



Texture-orientation mechanisms pool colour and luminance contrast

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Abstract

Do texture-sensitive mechanisms operate separately on, or pool, luminance and colour contrast information? We addressed this question by measuring threshold-versus-amplitude functions for orientation-modulated (OM) gratings comprised of gabor elements defined by either colour or luminance contrast. In both the uncrossed (all elements in test and mask defined by either colour or luminance contrast) and crossed (equal mixtures of luminance and colour contrast in both test and mask) conditions, evidence of sub-threshold facilitation between test and mask was obtained. The sub-threshold facilitation in the crossed condition could not be accounted for by luminance artifacts in the ostensibly isoluminant gabors. The results are consistent with a single visual mechanism sensitive to OM textures that pools information from both the luminance and chromatic post-receptoral mechanisms. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Textures are dense arrays of elements with certain uniform statistical properties. In natural scenes, spatial changes in texture typically indicate either object boundaries or changes in surface curvature. Numerous studies testify to our visual system being highly sensitive to a variety of forms of textural change. An important question concerns whether separate luminance contrast and chromatic contrast mechanisms, or ones that pool local luminance and chromatic contrast information, mediate the detection of textural change.

The extent to which luminance and chromatic signals are processed independently by the visual system is important to our understanding of how colour and luminance information is utilized for the analysis of image structure. In the physiological literature, single-unit recordings in monkey visual cortex have generally failed to find neurons that respond uniquely to colour or luminance (Derrington, Krauskopf, & Lennie, 1984; Thorell, DeValois, & Albrecht, 1984; Lennie, Krauskopf, & Sclar, 1990). The psychophysical literature can be roughly divided between studies of contrast de-

tection and studies measuring performance with supra-threshold contrast stimuli. In the former group, virtually all evidence points to independent chromatic and luminance mechanisms. Detection and discrimination thresholds for spectral stimuli have been modeled successfully on the basis of independent responses from a single luminance channel and two colour-opponent channels (Guth & Lodge, 1973; Kranda & King-Smith, 1979; Thornton & Pugh, 1983; Krauskopf & Gegenfurtner, 1992; Cole, Hine, & McIlhagga, 1993; Yeh, Pokorny, & Smith, 1993; Miyahara, Pokorny, & Smith, 1996). The independence of luminance and colour mechanisms has been explicitly tested and confirmed in studies of sub-threshold summation between colour and luminance contrast (DeValois & Switkes, 1983; Switkes, Bradley, & DeValois, 1988; Cole, Stromeyer, & Kronauer, 1990; Losada & Mullen, 1994; Mullen & Losada, 1994; Chen, Foley, & Brainard, 2000; but see Gur & Akri, 1992, for the contrary result), in studies of contrast adaptation (Krauskopf, Williams, & Heeley, 1982; Bradley, Switkes, & DeValois, 1988), in studies of noise masking (Gegenfurtner & Kiper, 1992; Sankeralli & Mullen, 1997; Giulianini & Eskew Jr, 1998; Stromeyer, Thabet, Chaparro, & Kronauer, 1999) and in a study using coloured textures (Li & Lennie, 1997). Finally, analysis of contrast detection thresholds for performing tasks other than contrast detection have also revealed

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independent mechanisms, such as with stereopsis (Simmons & Kingdom, 1997).

On the other hand, studies using dependent measures other than contrast detection thresholds have generally revealed a lack of independence between colour and luminance. For example, in visual search (D’Zmura, 1991; Palmer & Teller, 1993; Bauer, Jolicoeur, & Cowan, 1996; Nagy, 1999; Nagy & Winterbottom, 2000), contour integration (McIlhagga & Mullen, 1996; Mullen, Beaudot, & McIlhagga, 2000), and motion perception (Cavanagh & Anstis, 1991; Gegenfurter & Hawkin, 1995; Mullen & Boulton, 1992; Palmer, Mobley, & Teller, 1993) colour and luminance information appear to interact to determine performance. However, Legge, Parish, Luebker, and Wurm (1990) found no additive interaction between suprathreshold levels of colour and luminance for speed of reading of text, and Nagy (1999) (see also Nagy & Winterbottom, 2000) found evidence for the independent processing of luminance and chromatic signals in some visual search tasks.

What then of texture perception? Although it has been shown that texture segregation is possible at isoluminance, i.e. with colour alone (McIlhagga, Hine, Cole, & Snyder, 1990), that a colour difference between textures lying in different depth planes can facilitate the perception of transparency (Akerstrom & Todd, 1988), and that the addition of irrelevant colour variation can help mask texture boundaries (Morgan, Adam, & Mollon, 1992; Pearson & Kingdom, 2001), we are not aware of any studies that have explicitly tested the independence/non-independence issue for a texture task. Li and Lennie (1997) measured sensitivity to changes in the mean chromaticity or brightness of textures, and thus performance in their task may have been mediated by coarse-scale filters sensitive to the overall colour and luminance differences between the different texture regions, rather than by mechanisms sensitive to texture differences per se.

According to Bergen (1991, p. 132), texture segmentation is “a perceptual phenomenon in which regions differing only in their spatial structure, *not* (our emphasis) in colour and brightness, and without any physical contour defined by colour or brightness differences separating them, are seen as distinct”. Therefore, to establish whether texture-sensitive mechanisms independently access chromatic and luminance information, one requires a task in which the critical task is *not* the detection of luminance or chromatic contrast, but in which the elements comprising the texture can be defined either by colour or luminance contrast. To this end, we have used a task in which the texture elements are suprathreshold in colour or luminance contrast and the task is to detect global variations in the orientation of the elements. We have employed the orientation-modulated (OM) grating (Kingdom, Keeble, & Moulden, 1995), an example of which is shown in Fig. 1a. OM

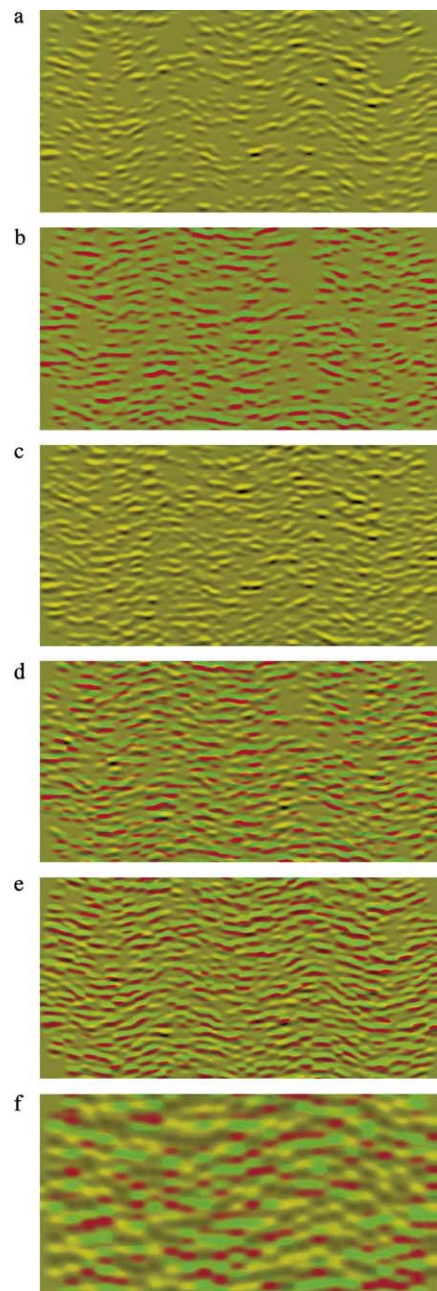


Fig. 1. Example portions of OM gratings used in the experiments (the actual stimuli were circular as shown in Fig. 2). Stimuli were comprised of (a) isochromatic gabors (amplitude = 15°), (b) isoluminant gabors (amplitude = 9°), (c) isochromatic test (amplitude = 5°) superimposed on an isochromatic mask (amplitude = 15°), (d) isochromatic test (amplitude = 10°) superimposed on an isoluminant mask (amplitude = 9°), (e) isochromatic test superimposed on a chromatic mask in which luminance contrast has been added to test for luminance artifacts and (f) low spatial frequency isochromatic test and isoluminant mask gabors with no gabor overlap. It is important to note that in stimuli containing both test and mask (i.e. c–f) the test and mask patterns are made from separate gabors. Only the envelope of the OM is spatially coincident.

gratings consist of dense arrays of elements, usually gabors or line elements, whose orientations vary sinusoidally across the display with specified amplitude,

spatial frequency and phase. A typical measure used with an OM grating is the threshold amplitude of OM, analogous to a contrast threshold obtained with a luminance-defined grating. OM gratings are useful for studying sensitivity to orientation gradients (Kingdom et al., 1995; Kingdom & Keeble, 1996, 1998, 2000; Gray & Regan, 1998; Kwan & Regan, 1998); orientation gradients are important to vision since they arise in the retinal-image projection of any non-planar textured surface and are therefore powerful perceptual cues to surface shape (Gibson, 1979; Cutting & Millard, 1984; Stevens, 1988; Knill, 1998, 2001; Li & Zaidi, 2000).

A conventional method for establishing whether two stimuli are detected by the same mechanism is to measure detection thresholds of one stimulus—the ‘test’—in the presence of various amplitudes of the other stimulus—the ‘mask’. If the mask is close to, or below, its own threshold, and one observes that the test is more easily detected than when presented alone, then this suggests that the mask and test are processed by the same mechanism.¹ On the other hand, an absence of facilitation in the near-sub-threshold region of the mask suggests that mask and test are detected by different mechanisms. Facilitation in the near-sub-threshold region produces the well-known ‘dipper’ associated with the function relating luminance-contrast increment thresholds with pedestal luminance contrast (Campbell & Kulikowski, 1966; Legge & Foley, 1980; Foley & Legge, 1981; Ross & Speed, 1991; Foley, 1994). This method has been used to test for mechanism independence in a number of domains, for example in the detection of luminance versus colour modulated patterns (Switkes et al., 1988; Mullen & Losada, 1994; Gowdy, Stromeyer, & Kronauer, 1999; Foley & Chen, 1999; Chen et al., 2000), luminance versus contrast modulated patterns (Schofield & Georgeson, 1999), edges versus bars (Burr, Morrone, & Spinelli, 1989), and one type of texture modulation versus another (Kingdom & Hayes, 2000). The last of these studies is particularly relevant as it demonstrated with OM gratings sub-threshold facilitation in the function relating threshold increment amplitude to pedestal amplitude. This suggests a potential method for testing whether texture-sensitive mechanisms additively combine colour and luminance information. If one measures test thresholds for an OM grating made from colour-defined elements in the presence of a mask made from luminance-defined elements, and vice-versa, the presence of sub-threshold facilitation would imply that texture-sensitive mechanisms add-

itively combine local colour and luminance information. On the other hand, an absence of sub-threshold facilitation would imply that texture-sensitive mechanisms access colour and luminance information independently.

2. Methods

2.1. Subjects

Five subjects were employed. One subject was one of the authors, PP, and the remaining four subjects were naive to the purpose of the investigations. All had normal or corrected-to-normal acuity and colour vision (100% on Dvorine Plates). In accordance with the tenets of the Declaration of Helsinki, informed consent was obtained from each participant before testing.

2.2. Stimuli

2.2.1. Generation and calibration

The stimuli were generated by a VSG 2/3 videographics board (Cambridge Research Systems) and presented on a flat-screen colour monitor (Sony F500 Trinitron). Only the red and green phosphors were used to construct the isoluminant red–green and isochromatic yellow–black stimuli. The displays were generated using linearized gamma-corrected colour look-up-tables (CLUTs), created by suitable selection of eight bit (256 intensities) from 12 bit (1024 intensities) digital-to-analog converters, following calibration with a photometer (model OP200-E, Cambridge Research Systems). In the CLUT for the isochromatic yellow–black display, the intensities of the red and green guns were set at equal steps in luminance. In the CLUT for the red–green isoluminant display, one of the two (red or green) LUTs was inverted. In both the isoluminant and isochromatic displays, the background of the stimuli was a uniform yellow. Maximum screen luminance was 27 cd m⁻².

2.2.2. Gabor micropatterns

Gabor micropatterns were generated by multiplying a cosine function by a two-dimensional gaussian envelope:

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

In Eq. (1), a is amplitude or contrast, f spatial frequency, θ orientation, and σ the space constant of the gaussian envelope. In the first two experiments, f was set to 3.5 cpd at a viewing distance of 100 cm and σ to 0.11°, giving the gabors a spatial-frequency bandwidth at half-height of 1.5 octaves. The isochromatic (yellow–black) gabors had in-phase modulations of the red (r) and green (g) phosphors:

¹ The exact cause of the dipper function remains contentious. It is believed to be due either to a threshold (i.e. accelerating) non-linearity (Foley & Legge, 1981) or uncertainty reduction in the channels that transduce the stimulus (Pelli, 1985). However, for the purposes of the present investigation the precise cause of the dipper function is immaterial.

$$\begin{aligned} r &= r_{\text{mean}}(1 + g(x, y, \theta)) \quad \text{and} \\ g &= g_{\text{mean}}(1 + g(x, y, \theta)) \end{aligned} \quad (2)$$

while the isoluminant (red–green) gabors had opposite-phase modulations of the red and green phosphors:

$$\begin{aligned} r &= r_{\text{mean}}(1 + g(x, y, \theta)) \quad \text{and} \\ g &= g_{\text{mean}}(1 - g(x, y, \theta)). \end{aligned} \quad (3)$$

2.2.3. OM gratings

These comprised 1000 gabors, which could all be isochromatic (e.g. Fig. 1a) or all isoluminant (e.g. Fig. 1b). The diameter of each stimulus pattern was 8.6° at a viewing distance of 100 cm. The positions of all gabors were random. The orientations of gabors varied sinusoidally (3.0 cycles/display) along the horizontal axis of the display and the phase of the OM was randomly chosen on each trial. The amplitude of OM described by how much the orientation of the gabors changed from the mean, which was horizontal, to the peak, or trough of the waveform. On each trial, a test grating was presented simultaneously with a mask grating of identical spatial frequency and phase. The amplitudes of OM of the test and mask gratings were independently controlled. The envelopes of the test and mask gratings were spatially coincident but since the positions of the gabors were random, the individual test and mask gabors were not coincident (see Fig. 1c and d for examples). The dependent measure was the amplitude of the OM for the test grating. There were four conditions: (a) isochromatic test on an isochromatic mask (uncrossed luminance-test condition—see Fig. 1c); (b) isochromatic test on an isoluminant mask (crossed luminance-test condi-

tion—see Fig. 1d); (c) isoluminant test on an isoluminant mask (uncrossed chromatic-test condition); (d) isoluminant test on an isochromatic mask or (crossed chromatic-test condition).

2.3. Procedure

A two-interval forced choice procedure was used to measure the threshold amplitude of OM. On each trial two displays were presented, each for 200 ms, with a 1 s inter-stimulus interval. The only difference between the stimuli in the two intervals was the amplitude of OM of the test, which was zero in one interval. The same mask amplitude was presented in both intervals. Examples of two stimulus patterns presented in the two intervals of a given trial are shown in Fig. 2. Participants were asked to indicate which interval contained the stimulus with the larger perceived amplitude of OM. Each session began with a test amplitude greater than threshold and feedback as to the correctness of responses was given. Threshold amplitudes were estimated using a one-up two-down staircase procedure (Levitt, 1971) with a step size of 2 dBs (or a factor of 1.25), producing thresholds at the 70.7% correct level. The staircase procedure was terminated after 12 reversals, and the threshold calculated as the geometric mean amplitude taken across all trials excluding those up to the third reversal. Five thresholds were measured for each of seven mask amplitudes (0° , 3° , 6° , 9° , 12° , 24° and 48°) and for each of the four conditions giving a total of 140 thresholds per experiment. Thresholds were collected in pseudo-random order. The mean and standard error of the

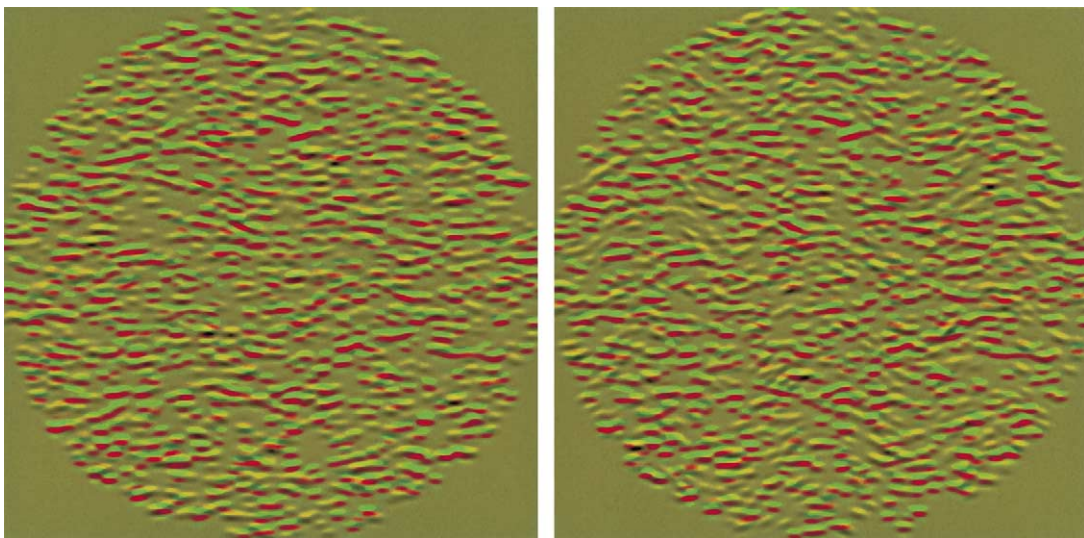


Fig. 2. Example stimulus pair that might be presented during the two intervals of a trial in the crossed luminance-test condition. The test OM grating is made from isochromatic gabors and the mask OM grating made from isoluminant gabors. In the stimulus on the left the amplitude of the isochromatic test grating is zero, whereas on the right it has an amplitude of 20° . The 5° amplitude of the isoluminant mask grating is the same in both stimuli. Participants were asked to identify the interval with the highest perceived amplitude of OM.

threshold estimates was calculated and these are shown in all figures.

2.3.1. Isoluminance

There are significant differences in the isoluminant point between individuals, so isoluminance was measured for each subject using the criterion of ‘worst performance’ (e.g. Kingdom & Simmons, 1996). OM thresholds were measured for stimuli made from gabors of 50% contrast, but whose $R/(R+G)$ ratios ranged from 0.35 to 0.65. The plot of thresholds versus $R/(R+G)$ ratio was fitted with a gaussian function using IGOR (Wavemetrics), and the $R/(R+G)$ ratio producing the highest threshold estimated. The isoluminant points determined in this way were 0.47, 0.42, 0.53, 0.47, and 0.44 for participants PP, S2, S3, S4 and S5. For two subjects, PP and S5, a minimum flicker technique was used to confirm the isoluminant point. In this technique, the $R/(R+G)$ ratio producing minimum perceived flicker was determined when the red and green CLUTs were exchanged at a rate of 30 Hz. The mean of 10 settings was taken to be the isoluminant point. This produced isoluminant $R/(R+G)$ ratios of 0.465 for PP and 0.435 for S5, which were very close to those found with the criterion of worst performance.

2.3.2. Equivalent contrasts

When defined in terms of the Michelson contrast of phosphor modulation, luminance and colour contrasts are not directly comparable. To enable the isochromatic and isoluminant conditions to be compared, we set the gabor contrasts to produce equal performance at an orientation acuity task using a stimulus closely comparable to the OM gratings used in the main part of the study. The stimulus consisted of 1000 randomly positioned gabors whose orientations were drawn randomly from a distribution with specified variance (i.e. there was no sinusoidal modulation of orientation). The minimum variance of orientations that allowed the stimulus to be reliably discriminated from a pattern with zero orientation variance was measured for patterns comprised of gabors of varying luminance or colour contrast. For all three subjects, contrast levels that produced equal orientation-variance discrimination thresholds were 30% and 60% for the luminance and colour patterns, respectively. This two-fold difference in contrast sensitivity is similar to that observed for single-element orientation discrimination by McIlhagga and Mullen (1996). These contrasts were used in all subsequent investigations.

2.4. Data analysis: model

Dipper functions were fitted to our threshold-versus-amplitude (TvA) data using the following model taken from Legge and Foley (1980):

$$F = a_1|r|^{2.4}/(|r|^2 + a_2^2) \quad (4)$$

In Eq. (4), F represents the response of the non-linear transducer, r the input to the non-linear transducer (here the amplitude of OM), a_1 a constant of proportionality and a_2 a parameter that determines the range of input that lies in the positively accelerating and compressive regions of the non-linearity. In one interval, the test has an amplitude of zero and the mask amplitude alone determines r . In the other interval (assuming an input to a common mechanism for both luminance and chromatic stimuli), r will be determined by the amplitude of both the mask and test. Thresholds are reached when there is a difference between the response of the non-linear transducer to the mask alone and to the mask-plus-test. The values of a_1 and a_2 that produced the smallest chi-square are shown in the figures.²

3. Results

3.1. Detection of OM in the presence of orientation modulation masks

In the first experiment, we measured the TvA functions in two crossed and two uncrossed conditions. The TvA functions obtained for five observers are shown in Fig. 3. Both test and mask values are shown in threshold units: test amplitudes were divided by the threshold for the test pattern in the presence of a zero amplitude mask pattern, while mask amplitudes were divided by the threshold for the mask in the presence of a zero amplitude test. The pooled results for the five subjects are fitted (shown as a thick line in Fig. 3) with the non-linear transducer function of Legge and Foley (1980). The results obtained in the two uncrossed conditions (isochromatic test on isochromatic mask; isoluminant test on isoluminant mask) shown in the left panels are quite similar. Both uncrossed conditions exhibit a significant dipper function, showing sub-threshold facilitation between mask and test (approximately twofold). The dipper functions in both uncrossed conditions reach a minimum at approximately the threshold for the mask, shown by the vertical line in each plot. These results for the detection of OM mirror those found previously for the detection of luminance and chromatic contrast (Cole et al., 1990; Losada & Mullen, 1994; Switkes et al., 1988), where maximal facilitation ranging in magnitude from a one-and-a-half to a two-fold decrease in

² Although parameters a_1 and a_2 interact, producing a set of solutions that produce similar chi square values for the goodness of fit of the functions, the set of these values results in fits that are not significantly different from those depicted. That is, our choice of available values of a_1 and a_2 has not significantly affected our conclusions.

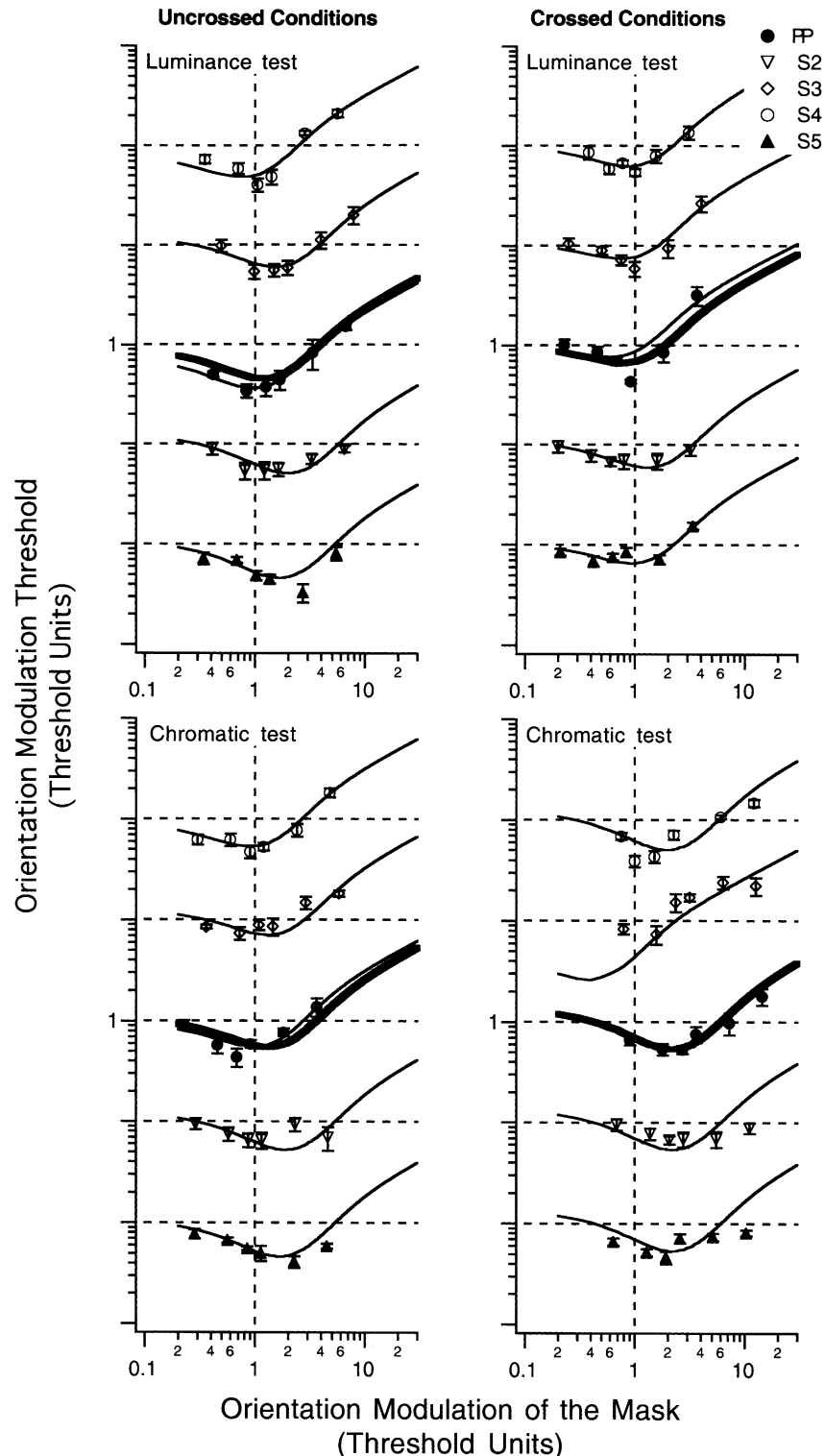


Fig. 3. Results of main experiment. Each panel shows OM thresholds as a function of mask OM. Axes are scaled in multiples of threshold: for the test, in the presence of a mask with zero amplitude (vertical axis), for the mask in the presence of a test with zero amplitude (horizontal axis). Each panel shows data from five observers. The thin lines are the best fit of the Legge and Foley (1980) model to each subject's data, and the single thick line is the best fit to the pooled data (see text for further description). All thresholds fall in the range of 0.1–10 as shown for the curves centered around the ordinates of 1. Error bars represent the standard error of the mean. The left panels show thresholds for the uncrossed conditions in which test and mask were made from the same type of gabors: isochromatic (top) and isoluminant (bottom). The right panels are for the crossed conditions: isochromatic test and isoluminant mask (top), isoluminant test and isochromatic mask (bottom).

thresholds was observed for mask amplitudes between one and two times mask threshold. This being said, there is an important difference with studies of contrast detection besides the dependent variable that makes the result here especially non-trivial. Whereas in contrast detection studies the colour and luminance variations are spatially coincident, our mask and test OMs are carried by separate, non-spatially-coincident (except by chance) gabors; only the envelope of the OM is spatially coincident. Yet in spite of the test and mask gabors being separate, it would seem that their orientation information is pooled. Indeed the dipper found here in the uncrossed conditions is comparable to that obtained with OM gratings when the test is an *increment* in amplitude and the mask a *pedestal* amplitude (Kingdom & Hayes, 2000).

Given that the uncrossed conditions demonstrate that the particular form of the simultaneous masking paradigm employed here shows a dipper function, we now examine the results for the crossed conditions. TvA functions for the crossed conditions are shown in the right panels of Fig. 3. The top panel illustrates the thresholds obtained for a luminance test on a chromatic mask (crossed luminance-test condition) and the bottom panel illustrates thresholds for a chromatic test on a luminance mask (crossed chromatic-test condition). In the crossed luminance-test condition, sub-threshold facilitation is evident (≈ 1.5 -fold decrease) and the minimum point of the dipper occurs for an OM amplitude approximate to the threshold for the mask (vertical line) in 4/5 of the participants. In the crossed chromatic-test condition, the magnitude of the facilitation is approximately twofold. The magnitude of the facilitation at the threshold for the mask is similar to that obtained in the crossed luminance condition (≈ 1.5 -fold decrease). However, the minimum of the TvA function occurs for amplitudes twice that of the threshold for the mask, suggesting suprathreshold rather than sub-threshold facilitation. The mechanism responsible for these interactions is elaborated upon in the discussion section.

3.2. Luminance artifacts

The simplest explanation for the result with the crossed luminance-test condition is that the ostensibly isoluminant gabors were contaminated with significant amounts of luminance contrast, most likely as a result of chromatic aberration. To test for this possibility, we conducted two control experiments. In the first, we measured thresholds in the crossed luminance-test condition using chromatic mask gabors with various added amounts of luminance contrast (Fig. 1e). The rationale for this is that if the chromatic gabors contained artifactual luminance contrast, then a suitable amount of added luminance contrast should cancel the artifact and eliminate the sub-threshold facilitation evident in the

previous experiment. However, elimination of the sub-threshold facilitation at the chromatic mask threshold might also be expected for another reason. The addition of luminance contrast to an isoluminant mask could elicit a response in a luminance mechanism that was then pooled with that from the luminance-defined test pattern. In this case, the minimum of the dipper would be expected to shift to the left since the OM thresholds for isochromatic gabors are less than those for isoluminant gabors. As is demonstrated in Fig. 4, such a leftward shift would also lead to an elimination of sub-threshold facilitation at the threshold for the isoluminant pattern.

In this experiment, the mask gabors were generated by combining luminance- and colour-contrast, in-phase to produce dark-red light-green gabors and opposite-phase to produce light-red dark-green gabors, using 0%, 5%, 10%, 15% and 20% added luminance contrast. Two of the three subjects exhibited normalized thresholds near unity, i.e. no apparent sub-threshold facilitation, when 5% luminance contrast was added in phase to the chromatic mask gabors at the OM threshold for the chromatic mask. To determine which of the two alternative explanations given above could account for the

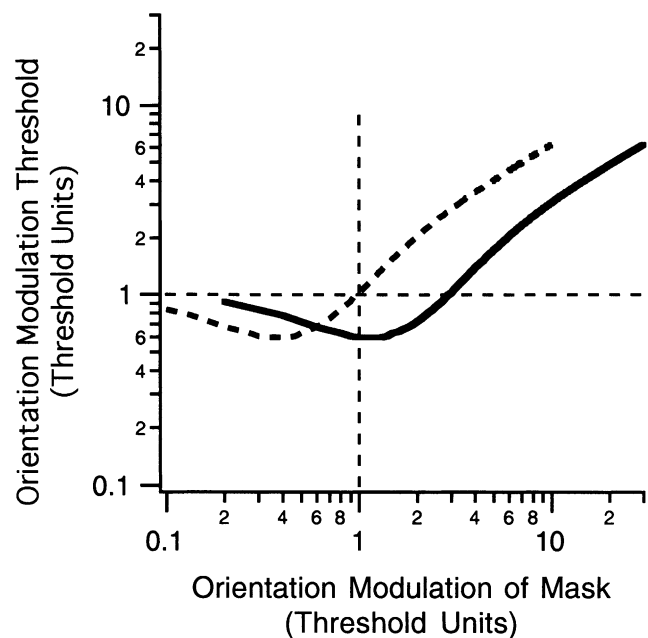


Fig. 4. Effect of a leftward shift in the dipper function. The solid line illustrates a dipper shaped function drawn using Legge and Foley (1980) non-linear transducer (see text for more details), while the broken line illustrates the result of shifting the function to the left. Such a shift may eliminate any evidence of sub-threshold facilitation when the mask is set equal in amplitude to its own threshold. Since the OM threshold for an isoluminant pattern was found to be approximately twice that for an isochromatic pattern, the addition of a substantial amount of luminance contrast to the chromatic mask gabors could be anticipated to produce a leftward shift in the isochromatic test function similar to that depicted here.

elimination of sub-threshold facilitation, we then measured OM thresholds for two mask amplitudes: one equal to the threshold for an isoluminant mask and one equal to the threshold for an isochromatic mask. OM thresholds using the ostensibly isoluminant chromatic gabors (0%) and the chromatic gabors with 5% luminance contrast added are shown in Fig. 5. Although the addition of a 5% luminance artifact to the chromatic gabors eliminated the facilitation at the chromatic mask threshold, it would appear that this is due to a leftward shift in the TvA function rather than a loss of facilitation. This result is not consistent with a luminance artifact being responsible for the sub-threshold facilitation in the crossed conditions.

The second experiment we ran to test for luminance artifacts involved changing the stimulus parameters to minimize any influence of chromatic aberration. Chromatic aberration is believed to be reduced by lowering the spatial frequency of the stimuli (Bradley, Zang, & Thibos, 1992; McIlhagga & Mullen, 1996; Mullen et al., 2000). We therefore reduced the spatial frequency of our gabors to 1.5 cpd. With a space constant of 0.17° , these gabors had a spatial frequency bandwidth at half-height of 2.5 octaves. In addition, the stimuli were presented with an on-and-off temporal ramp of 100 ms to minimize any temporal transients. Due to the increased size of the gabors, the number of gabors was reduced to 500. The spatial frequency of OM was set to 1.5 cycles/display, or 0.17 cpd. In addition, the gabors were positioned on a grid (± 10 pixels jitter) such that no gabors overlapped (Fig. 1f). Each grid location was randomly assigned either a gabor from the test or a gabor from the mask (250 each). Thresholds were only measured for the uncrossed and crossed test luminance-test conditions.

Fig. 6 shows results for two observers (PP and S5). The figure shows that a decrease in the spatial frequency of the gabors or a change in the spatial arrangement of the gabors has not significantly affected the amount of sub-threshold facilitation in the crossed luminance-test condition. An approximate two-fold decrease in the OM thresholds is obtained for both of the observers.

4. Discussion

In this study, we utilized a conventional sub-threshold facilitation paradigm to decide whether texture-orientation mechanisms independently access colour and luminance contrast information, or pool that information. Our results suggest the latter. We observed sub-threshold facilitation between colour and luminance in the detection of OM, and control experiments demonstrated that the facilitation was unlikely to be caused by luminance artifacts.

The OM gratings used in this study are examples of what for many are second-order stimuli; that is, stimuli

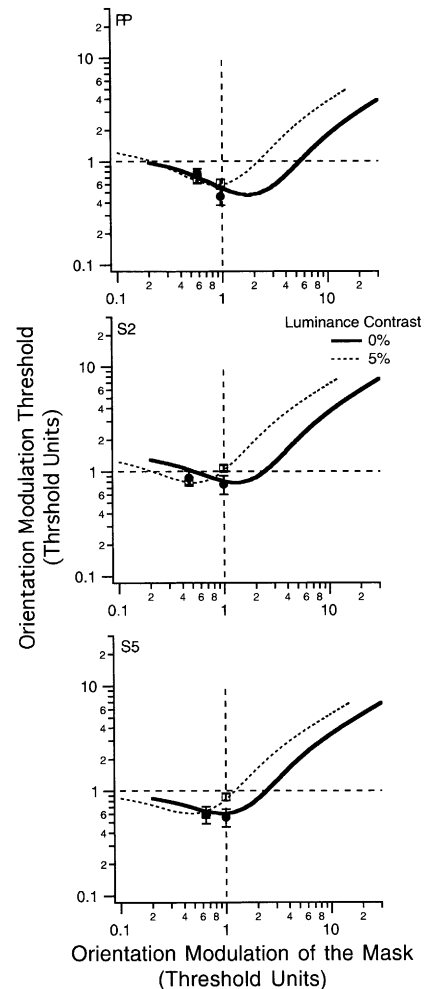


Fig. 5. Results from the first control experiment to test for luminance artifacts. OM thresholds are shown for an isochromatic test on a chromatic mask, for three subjects. The solid line and filled circles on each plot represent the thresholds obtained when the chromatic gabors were ostensibly isoluminant (0% added luminance contrast). With the exception of one of the subjects (PP), the solid lines shown represent the fits of the Legge and Foley (1980) model to the crossed luminance test condition in the previous experiment (shown the upper right panel in Fig. 3). For PP, we have allowed the model to determine the best fit to the two points in the 0% condition. The open symbols represent the thresholds obtained when 5% luminance contrast was added to the chromatic gabors. To determine whether the results reflected a leftward shift of the dipper function, the fits for the 5% added luminance condition were constrained to be the same shape as those obtained in the 0% condition, and permitted to shift horizontally to obtain the least squares fit (shown by the broken line). For PP, a vertical shift in the function was also required to account for the data in the 5% luminance contrast condition. The magnitude of the leftward shift was approximately the difference between the OM thresholds for the isochromatic and isoluminant masks determined for each subject. Error bars represent the standard error of the means.

modulated in something other than luminance or colour. The sub-threshold facilitation obtained in the uncrossed conditions in this study supports the idea that there exist specific mechanisms for detecting OM (Kingdom, Hayes, & Keeble, submitted; Kingdom et al.,

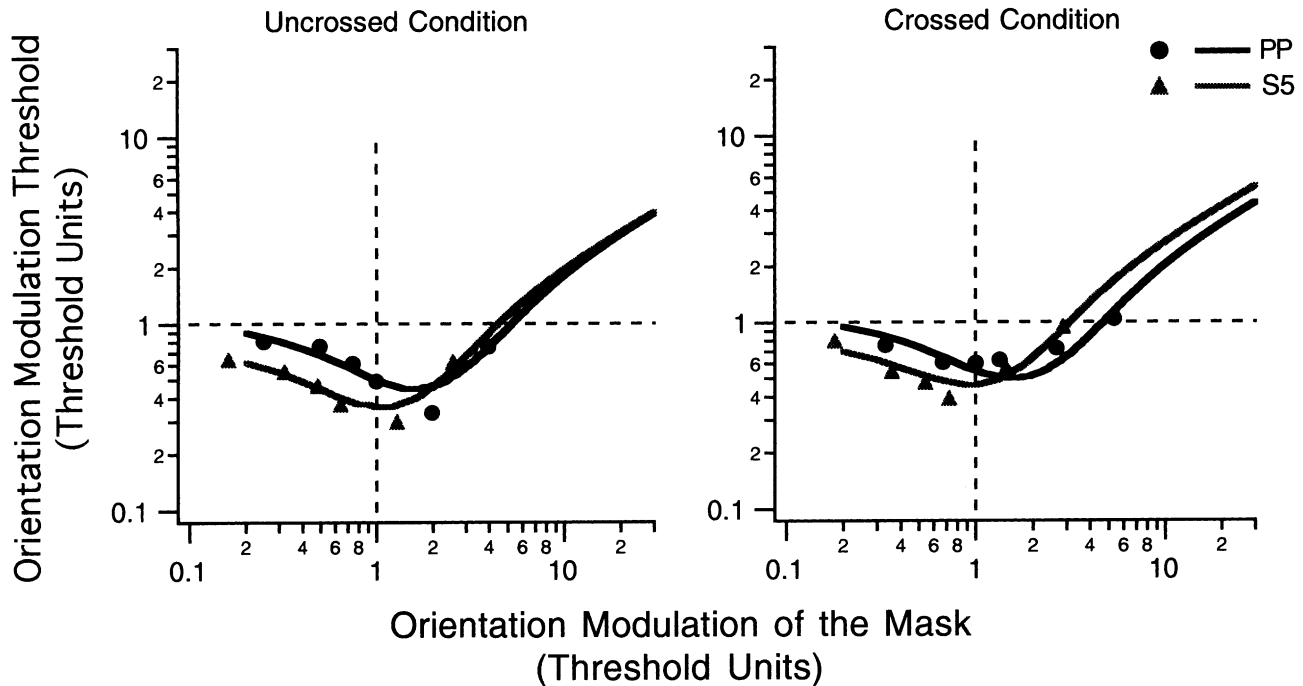


Fig. 6. Results for OM gratings using low spatial frequency gabors positioned on a grid to prevent overlap (see Fig. 1f). OM thresholds are shown for an isochromatic test on both an isochromatic (left panel) and isoluminant (right panel) mask. Best fit functions based on the model of Legge and Foley (1980) are shown for two subjects (PP: gray line; S5: black line). Each threshold represents the average of five estimates. Error bars represent the standard error of the mean.

1995; Kingdom & Keeble, 1996, 2000; Kwan & Regan, 1998; Prins & Kingdom, in press). The method used here of combining modulations defined by different carriers could in principle be extended to a variety of second-order stimuli, in order to determine what sorts of features are pooled by second-order mechanisms, what sorts of features are accessed separately, and what is the precise carrier tuning of those second-order mechanisms.

We found that OM thresholds in the crossed luminance-test condition were less affected by chromatic masks than chromatic-test thresholds were by luminance masks. Interestingly, the analogous asymmetry has been observed in the contrast detection domain (Cole et al., 1990; Mullen & Losada, 1994; Switkes et al., 1988). In our crossed luminance-test condition, 4/5 subjects showed facilitation at and below the threshold for the chromatic mask and evidence of sub-threshold facilitation was illustrated in both the control experiments described. These results are consistent with the hypothesis that the mechanism that detects the OM in our stimuli additively combines local luminance and chromatic information.

For the crossed chromatic-test condition, the evidence for non-independence is less clear. Sub-threshold facilitation ($1.5\times$ improvement) was exhibited by 3/5 participants in the crossed chromatic-test condition. The maximum facilitation in this condition occurred for

masks with amplitudes approximately twice the OM threshold for the mask. Suprathreshold facilitation when mask amplitudes are two times mask thresholds have been interpreted as being consistent with independent mechanisms when obtained in crossed conditions (Cole et al., 1990; Switkes et al., 1988), but consistent with a common mechanism when obtained in uncrossed conditions (Mullen & Losada, 1994; Switkes et al., 1988). Thus, the significance of the facilitation in our crossed chromatic-test conditions remains unclear.

It is possible that the suprathreshold facilitation in the crossed chromatic-test condition may have been due to the introduction of local cues, as has been suggested for analogous findings in some contrast detection studies (Cole et al., 1990; Mullen & Losada, 1994; Switkes et al., 1988). The presence of any indicator of the location of the stimulus (i.e. outline, arrow) has been shown to reduce thresholds (Boynton, Hayhoe, & MacLeod, 1977; Cole et al., 1990; Gowdy et al., 1999; Montag, 1997). Gowdy et al. (1999) have reported that the presence of luminance edges may facilitate the detection of chromatic contrast by demarcating the different parts of the stimulus and hence enhancing their discriminability. The possibility that such cues play a role in facilitating performance arises anytime stimuli are suprathreshold in the critical dependent variable. In our stimuli, the envelope structure of the mask and test were spatially coincident, and hence a suprathreshold mask might have

provided local cues to aid discrimination of the different regions of the test.

It has been suggested that second-order stimuli such as OM gratings are detected by mechanisms that can be modelled as filter-rectify-filter (FRF) operators (Fogel & Sagi, 1989; Malik & Perona, 1990; Rubenstein & Sagi, 1990; Landy & Bergen, 1991; Graham & Sutter, 1998). While the specific details of FRF models vary, all consist of two stages. The first stage involves the construction of filter-response energy maps at each scale and orientation from the non-linearly transformed (e.g. full-wave rectified) responses of linear, simple-cell-like filters. In the second stage, filters with larger receptive fields than their first stage counterparts detect any differences in energy between adjacent regions of the texture. Psychophysical studies have shown that both the first and second stages of texture-modulation detection mechanisms are tuned to both orientation and spatial frequency (Sutter, Sperling, & Chubb, 1995; Arsenault, Wilkinson, & Kingdom, 1999; Dakin & Mareschal, 2000; Kingdom & Keeble, 2000; Prins & Kingdom, in press). The most parsimonious interpretation of the results of the present study is that while the individual texture elements might be detected by different post-receptoral mechanisms, specifically the cone-subtractive red–green and the cone-additive luminance mechanisms, the outputs of these first-stage mechanisms are pooled indiscriminately by the second stage. An independent first stage and a non-independent second stage have also been proposed for contour integration (McIlhagga & Mullen, 1996; Mullen et al., 2000). Further studies are needed to determine if the absence of tuning along the colour/luminance dimension is a general property of second-order mechanisms, or specific to the detection of OM.

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