that this property is a consequence of the two stages, namely the computation of the local luminance contrasts and the detection of the texture discontinuities, being "tied" at the level of spatial scale. In other words the computation of fine scale texture discontinuities is subserved by mechanisms tuned to fine scale luminance contrasts while the computation of coarse scale texture discontinuities is subserved by mechanisms tuned to coarse scale luminance contrasts.

In this communication we examine the spatial scale relationships between luminance contrast and texture processing for a textural feature that has been shown to be highly salient for texture segregation, namely orientation (Beck, 1966; Nothdurft, 1985, 1991; Wolfe, 1992; Lamme, Van Dijk & Spekreijse, 1992; Zucker, 1985; Landy & Bergen, 1991; Bergen, 1991). In order to

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examine the spatial scale relationships between luminance contrast and orientation-gradient processing we have used stimuli which are narrowband in both domains. Our stimuli consist of arrays of Gabor micropatterns whose individual orientations vary sinusoidally across the display. The Gabor micropatterns are narrowband in the luminance domain while the sinusoidal variations in micropattern orientation are narrowband in the textural orientation domain. Textures with sinusoidal modulation of orientation were first demonstrated by Zucker (1983). It should be noted that the employment of sinusoidal modulations of orientation does not imply any *a priori* commitment to the belief that the mechanisms which detect those sinusoidal modulations are linear. We use sinusoidal modulations as one possible method of specifying the spatial scale of the orientation changes in our stimuli.

An example stimulus is shown in Fig. 1(a). The task for the subjects was to detect the presence of the modulation of orientation that is visible in the figure. Landy and Bergen (1991) were the first to investigate orientation-defined texture segregation using stimuli which were narrowband in the luminance domain though they used hard- or trapezoidal-edged targets which were broadband in the texture domain. They used bandpass-filtered noise textures in which the target and background differed in the mean orientation of the kernel used to filter the noise. Our employment of Gabor micropatterns rather than filtered noise has the advantage that micropattern density and micropattern spatial scale can be separately manipulated.

The first purpose of the study was to examine the spatial tuning of visual sensitivity to the orientation modulation in Fig. 1(a). Is the spatial tuning bandpass or lowpass? The second purpose was to examine whether the spatial tuning was scale invariant, that is invariant with viewing distance when measured in *object* rather than *retinal* coordinates, as might be expected from

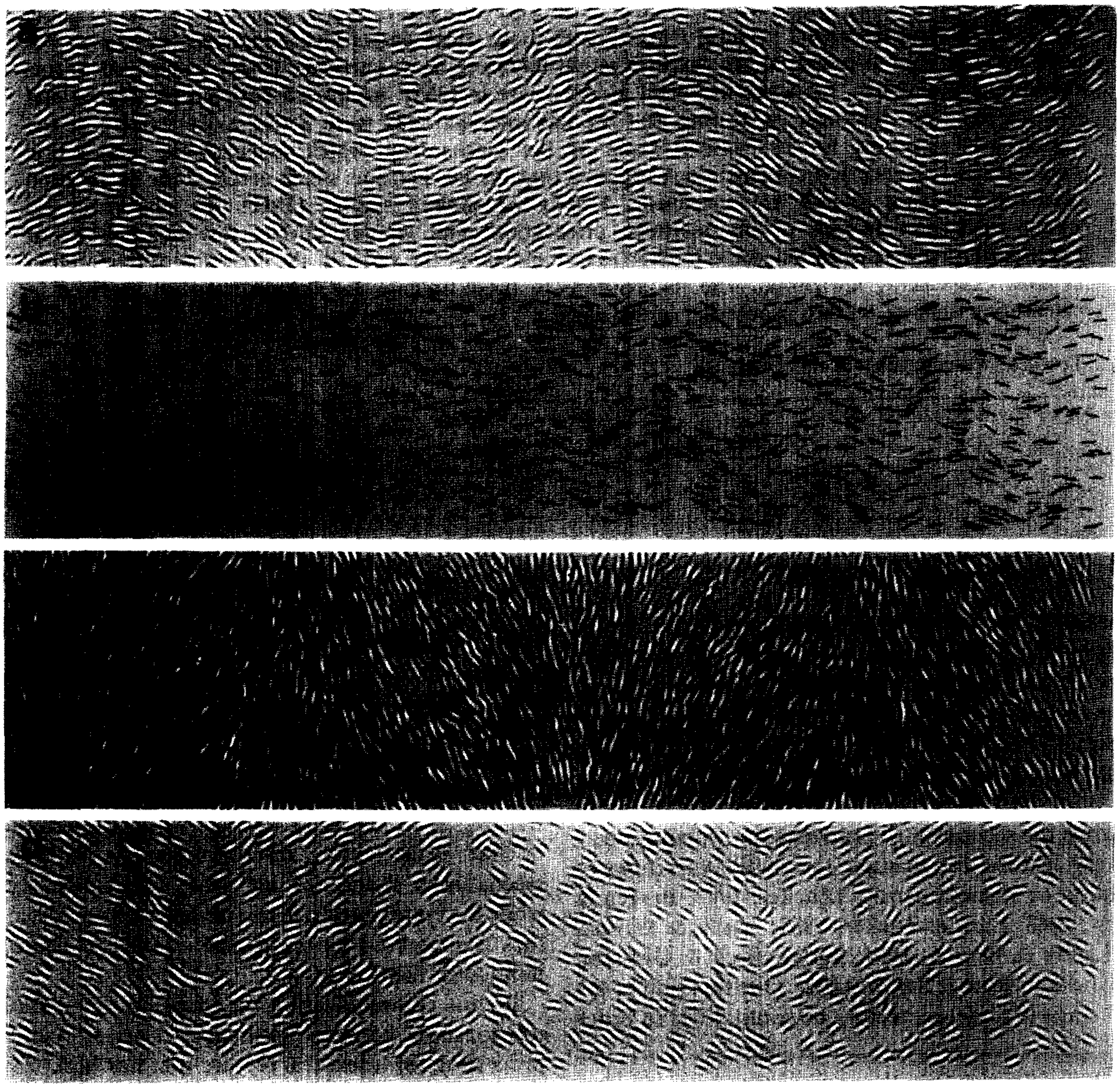


FIGURE 1. Orientation modulated textures used in the experiments. (a) Sinusoidally modulated Gabor micropattern texture. (b) Sinusoidally modulated line micropattern texture. (c) Sinusoidally modulated Gabor micropattern texture but with micropatterns modulated about the vertical as opposed to horizontal. (d) Square-wave modulated texture. Note that in all four types of stimulus the *direction* of the modulation is always along the horizontal axis.

previous studies. Third we wanted to test a prediction that arguably follows from Bergen's (1991) suggestion that the two levels of analysis, local luminance and global texture, are tied at the level of spatial scale. It follows that if the processing of orientation modulation in our stimuli is tied in spatial scale to the processing of local luminance contrasts, we might expect that the spatial tuning of sensitivity to orientation modulation would be narrower for stimuli with narrowband-in-luminance micropatterns compared to stimuli with broadband-in-luminance micropatterns. We therefore predicted narrower spatial tuning to orientation modulation for the Gabor micropattern stimulus in Fig. 1(a) compared with the line micropattern stimulus in Fig. 1(b). Finally we wanted to examine whether the detection of the orientation modulation in our stimuli exhibited behaviour consistent with a linear model. For this we used a common paradigm used to study how the visual system processes complex multi-element arrays, namely to compare human performance with that of an ideal statistical decision maker. Statistical decision models have been successful in accounting for the detection of sine-wave gratings in spatially uncorrelated noise (Burgess, Wagner, Jennings & Barlow, 1981; Legge, Kersten & Burgess, 1986; Kersten, Hess & Plant, 1988), line signals in noise (Kingdom, Moulden & Hall, 1987) and of dot density in noise (Van Meeteren & Barlow, 1981). They are thus potentially applicable to the detection of sinusoidal variations of orientation in our random-micropattern textures. A brief report of some of the experiments described here has already been given elsewhere (Keeble & Kingdom, 1992).

METHODS

Subjects

Six subjects were employed in the experiments. Two, FK and DK, were authors and four, VT, SB, JS and SA, were university research workers who were naive as to the purpose of the experiments. All had normal or corrected-to-normal vision. Not all subjects completed all the experiments described.

Stimuli

Generation. The stimuli were generated by a Mac IIfx and displayed on a SuperMac Trinitron monitor. The displays were all monochrome (black–white) and were gamma corrected by suitable selection of intensity levels from an 8-bit (256 grey levels) look-up table following calibration using a UDT (United Detector) photometer.

Gabor micropatterns. These were generated by multiplying a cosine function by a two-dimensional isotropic gaussian envelope

$$L(x, y, \theta) = M + a\cos[2\pi f(x\cos\theta - y\sin\theta)] \times \exp[-(x^2 + y^2)/2\sigma^2] \quad (1)$$

In equation (1) M is the mean luminance, a the amplitude, f spatial frequency and s the space constant of the gaussian envelope. s was set equal to $0.6/f$, giving the micropatterns a spatial frequency bandwidth at half-height of 0.94 octaves. Two different sized Gabor micropatterns were used with centre spatial frequencies of 2.4 and 4.8 c/deg when viewed at the standard distance of 62 cm. The Gabor micropatterns all had a contrast (a/M) of 39% and were presented on a background of 34 cd m^{-2}.

Line micropatterns. The line micropatterns were anti-aliased segments 0.375×0.031 deg when viewed from 62 cm. They were black lines of approximately zero luminance presented on the same grey background as the Gabor micropattern textures [see Fig. 1(b)].

Orientation modulated textures. The standard stimulus shown in Fig. 1(a) was a display 30×7 deg containing 1000 micropatterns. The position of each micropattern within the display window was completely randomized. The orientation of the micropatterns on the other hand was constrained as follows. All micropatterns lying on a vertical line at a given horizontal location were given an orientation drawn randomly from a gaussian distribution of orientations with a specified mean and standard deviation. The nominal mean orientation of the micropatterns at each vertical location varied sinusoidally along the horizontal axis of the display, with that modulation being about the horizontal. The amplitude of orientation modulation determined by how much the orientation of the micropatterns changed throughout one complete cycle of orientation modulation. For example, an amplitude of orientation modulation of 10 deg implied that the micropatterns changed by 20 deg throughout one complete cycle of orientation modulation. The standard deviation of the Gaussian distribution of orientations in the standard condition was 10 deg and this represented the amount of orientation "noise" in the stimulus.

Procedure

A two-interval forced-choice (2IFC) paradigm was used in all experiments to measure the threshold amplitude of orientation modulation. On each trial two displays were presented, each for 107 msec and separated by a 2 sec inter-stimulus-interval. The task for the subject was to decide which interval contained the stimulus with the modulation of orientation. The only difference between the two stimuli presented on a given trial was in their amplitude of orientation modulation which in one of the stimuli was always zero. The method of constant stimuli was used with five amplitudes of orientation modulation presented in random order, the magnitudes of which were determined by pilot studies. In all except the experiments dealing with spatial summation, five spatial frequencies of orientation modulation were employed and in each session all five spatial frequencies were displayed in random order. The phase of orientation modulation was also randomized on each trial. Feedback was given in the form of an auditory tone for an incorrect decision.

Analysis

We fitted cumulative gaussian functions to the plots of percent correct against amplitude of orientation modulation and determined the threshold as the amplitude of orientation modulation giving 75% correct.

RESULTS

Spatial summation with Gabor micropattern displays

We wished to examine the spatial summation properties of the mechanisms which detected the orientation modulation in our displays. We also wanted to know what size of display to use for the main body of experiments given the criterion that there be sufficient number of cycles of modulation and sufficient height of display at each spatial frequency for performance to have asymptoted.

In the first part of the study we measured performance as a function of the number of cycles of orientation modulation for various spatial frequencies of orientation modulation. The displays were all 7 deg in height and consisted of 4.0 c/deg Gabor micropatterns at a constant micropattern density of 4.76 micropatterns per deg^2 [see Fig. 1(a)]. Four spatial frequencies of orientation modulation were used: 0.066, 0.132, 0.264 and 0.528 c/deg. The maximum number of cycles used for each of the four spatial frequencies was 2, 4, 8 and 16 respectively.

Figure 2 presents the results for two subjects. There is a hint in the data that the number of cycles required to produce asymptotic performance is a function of the spatial frequency of orientation modulation, with higher spatial frequencies asymptoting at larger numbers of cycles. To obtain a more precise estimate of asymptotic performance the curves for the 0.132, 0.264 and 0.528 c/deg conditions were fitted with an exponential function of the form

$$T = b \exp(aN) + c$$

where T was the threshold amplitude of orientation modulation in deg and N the number of cycles. a, b and c were free parameters, with c representing the asymptotic value as N approached infinity. The criterion employed to determine the asymptotic value of T was the number of cycles required to reach 95% of the value of c.

The mean asymptotic values across the two subjects calculated in this way for the 0.133, 0.267 and 0.533 c/deg conditions were 1.56, 3.53 and 7.9 cycles respectively. The number of cycles required to reach asymptotic performance is therefore roughly proportional to the spatial frequency of orientation modulation. This results suggests that performance using the 95% criterion asymptotes at a display width of about 15 deg for the spatial frequencies tested. In other words detection of orientation modulation in our textures exhibits the properties of spatial frequency independent spatial summation.

In the second part of the study we measured performance as a function of the height of the display, using a 30 deg wide display. Figure 3 plots the effect of varying the height of the display for two spatial frequencies of orientation modulation. Using the 95% criterion, performance was calculated to asymptote at heights of 6.2 and 8.9 deg for the 0.133 and 0.533 c/deg conditions respectively, when averaged across the two subjects. This is a relatively small change, a factor of 1.44, in asymptotic height for a four-fold change in the spatial frequency of orientation modulation.

On the basis of the results of both studies on spatial summation we decided to employ for the main body of experiments a "standard stimulus" 30 deg wide × 7 deg in height containing 1000 micropatterns. We argue that this display should be sufficient to produce asymptotic performance for all the spatial frequencies of orientation modulation tested. In the experiments below we also present data for a spatial frequency of orientation modulation of 0.033 c/deg, which produces just one cycle of orientation modulation in a 30 deg wide display. In doing so we have made the assumption that asymptotic performance will also have been reached with this spatial frequency.

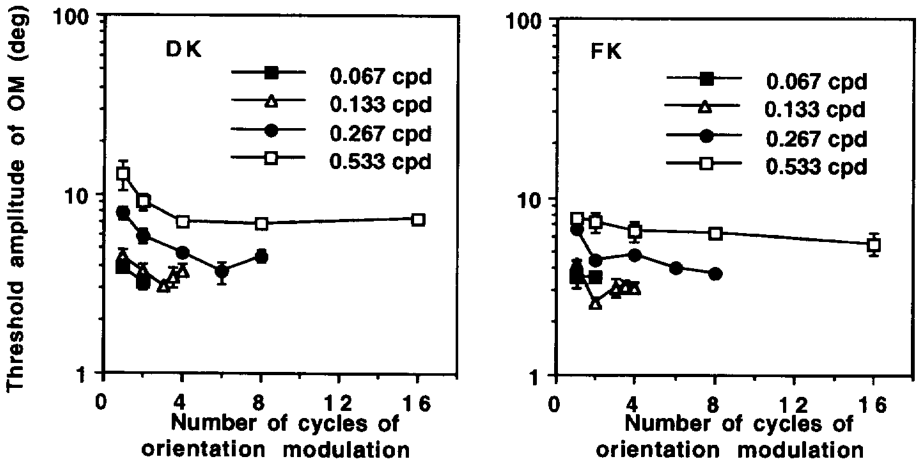


FIGURE 2. Threshold amplitude of orientation modulation (OM) plotted as a function of the number of cycles of orientation modulation for four different spatial frequencies of amplitude modulation: 0.067, 0.133, 0.267 and 0.533 c/deg. Data for two subjects.

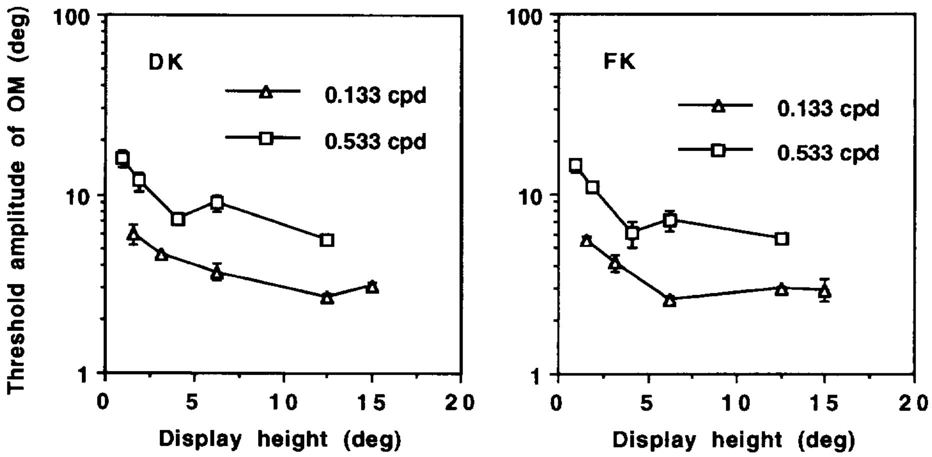


FIGURE 3. Effect of display height for two spatial frequencies of amplitude modulation: 0.133 and 0.533 c/deg. Data for two subjects.

Spatial tuning of the detection of orientation modulation

In the Introduction we stated that we wished to examine (a) whether the spatial tuning to orientation modulation was bandpass or lowpass, (b) whether the spatial tuning was object scale invariant and (c) whether the spatial tuning for line micropattern textures was broader than for Gabor micropattern textures. We therefore measured orientation modulation thresholds at a number of spatial frequencies of orientation modulation using the stimuli shown in Fig. 1(a) (Gabor micropatterns) and Fig. 1(b) (line micropatterns). The resulting orientation modulation functions (OMFs) are shown in Figs 4 and 5 for the Gabor and line micropattern texture respectively. The OMFs are plotted in terms of sensitivity to orientation modulation, which is defined as the reciprocal of the threshold orientation modulation. Each graph presents results from viewing the stimuli at three distances. Note that spatial frequency of orientation modulation is plotted in c/deg resulting in a shift of the range of spatial frequencies tested to higher spatial frequencies as viewing distance is increased.

Examination of Figs 4 and 5 reveals a number of features. First, in nearly all cases the OMFs have a bandpass characteristic. Second, the peak spatial frequency (in c/deg) of each OMF changes with viewing distance. To obtain a clearer picture of the effects of both type of micropattern and viewing distance we fitted each OMF with a quadratic after first transforming both axes of the data logarithmically. We used a quadratic because it is a simple model-free function that can be used to obtain an estimate of the peak and spread of each OMF. We used the fitted quadratic to estimate two OMF parameters: the spatial frequency of peak sensitivity and the bandwidth. The spatial frequency of peak sensitivity was calculated as the point where the fitted function peaked. The bandwidth was calculated as the width in octaves between the points at which the value of log(1/threshold) was half the maximum value of log(1/threshold) in the fitted curve.

The effect of viewing distance on the spatial frequency of peak sensitivity in the OMFs is shown in Fig. 6(a, b) for the Gabor and line micropattern displays respectively. The points in Fig. 6(a, b), which are plotted in log–log coordinates, are fitted by straight lines with slopes 0.81 and 0.85 respectively, which are quite close to direct proportionality. This means that if the OMFs were plotted in *object* rather than *retinal* units, that is in c/cm rather than c/deg, there would be little effect of viewing distance on the spatial frequency of peak OMF sensitivity. This confirms our prediction that the spatial tuning of sensitivity to orientation modulation is largely invariant with viewing distance when measured in object units. The data also show that the peak spatial frequency of sensitivity to orientation modulation is about 50 times lower than the peak luminance spatial frequency of the Gabor micropatterns, and this is approximately constant with viewing distance.

Figure 7 presents OMF bandwidths for each type of micropattern and viewing distance averaged across the three subjects for which data on both types of micropattern display was collected. The estimates of bandwidth computed in the way described above are large, averaging 7.63 and 7.65 octaves for the Gabor and line micropattern displays respectively. It is possible that these bandwidth estimates are overestimates because of the relatively small 4 octave range of spatial frequencies tested. An ANOVA (analysis-of-variance) conducted on the bandwidth measures with Subjects, Viewing Distance and Type of Micropattern as dependent variables showed no significant differences between subjects [$F(2,12) = 3.72$; $P = 0.055$], between Viewing Distances [$F(2,12) = 0.06$; $P = 0.94$] and between Type of Micropattern [$F(1,12) = 0.003$; $P = 0.96$]. This ANOVA, as well as the ones described below, was calculated using the general linear model in Systat (Wilkinson & Leland, 1989), in which the error term was the sum of all the possible interaction sums-of-squares. Thus our prediction that the OMF bandwidths would be larger for the line micropatterns compared with the Gabor micropattern displays is not confirmed by our data.

One question that arises is whether the shift in the spatial frequency of peak sensitivity with viewing distance when spatial frequency is measured in retinal units

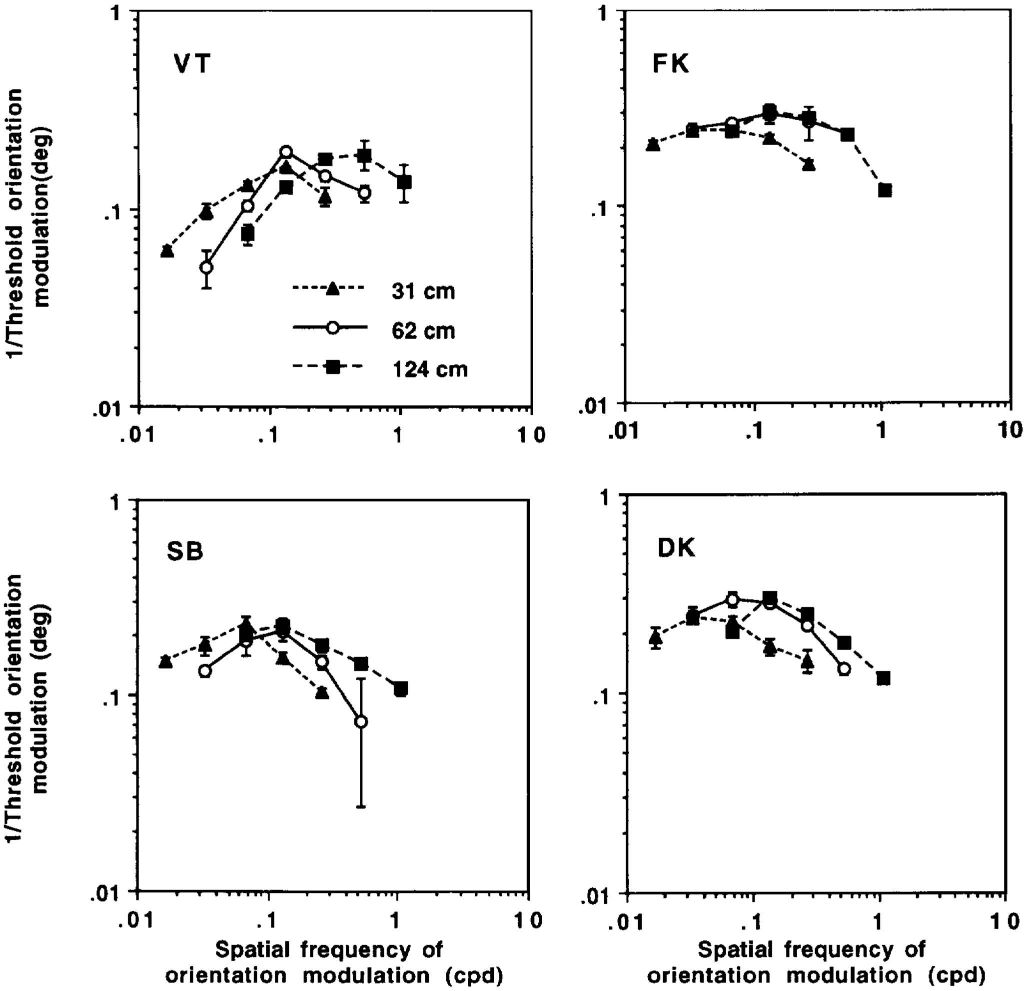


FIGURE 4. Orientation modulation functions (OMFs) for Gabor micropattern displays [see Fig. 1(a)] at three viewing distances 31, 62 and 124 cm. Note that spatial frequency of orientation modulation on the abscissae is given in conventional retinal units of cycles per deg. Data for four subjects.

is due to a change in the *scale* (size or spatial frequency) or due to a change in the *density* of the micropatterns. To test which of these was the critical factor we measured OMFs under two additional conditions. First, OMFs for Gabor micropattern displays were measured using the standard sized display but with half the number and hence half the density of micropatterns (500 instead of 1000). Second, OMFs were measured using the standard sized display with half the number of, but double-in-size, micropatterns. The double-in-size Gabor micropatterns were scaled versions of the standard micropatterns and thus had a centre spatial frequency of

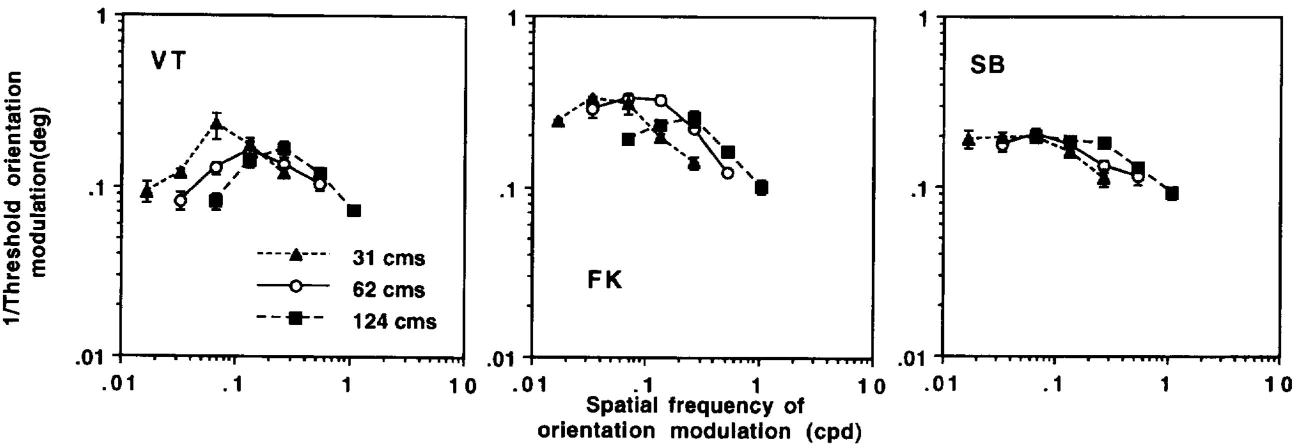
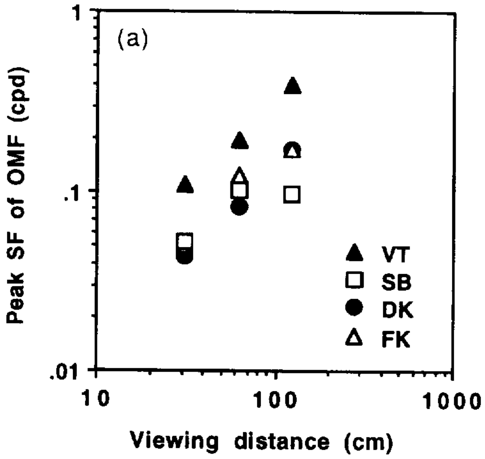


FIGURE 5. OMFs for line micropattern displays [see Fig. 1(b)] at three viewing distances. Data for three subjects.



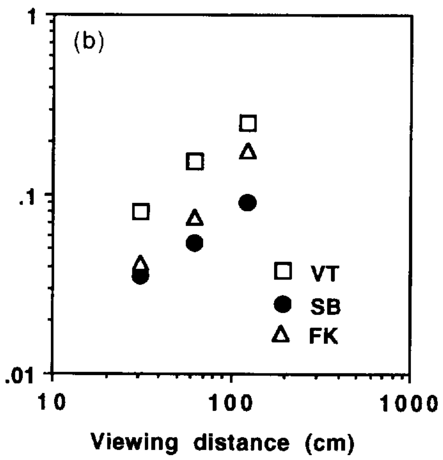


FIGURE 6. Effect of viewing distance on peak OMF spatial frequency for (a) Gabor and (b) line micropattern displays. Individual subject's data are shown.

2.4 c/deg (as opposed to 4.8 c/deg) but with the same bandwidth of 0.94 octaves as the micropattern employed in the standard condition.

Figure 8 compares the peak spatial frequencies for the standard condition, the half density condition and the half-density-plus-double-size-condition. While halving the density had a small effect on the position of peak spatial frequency, doubling the size of the micropatterns changed the spatial frequency of peak sensitivity by an average of about 3.5 across the two subjects. The factor of 3.5 is larger than the factor of 2 that one might have expected, and this may be due in part to the contribution of the small effect of density found in the first comparison. The results show however that the shift in peak spatial frequency with viewing distance observed in the previous experiments was primarily due to a change in the scale rather than the density of the micropatterns, at least within the range of conditions used in these experiments.

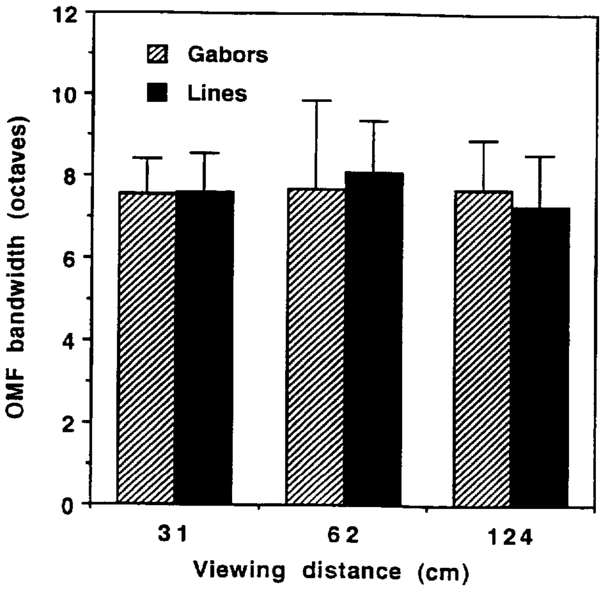


FIGURE 7. OMF bandwidths in octaves for both Gabor and line micropattern displays for each viewing distance. Data are averaged across the three subjects who completed experiments on both types of pattern.

Test of linearity of the second stage of processing

Since our textures were produced using micropatterns whose orientations were drawn randomly from a specified distribution at any given location in the display (see Methods for details) one test of linearity consists of examining the extent to which performance can be explained by supposing that the visual system is acting as a linear statistical decision maker. One way of conceptualizing the operation of a linear statistical decision model is to suppose that on each trial a template of each of all the possible targets (given phase and spatial frequency randomization) is matched to both alternative stimuli and the one giving the highest cross correlation is then chosen as the target (Burgess & Ghandeharian, 1984; Kingdom *et al.*, 1987). This strategy becomes optimal when all the information available in each stimulus is used and performance in this case can be said to be that of an "ideal" observer. When the performance of the ideal observer is plotted in terms of squared detection thresholds against the amount of externally added noise variance, the function is linear (Legge, Kersten & Burgess, 1988). If human performance is also found to be linear on the task, even though inevitably of lower slope than the ideal observer due to sub-optimal sampling of the available information in the stimulus, then this supports the notion that the visual system is performing the task using a computationally equivalent strategy to that of an ideal statistical decision maker.

We tested this model with the Gabor micropattern displays [Fig. 1(a)] by examining the effect of the standard deviation of orientation noise added to the nominal mean orientation of each micropattern. This standard deviation was set in all previous experiments to be 10 deg. In this experiment we measured thresholds at standard deviations (SDs) of 0, 5, 10, 15 and 20 deg. Figure 9 plots the squared thresholds against the variance (SD^2) of orientation noise, for each spatial frequency of orientation modulation. The plots have been fitted with quadratics in order to reveal any consistent non-linearities in the functions. As can be seen from Fig. 9, in all except the highest spatial frequency

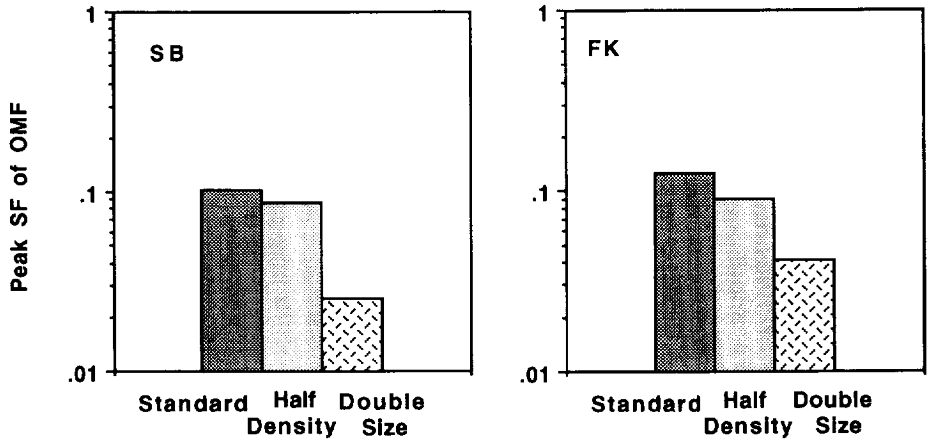


FIGURE 8. Comparison of peak OMF spatial frequency between the standard condition, half density condition and half-density-plus-double-size condition. Data for two subjects.

condition the functions curve upwards as the orientation noise variance increases. We have not attempted to compute and show the performance of an ideal observer because for the purposes of this study it is sufficient to show whether the human data exhibits linear behaviour or not. It should however be noted that ideal observer performance will not depend on the spatial frequency of orientation modulation. The non-linearity in our data is inconsistent with a linear statistical decision model underlying the detection of the orientation modulation in our displays. The nature of the non-linearity is in nearly every case a worsening of performance as noise variance increases over and above that which would be expected on purely statistical considerations.

DISCUSSION

Before considering the theoretical implications of these results a summary of the principal findings is as follows.

(i) Sensitivity to orientation modulation exhibits properties of spatial frequency independent spatial summation.

(ii) Orientation modulation functions (OMFs) are in nearly all cases bandpass.

(iii) The spatial frequency of orientation modulation to which subjects were most sensitive, when measured in object units (e.g. c/cm), was invariant with viewing distance, for both Gabor and line element micropattern displays. The salient factor underlying this invariance appears to be the scale rather than the density of the micropatterns.

(iv) The bandwidths of the OMFs were the same for both Gabor and line segment micropattern textures.

(v) Squared detection thresholds for orientation modulation were found to be a non-linear, accelerating, function of the variance of the orientation noise added to the micropatterns.

What do these results tell us about the mechanisms of orientation-defined texture processing? We stated in the Introduction that texture processing is usefully considered as a two-stage process. For our stimuli the first stage arguably involves the processing of the luminance detail of the individual micropatterns, while the second

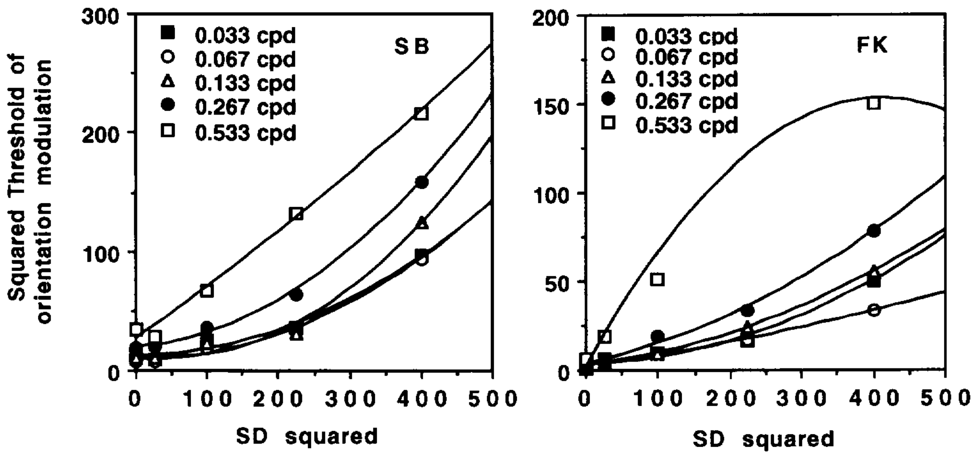


FIGURE 9. Effect of variance of orientation noise on orientation modulation detection thresholds, for five spatial frequencies of orientation modulation and for two subjects. Best fitting quadratic functions are shown for each plot to reveal their non-linear behaviour. Data for two subjects.

stage involves the processing of the spatial variations in orientation across the stimulus. In assessing the relevance of the results of this study for both these stages we address four issues: (1) the scale invariance of orientation-defined texture processing; (2) the nature of the first stage input; (3) the spatial tuning of the second stage; (4) the non-linearity of the second stage.

Scale invariance

The finding that the spatial frequency tuning of the OMF was invariant with viewing distance when measured in *object* units is consistent with many previous studies which have shown scale invariance in a variety of texture segregation tasks (Nothdurft, 1985; Landy & Bergen, 1991; Bergen, 1991; Bach & Meigen, 1992). Our results show that the critical stimulus variable determining the peak spatial frequency of the OMF is the scale of the individual micropatterns rather than their density. Further experiments will be required to determine whether the critical factor in the scale of the micropatterns is the luminance spatial frequency or some other feature such as the length of the constituent bars or the overall micropattern size. These results therefore suggest that the visual system takes into account the change in the scale of the micropatterns in the retinal image as viewing distance is changed when measuring the orientation gradients in the stimulus. In other words the visual system computes the rate of change of orientation per unit scale of micropattern. This mechanism embodies the principle implied in Bergen's (1991) hypothesis that the spatial scales at which local luminance gradients and global texture gradients are analysed are tied.

It has been argued that scale invariance is an important property of perceptual systems because it simplifies the computation of absolute shape (e.g. Parker, 1993). The spatial changes in local orientation exemplified in our stimuli would most likely arise in natural scenes from textured surfaces folded in depth, as for example in the retinal image of an undulating field of corn. For such ground-surface textures the elements themselves need not be physically oriented for them to become oriented in the retinal image as a result of the process of foreshortening. The scale invariance we have found in the spatial tuning of sensitivity to orientation modulation may therefore reflect the operation of mechanisms ultimately concerned with the computation of three-dimensional shape-from-texture.

Nature of first stage input

We predicted that the OMF bandwidths would be greater for the line micropattern displays [Fig. 1(b)] compared to the Gabor micropattern displays [Fig. 1(a)]. This prediction followed from the axiom that mechanisms sensitive to luminance contrast are more selective for spatial frequency than for bar width (Albrecht, DeValois & Thorell, 1980). Lines are wideband stimuli, and thus would be expected to stimulate multiple spatial frequency tuned mechanisms and thus multiple second-stage mechanisms if the two levels of processing were tied. However this prediction was not supported by our data which showed no difference in OMF bandwidth between line and Gabor micropattern stimuli. Although we have no definite explanation for this finding we can speculate on possible reasons for it. First, although line micropatterns are broadband they undoubtedly stimulate some mechanisms more strongly than others and those that are relatively weakly stimulated may not provide a sufficiently strong input to activate their associated second stage mechanisms. Second, the line micropatterns may act as selectively as Gabor micropatterns for second stage mechanisms by virtue of their being encoded in textures by cortical neurones which are "end-stopped" (Hubel & Wiesel, 1965; Dreher, 1972; Kato, Bishop & Orban, 1978), especially if selectivity for line length were tied to the dominant spatial frequency of the neurone. Interestingly, end-stopping in cortical neurones has been suggested to be important for the detection of curvature (Dobbins, Zucker & Cynader, 1989). This hypothesis leads to the testable prediction that micropattern length, and not just luminance spatial frequency content, should be a salient factor in determining the spatial tuning characteristics of sensitivity to orientation modulation and we hope to test this prediction in the near future.

Spatial tuning of second stage

Our finding that the OMFs are in nearly all cases bandpass shows that there are spatial limits to the detectability of orientation gradients. This is consistent with results from previous studies which have shown that the size of the gradient in orientation across a texture border is an important factor in texture segregation (Nothdurft, 1985, 1991, 1993; Landy & Bergen, 1991). However our results show that the mechanisms sensitive to orientation gradients are optimally tuned to quite low rates of orientation change. We found that the spatial frequency of orientation modulation to which subjects were most sensitive was about 40–50 times lower than the dominant spatial frequency of the Gabor micropatterns in the stimulus. For example with 4.0 c/deg Gabor micropatterns, peak sensitivity to orientation modulation occurred at about 0.09 c/deg.

One might argue that the low spatial frequency tuning we have observed reflects the operation of mechanisms which deal principally with continuously varying orientation discontinuities and not those which deal with the abrupt orientation discontinuities which characterize stimuli usually employed in studies on texture segmentation. We wondered therefore how the OMFs for sinusoidally modulated patterns would compare with those for similar texture patterns with abrupt orientation discontinuities. To answer this question we compared performance for the sine-wave display in Fig. 1(a) with the square-wave display in Fig. 1(d), which contains abrupt discontinuities in orientation. The results are shown in Fig. 10. The spatial tuning to both the sine-wave and the square-wave stimuli is quite similar in all four subjects, with sensitivity slightly higher overall for the square-wave stimuli. Figure 12(a) plots the (geometric) mean ratio of sensitivity of the square-wave to

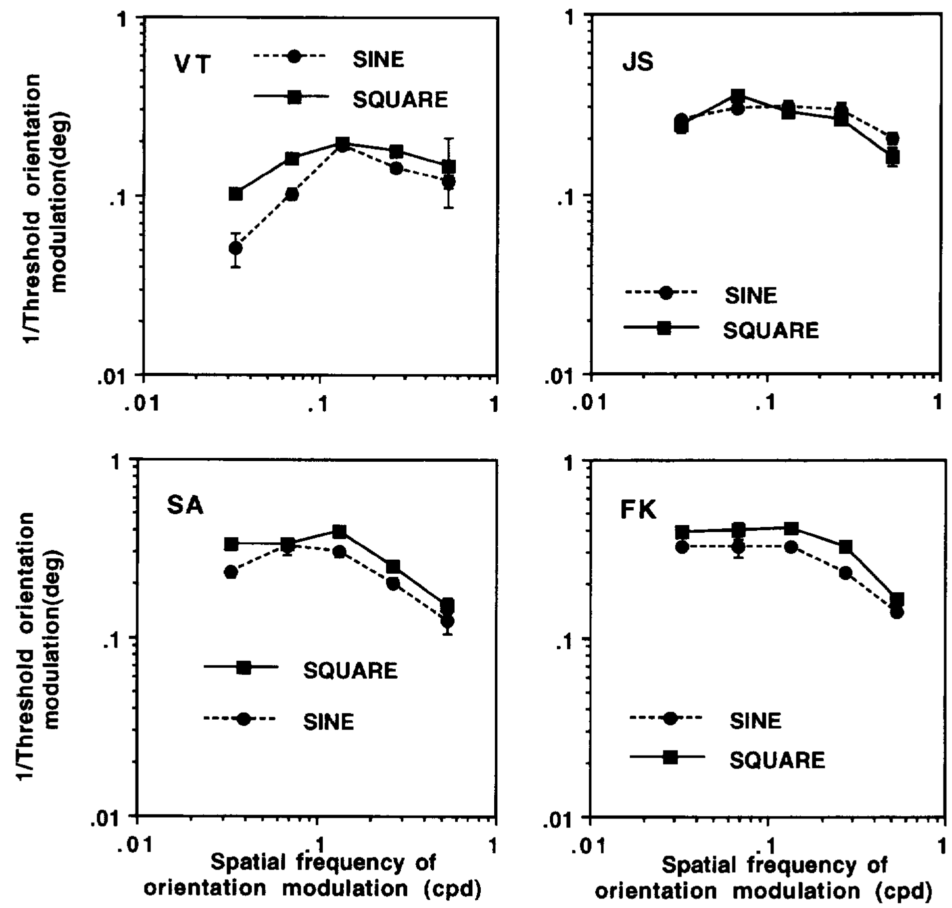


FIGURE 10. OMFs for sine-wave [see Fig. 1(a)] and square-wave [see Fig. 1(d)] orientation modulated textures. Data for four subjects.

sine-wave displays averaged across the four subjects. The ratio averaged across spatial frequency of orientation modulation is 1.34. This difference in absolute sensitivity could reflect a difference analogous to the r.m.s. between the two waveforms, which would predict a ratio of 1.41. On the other hand it could imply that it is the fundamental harmonic component of the square-wave at each spatial frequency of orientation modulation that is being detected, which alone would predict a ratio of 1.27. However, the evidence from the orientation-noise experiment is not consistent with a linear operator for the second stage of processing as we argue below, so the exact significance of the slightly superior performance of the square-wave compared with sine-wave stimuli is yet to be established. Whatever the basis for the overall difference in sensitivity between the two types of waveform however, the important finding is that their spatial tunings are very similar. We conclude that the low spatial frequency tuning observed with our continuously varying sinusoidal stimuli can be generalized to stimuli with abrupt orientation discontinuities.

As we suggested earlier, orientation gradients in the retinal image often arise in natural scenes when viewing ground-plane textured surfaces folded in depth. It is therefore worth comparing the spatial tuning of orientation modulation with that of stereo-depth modulation. Tyler (1983) and Rogers and Graham (1982) found peak sensitivities for stereo-depth modulations to range between 0.2 and 0.5 c/deg, whereas we found peak sensitivity to orientation modulation to range from about 0.06 to 0.2 c/deg, depending on micropattern scale. This difference may in part be due to differences in the nature of the stimuli used in the two types of study. In the stereo-depth modulation studies random-dot stereograms were employed whereas we employed micropattern-based arrays. Random-dot stereograms are broadband in the luminance spatial frequency domain and it follows therefore that the detection of stereo-depth modulation in such stimuli may be mediated by mechanisms tuned to relatively high luminance spatial frequencies (above 2.0 c/deg), since these mechanisms have been shown to have the best stereoacuity (Schor & Wood, 1983). These high luminance spatial frequency tuned mechanisms may in turn stimulate mechanisms sensitive to relatively high rates of stereo-depth modulation. On the other hand the differences in the measured spatial tunings of orientation and stereo-depth modulation sensitivity may reflect genuine differences in the mechanisms themselves, and this is evidenced by our finding that even with our broadband-in-luminance line micropatterns we found peak sensitivities to orientation modulation to lie between about 0.03 and 0.3 c/deg, depending on micropattern size. The way to resolve this issue will be to measure sensitivity to stereo-depth modulation using narrowband-in-luminance stereograms in order to determine the relationship between the luminance spatial scale of the stimulus and the position of peak sensitivity to its stereo-depth modulation.

Non-linearity of second stage

The second property that our results reveal about the second stage mechanisms of orientation-defined texture processing is that they appear to be non-linear. We found a consistently non-linear relationship between orientation modulation detection thresholds and the amount of added orientation-noise variance. This finding makes it unlikely that a linear filter acting on a more-or-less veridical map of local orientations underlies the detection of orientation modulation in our stimuli. Although we cannot rule out the possibility that transducer non-linearities such as contrast normalization and spatial non-linearities such as rectification, acting on the luminance profiles of the individual micropatterns, could underlie the results of the added orientation noise experiment, it is more likely that cooperative processes are responsible. Cooperative processes have been implicated in a variety of studies involving orientation-defined textures (Zucker, 1983, 1985; Link & Zucker, 1987; Or & Zucker, 1989) and contour extraction (Zucker & Davis, 1988; Link & Zucker, 1988; Field, Hayes & Hess, 1993) and recently a number of neural network models have been designed to simulate their operation (Lowe, 1988; Parent & Zucker, 1989; Sha'shua & Ullman, 1988; Gigus & Malik, 1991). These cooperative processes are believed to take the form of facilitatory and inhibitory interactions between neighbouring orientationally-selective neurones in the cortex. One purpose of such processes is to highlight those surface markings which show "good continuity", or, as Parent and Zucker (1988) have put it, to highlight those surface markings which show a high degree of local curvature consistency. They thus exploit the fact that good continuity is a prominent feature of textures and contours in natural scenes. In terms of the results of our experiments with orientation noise, increasing the amount of noise would be expected to increasingly disrupt the possibility of facilitatory interactions between neighbouring micropattern detectors with similar orientation preferences. This would result in greater degradation of performance at high orientation noise levels than would be expected solely on statistical grounds and would therefore predict the accelerating non-linearity we observed in our orientation-noise data.

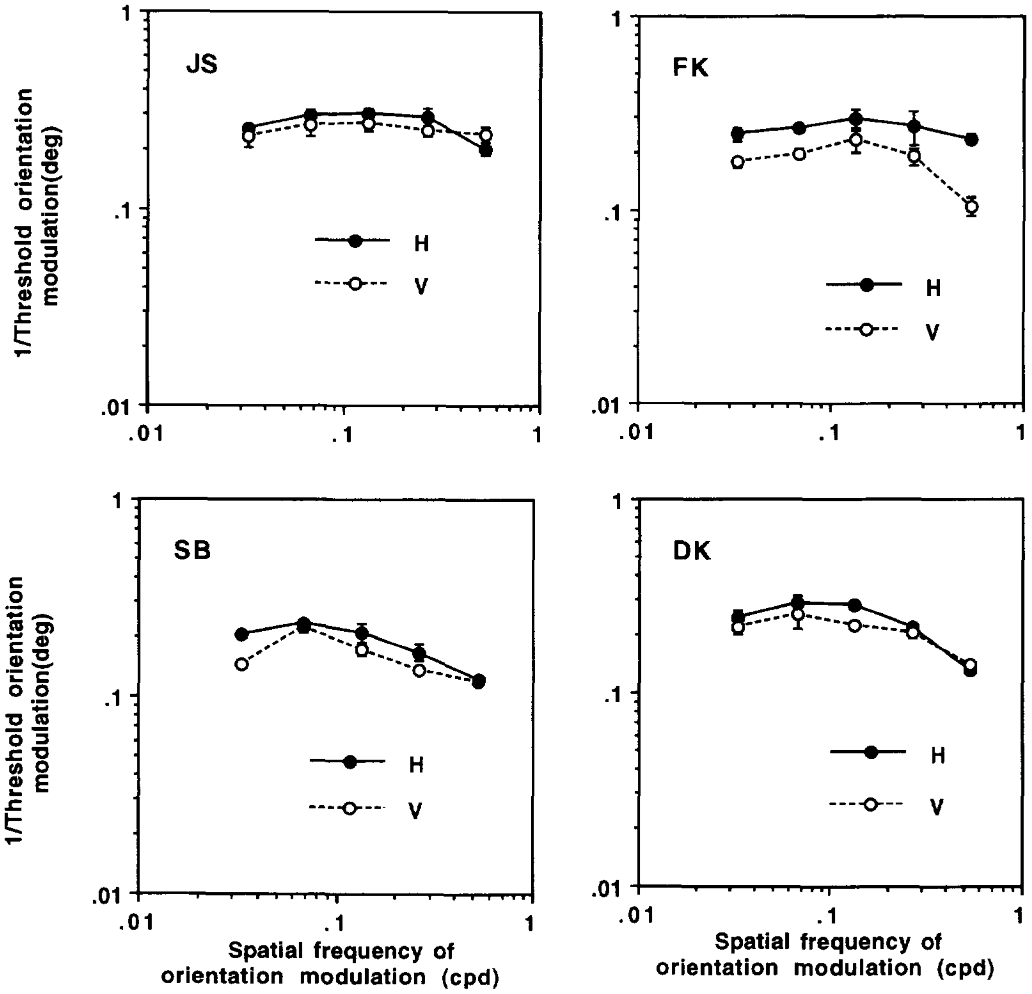


FIGURE 11. OMFs for stimuli in which the modulation is about the horizontal (H) [see Fig. 1(a)] compared with being about the vertical (V) [see Fig. 1(c)].

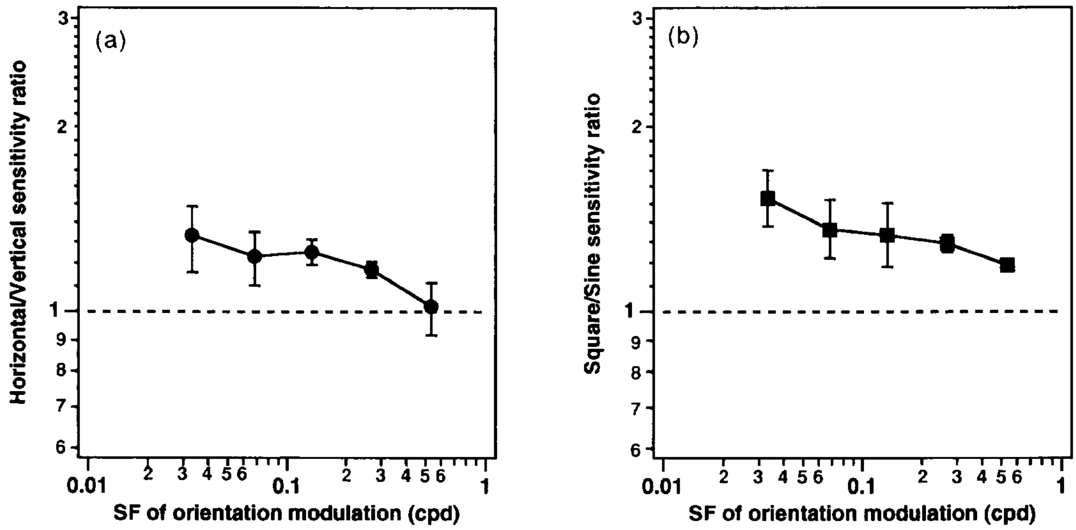


FIGURE 12. (a) Ratio of square-wave to sine-wave sensitivities using data shown in Fig. 10. (b) Ratio of micropattern modulation about the horizontal sensitivity to micropattern modulation about the vertical sensitivity using data presented in Fig. 11.

Although we have considered the possibility that cooperative processes form part of the second stage of orientation-defined texture processing, one could consider them as constituting a separate, intermediate, stage. It is reasonable to assume that the first stage mechanisms which derive information about the orientation of each micropattern provide more or less veridical information, in spite of nonlinearities such as contrast normalization and rectification, and the additional effects of neural noise. However cooperative processes would effectively transform the map of local orientations by favouring those that lay along curves and straight lines. Thus the mechanism responsible for making explicit the presence of orientation modulation in the stimuli would receive as input a weighted map of local orientations following passage through the cooperative network. One could therefore speak of a three-stage process: an initial stage in which local micropattern detectors are activated, an intermediate stage involving cooperative interactions between those detectors and a third stage involving the actual detection of orientation modulation.

That cooperative processes may be involved in the detection of the orientation modulation in our displays is evidenced phenomenologically by the strong subjective flow patterns observed in Fig. 1 (a–d). Zucker (1985) has defined a flow pattern as "a dense covering of a surface with a family of curves that are locally parallel almost everywhere". Consider Fig. 1(a, c), in both displays the direction of the orientation modulation is horizontal and of similar amplitude. However, whereas in Fig. 1(a) the modulation of the micropatterns is about horizontal, in Fig. 1(c) it is about the vertical. In Fig. 1(a) the perceived flow patterns are continuous across the display and look sinusoidal, while in Fig. 1(c) they are close to vertical and look more like tangent functions. We wondered whether such marked differences in the appearance of the flow patterns between Fig. 1(a, c) would be reflected in a marked difference in the spatial tuning to their orientation modulation. On the other hand a simple linear orientation gradient detector would register the same response to both stimuli. Figure 11 compares the measured OMFs for both classes of stimuli and as can be seen they are in fact quite similar. Figure 12(b) plots the (geometric) mean ratio of sensitivity to the horizontal mean orientation stimuli [Fig. 1(a)] to sensitivity to the vertical mean orientation stimuli [Fig. 1(c)], for each spatial frequency of orientation modulation, with data averaged across the four subjects. The overall mean ratio is 1.2 and this represents a significant difference in thresholds [$F(1,31) = 12.25$; $P < 0.001$] when tested using an ANOVA with Subjects, Mean Micropattern Orientation and Spatial Frequency as factors. The difference is nevertheless quite small and given the similarity in the shape of spatial tuning in the two classes of stimulus the results of this experiment do not unequivocally support either a simple linear gradient detector model nor one involving non-linear cooperative mechanisms. Thus while the results using added orientation noise described earlier are consistent with the involvement of cooperative processes, further research is needed to establish firmly whether such processes underlie the detection of the orientation modulation in our stimuli.

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