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Corner effect in induced hue: Evidence for chromatic band-pass filters

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Abstract—An experiment is described which investigates the spatial determinants of the apparent difference in hue between the central grey patches of chromatic 'H' pattern pairs, an effect similar to that first demonstrated by Wright (1969, *The Measurement of Colour*, Hilger, London) in coloured gratings. The hue difference is shown to be analogous to the brightness difference in achromatic 'H' patterns demonstrated by Moulden and Kingdom (1989, *Vision Res.* **29**, 1245–1259). The origin of both effects is argued to be the presence of the corner intersections in the 'H' patterns, which are powerful stimuli for cells with circularly-symmetric, centre-surround organization. It is suggested that the results of the experiment with the chromatic 'H' patterns implicates the operation of cells with a spectrally double-opponent, rather than single-opponent receptive field organization.

INTRODUCTION

Recently Moulden and Kingdom (1989a) provided evidence that corners can have a particularly powerful effect on the brightness of adjacent regions (a finding also obtained by Morgan and Ward (pers. comm.)). This conclusion was arrived at after an investigation into the cause of the brightness difference observed between the grey patches in pairs of 'H' patterns, an example pair of which is shown in the lower half of Fig. 1. An 'H' pattern pair consists of two stimuli, each of which consists of three vertical bars alternating in square-wave sequence, two 'flanking' bars on either side of a middle 'coaxial' bar, and a grey square patch situated midway down the coaxial bar. The two patterns forming the pair differ only in the phase of the alternating sequence: they are referred to as BWB (black–white–black) and WBW (white–black–white) respectively. The grey patch in the BWB stimulus appears darker than the identical grey patch in the WBW stimulus, the effect increasing with viewing distance. To demonstrate the critical feature underlying the brightness difference in the H patterns, examine the pair of 'cruciform' patterns in the upper half of Fig. 1 which may be considered to be component parts of the H patterns. The two cruciform patterns are identical except for orientation, and, as one might expect, their grey patches are equally bright. It therefore follows that the salient feature in the H pattern is that portion of the flanking bars which extends vertically above and below the flanks of the component cruciform. Morgan and Ward (pers. comm.) have shown that it is the presence of the *corner intersections* of the flank and coaxial bars with the central grey patch that are responsible for the effect, and more recently we have confirmed their findings (Moulden and Kingdom, 1989a).

Corners are powerful stimuli for centre-surround, circularly symmetric receptive fields such as those of ganglion cells in the mammalian retina. Figure 2 shows the receptive fields of four on-centre cells positioned in the four corner intersections in a

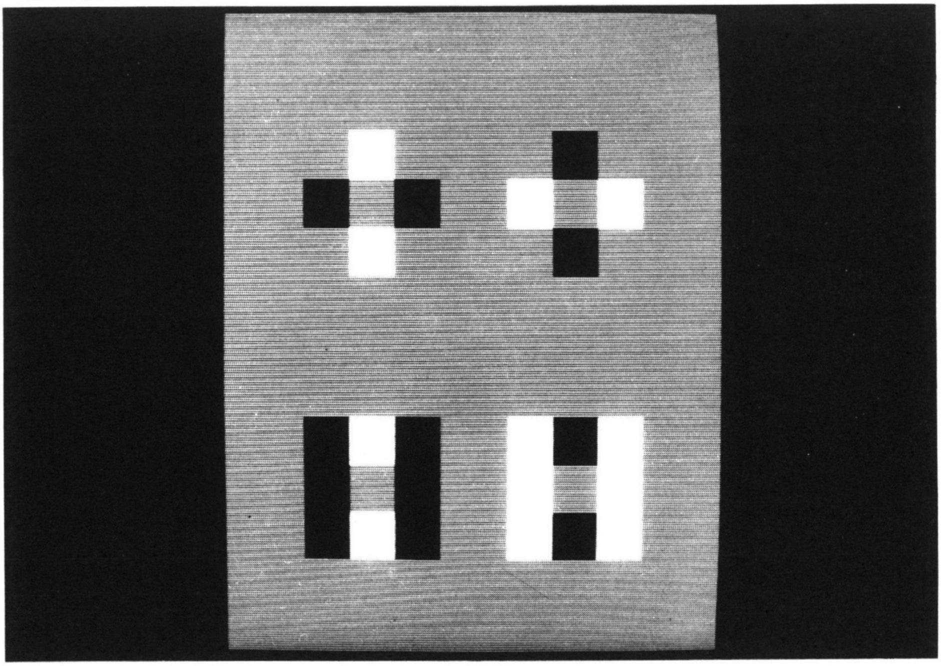


Figure 1. Cruciform (top) and H pattern (bottom) pairs. Top left = cruciform BWB, top right = cruciform WBW, bottom left = H BWB, bottom right = H WBW (W = white, B = black). In the H patterns, the central grey patch appears darker in the BWB condition than in the WBW condition. The effect increases with viewing distance. The effect is absent (or if anything slightly reversed for some observers: see Moulden and Kingdom, 1989b) in the cruciform conditions, demonstrating that the extended flanking bars are responsible for the effect in the H patterns.

BWB H pattern. The strong response occurs because in these positions, and only in these positions, a substantial proportion of each receptive field surround falls within the extended flank bar *and* the grey patch, thus releasing inhibition from the cell to a greater extent than when the receptive field is positioned anywhere else along the border of the grey patch. In otherwords 'hot-spots' would occur in these corner positions in the neural image produced at the ganglion cell level, as shown by the convolution demonstration in Moulden and Kingdom (1989a). Similar 'hot-spots' of maximal activity would appear in the response of off-centre units in the WBW stimulus.

We suggest (following Morgan and Ward) that it is these 'hot-spots' that cause the brightness difference in the H patterns. This argument rests on two assumptions. The first is that the brightness of a region is to a large extent determined by the contrast of that region at the border with its surround. The second is that the output of the ganglion cell layer, since it carries information about the pattern of luminance discontinuities in the visual input, is the carrier of contrast information, even though that information may not be made explicit until a later, cortical, stage to which the ganglion cell layer is input. As a rule of thumb one can say that the contrast of an edge, as encoded at the retinal level, is given by the difference in response of ganglion cells on each side of the edge (since when the cell is centered on the edge its response is zero). The 'hot-spots' in the corners of the neural image of the H patterns would therefore

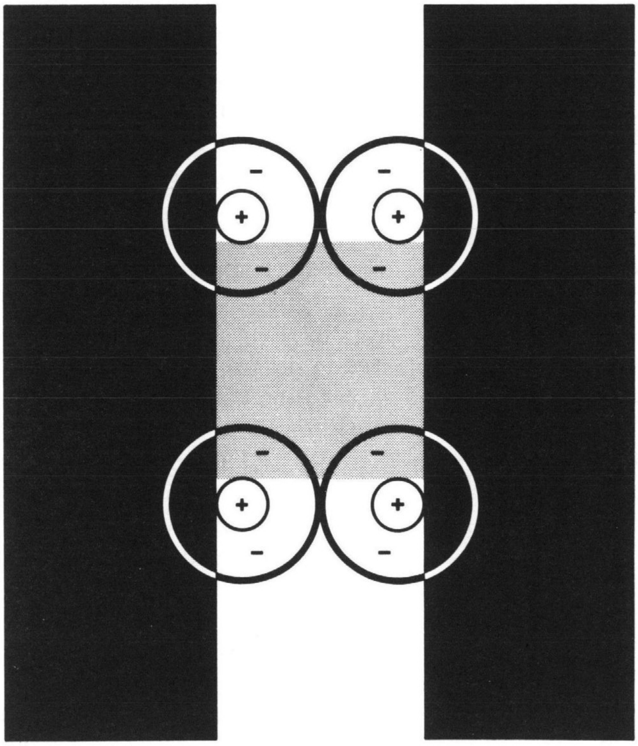


Figure 2. Receptive fields of retinal ganglion cells positioned in the corner intersections of H pattern, where they are strongly stimulated. See text for further details.

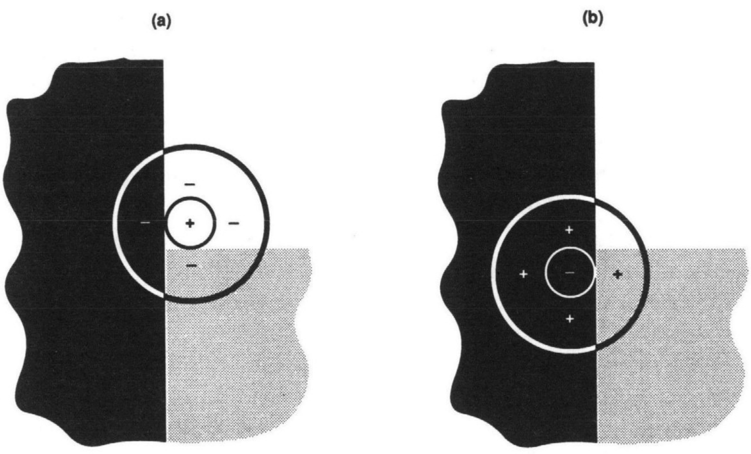


Figure 3. The critical comparison is the relative response of ganglion cells in the two positions shown, compared with when the cells are located mid-way along the borders of the surround bars with the grey patch. (a) on-centre cell on the white coaxial bar, (b) off-centre cell on the flank bar. In these positions both cells would give a positive response, but the difference (a – b) between them would be greater in magnitude than any difference that existed in their mid-border positions.

contribute an unusually large signal towards the internal contrast response for the coaxial bar–grey patch border taken as a whole, compared with the case where 'hot-spots' are absent (as in the cruciforms). This extra large signal on the coaxial bar–grey patch border effectively weights the coaxial bar in its contribution to the brightness of the grey patch through border contrast. Thus the grey patch in the BWB pattern, because its coaxial bar is white, appears darker than the grey patch in the black coaxial, WBW pattern. If one supposes that on- and off-centre ganglion cells respectively carry the positive and negative components of the convolution image, the absolute difference between the (opposite) effects of the coaxial and flank bars will be determined essentially by the difference in output of the two cells whose receptive fields are positioned as in Fig. 3. At all other locations along the grey patch border the pattern of off and on cell activity will be balanced in the two H patterns.

The evidence in support of this explanation comes from a series of experiments conducted by Moulden and Kingdom (1989a). In one experiment they measured the brightness of the grey patch in both WBW and BWB H patterns as a function of flank height while the height of the coaxial bar was fixed. They found that as the flanks were extended vertically from their baseline, cruciform, condition there was a sharp change in the brightness of the test grey patch which reached an asymptote once the size of the flank increment either above or below the cruciform flank height was between about 6–12 arcmin. This asymptotic value was constant regardless of the height of the grey patch. One would expect according to the corner story that as the flank filled up the surround of the receptive fields positioned as in Fig. 2. the brightness of the grey patch would change. Once the surround was filled there should be no further change in the brightness of the test patch. The value of 6–12 arcmin would imply that the surround of the receptive field was in the region of 9–18 arcmin which is consistent with current estimates of the width of the line spread function obtained from bar detection thresholds (for example approximately 16 arcmin according to Hines, 1976).

Using stimuli of the same basic form as the one described above, Wright (1969) demonstrated a phenomenon that may be the chromatic equivalent of the achromatic effects we have described. In his demonstration (p. 87), various coloured square patches were placed on both the yellow and blue phases of a yellow–blue square-wave grating. When viewed at a suitable distance, a given coloured patch appeared different in hue depending on the phase on which it was positioned. Although Wright provided no quantitative measurements of the magnitude of the hue differences in his demonstration, he cites an unpublished study by Gindy (1963) in which quantitative measurements were made. On the basis of Gindy's findings Wright (p. 53) suggested that the effects in his demonstration were "···probably due to a combination of effects e.g., contrast, light scatter in the eye, chromatic aberration in the eye, eye movements and local adaptation".

We have been unable to obtain copies of the work of Gindy (1963) and we describe here some quantitative experiments of our own which we conducted in order to discover whether the chromatic induction effect is also susceptible to an explanation in terms of the corner effect. The H pattern pairs we employed may be regarded as the components of a chromatic grating containing grey square test patches on both phases, producing a stimulus whose critical features are very similar to Wright's (1969) stimulus.

METHOD

Stimulus generation

All stimuli were generated by an 8-bits-per-gun PLUTO II colour-graphics display system (IO Research, London) interfaced to a Corvus Concept host computer. The programs were written in PASCAL using ASM68K assembly language subroutines to interface the host and graphics computers. All luminance calibrations were performed with a purpose-built photodiode and amplifier system with a photometric filter. The aperture of the photodiode was positioned against the glass surface of the monitor over a small patch of pixels, whose RGB value had been preset.

The chromatic stimuli were displayed on a Microvitec Cub Model 1449 colour TV monitor. The CIE coordinates of the phosphors were R: $x = 0.625$, $y = 0.34$; G: $x = 0.31$, $y = 0.592$; B; $x = 0.15$, $y = 0.063$. Each pixel measured 0.61 mm in height by 0.38 mm in width subtending 1.82 and 1.13 arcmin respectively at the 114-cm viewing distance. Since there are substantial context dependent screen effects on the outputs of the three (RGB) channels in many TV monitors (Harris *et al.* 1987), all calibration measurements were performed on the component parts of the stimuli as they would appear on the screen in the actual experiment. In the hue-cancellation method employed to estimate the hue of the test patch, either one or two of the three RGB channels remained constant while the remaining channel(s) were adjusted by the subject until a neutral grey was perceived, as described below. To calibrate the luminances of each adjustable channel, the remaining two channels were set to their appropriate value as specified for the grey background, and the luminance of the test patch measured as a function of the intensity of the adjustable channel. A measure of the luminance of the adjustable channel for a given intensity level was then given by subtracting the luminance of the patch when the channel was set to zero from that of the patch at that level.

As a further check against any context-dependent screen effects producing spurious results, all experimental conditions were repeated with the surround of the grey patch occluded by white card fixed to the monitor surface. Under such conditions the subject who performed under these control conditions, FK, was unable to tell which condition was present on any trial.

It should be emphasized that the experiments reported here were essentially designed to uncover the qualitative effects of the flanking bars on the hue of the central test patch. The method employed to calibrate the intensive contribution of the three RGB channels to the luminance of the grey patch is relatively crude but perfectly adequate for the purpose of the experiment.

Subjects

The two authors acted as subjects in all the experiments described. Both were experienced psychophysical observers. FK had normal, BM, corrected vision. Both subjects had normal colour vision, obtaining 100% correct scores on Stilling's Pseudo-Isochromatic plates (Drever, 1935).

Stimuli–spatial dimensions

The stimuli employed are illustrated in Fig. 4. The baseline cruciform condition was a matrix of five square patches, consisting of a central grey test patch whose hue was the

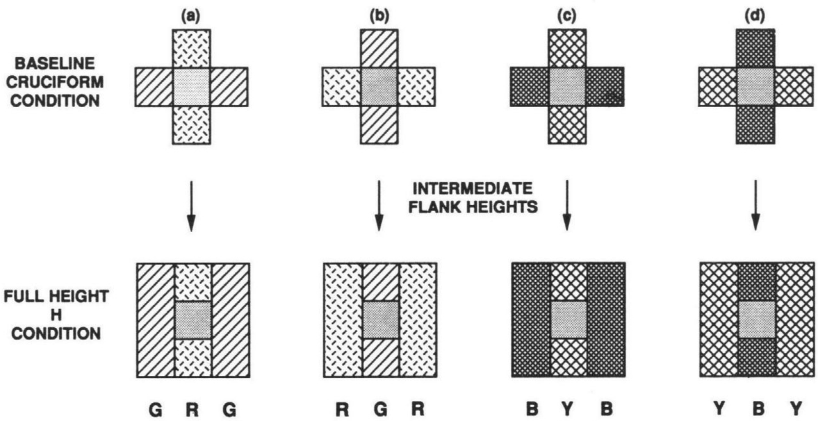


Figure 4. Stimuli employed in the experiment. The top row shows the baseline cruciform conditions, while the bottom row shows the full flank height H patterns. In between these two conditions were three intermediate flank height conditions. R = red bar, G = green bar, B = blue bar, Y = yellow bar.

dependent variable, bordered by four inducing 'arms'. Each patch was a square, 18.1 arcmin on a side. Five flank heights were employed, 18.1, 27.2, 36.2, 45.3, and 54.3 arcmin. The 1st and 5th flank height conditions represent respectively the baseline cruciform and full H patterns illustrated in Fig. 4. Flank height can also be expressed as the increment in flank height either above or below the flank in the component cruciform, in which case the values are 0, 4.6, 9.1, 13.6 and 18.1 arcmin.

Stimuli–luminance dimensions

The digital values (8 bits per channel) of the RGB channels were set as follows for the various colours employed. For the grey background and fixed channel(s) in the grey test patch, the RGB values were set by adjustment to produce a subjectively neutral grey, and the RGB levels recorded. The luminance of the grey was then measured to be 17.4 cd m^{-2}. For the surround bars, only the appropriate channel was used for the red, green and blue bars, the remaining channels being set to zero. For the yellow bars, the B channel was set to zero, while the R and G channels were adjusted to produce a saturated yellow. In the RG (red–green) H stimuli, there were two luminance conditions (a) isoluminant, as defined by minimum heterochromatic flicker and (b) non-isoluminant. In both conditions the luminance of the red bars was set to its maximum value of 16.3 cd m^{-2}. In the isoluminant condition, the luminance of the green bars was set by the method of heterochromatic flicker photometry. Using a 5 × 5 checkerboard matrix of red and green squares, each 18.1 arcmin square, the matrix was colour reversed at a rate of about 15 Hz, and the intensity of the G channel adjusted until there was minimum perceived flicker. This gave a G luminance of 27.8 cd m^{-2} at the isoluminant point for subject FK, and 19.1 cd m^{-2} for subject BM. In the second RG condition a more intensive green was employed of 55.0 cd m^{-2}. In the BY (blue–yellow) H stimuli, the luminances of the blue and yellow bars were 11.7 cd m^{-2} and 43.5 cd m^{-2} respectively.

Procedure

In all the experiments described, viewing was binocular with natural pupils. Since the test patch was small, no fixation point was necessary. The method of adjustment was employed to set the level of the channel(s) which resulted in the test patch appearing a neutral grey. At the outset of each measurement the settings for the adjustable channel(s) were randomly adjusted. During adjustment, the procedure was as follows. For the RG stimuli, both the R and G channels were adjusted together, a button press resulting in a reduction in the level of one channel and an increase in the level of the other. This kept the average intensity of the grey patch approximately constant to within a range of 6%. In the BY condition, only the B channel was adjusted: any change in average intensity of the grey patch was felt to be insufficiently large for a corresponding adjustment of the R and G values to be necessary. In all conditions, the subjects concentrated on the hue of the test patch and ignored any small changes in brightness that occurred during adjustment.

In order to prevent the build up of after-images and long-term adaptation, the stimuli were alternated with a homogeneous grey background during adjustment, with a stimulus exposure time of 1 s and an inter-stimulus-interval of 2 s.

For each condition in each experiment, five measurements were made per subject.

RESULTS

Figures 5 and 6 present the results for the RG and BY H patterns respectively. In Fig. 5, the ordinate gives the percentage difference between G-R luminance settings for the test patch and that of the background grey, while in Fig. 6 the ordinate gives the difference in the B luminance setting for the test patch and background grey. The abscissae in both figures represent absolute flank height. The two plots on each graph represent the results for the two members of each H pattern pair. The left-most data points are for the baseline, cruciform condition, the right-most data points are for the full flank, height H pattern. Any differences in the settings for the baseline cruciform conditions reflect orientation anisotropies in those stimuli, and as can be seen these appear to exist in most of the conditions, and are substantial in the BY conditions (Fig. 6). Of principal interest, however, is the effect of the change in flank height from the cruciform to full flank condition for each of the members of a given H pattern pair. In all but one condition, an increase in flank height has an opposite effect for each member of an H pair. Only in BM's isoluminant GRG condition is there no apparent effect of flank height. In the RG occluded bar condition, there is no orientation anisotropy between the RGR and GRG conditions, nor any effect of flank height for either, confirming that both these observed effects in the other conditions are perceptual in origin. In the BY occluded-bar condition there is a small difference between the B channel settings for the BYB and YBY stimuli at all heights, suggesting the presence of a small physical artefact. However, since in the unoccluded bar conditions the direction of the difference is *reversed*, we can conclude that the effects in the latter are also perceptual in origin.

Since we are principally interested in the *difference* in the hue of the grey patches between H pair members, the data are replotted in Fig. 7 accordingly. The ordinate in Fig. 7 plots the difference between the functions for the two H pair members shown in Figs 5 and 6, with the data normalized to zero in the cruciform condition to eliminate the orientation anisotropies. In all the graphs there is an increase in the hue difference with flank height. In the RG conditions this means that the grey patch in the RGR condition appears more reddish (or less greenish) with an increase in flank height, while the reverse is the case with the GRG stimulus. In the BY conditions, the BYB stimulus appears more bluish (or less yellowish) with an increase in flank height, while the reverse is the case for the YBY stimulus. There is a suggestion in FKs RG data that an

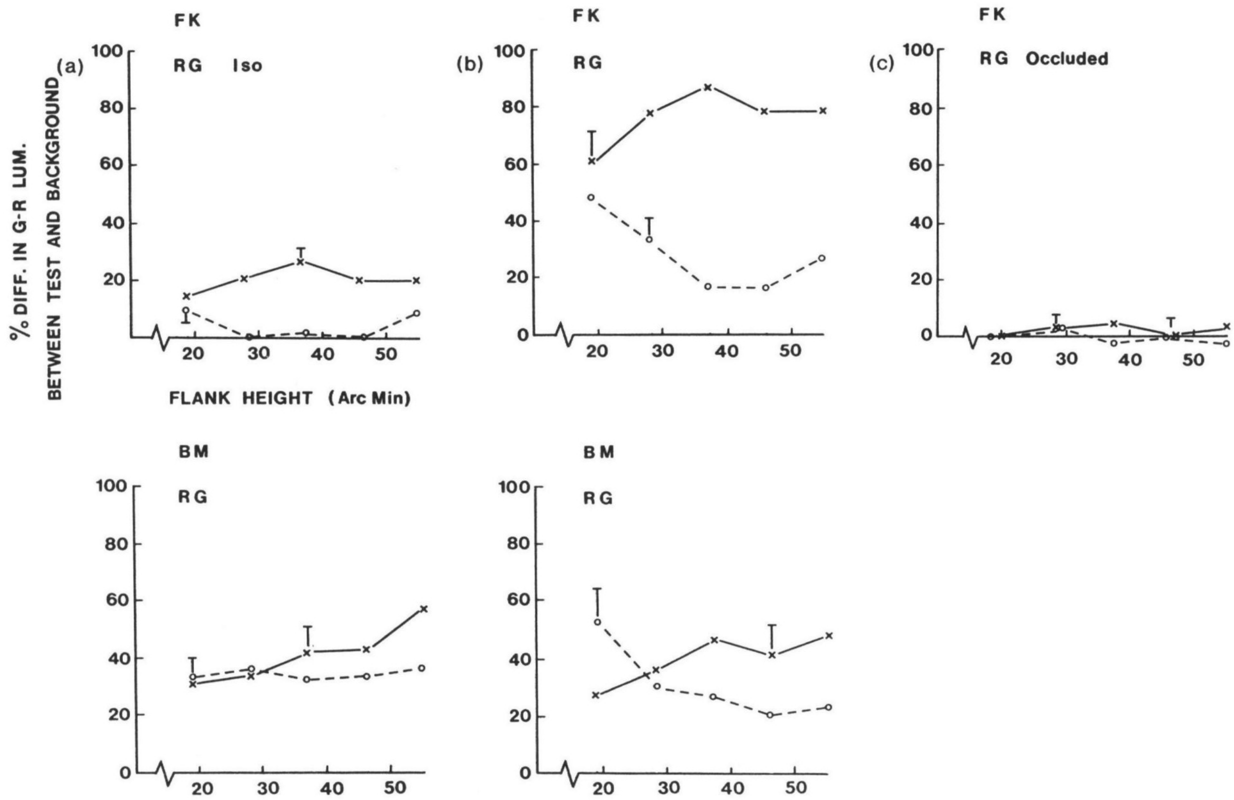


Figure 5. Results for the red–green H patterns for both subjects, FK and BM. (a) Isoluminant condition, both subjects; (b) non-isoluminant condition, both subjects; (c) surround bars occluded, FK only. The ordinate represents the percentage difference in the G–R luminance settings for the test patch and the grey background. The abscissa represents total flank height. Dashed line = GRG condition, continuous line = RGR condition. Error bars give one S.E. for the data point with the largest S.E. calculated from the 5 settings for that data point. Any difference in the values between the RGR and GRG conditions for the left-most data points, the cruciform condition, imply orientation anisotropies.

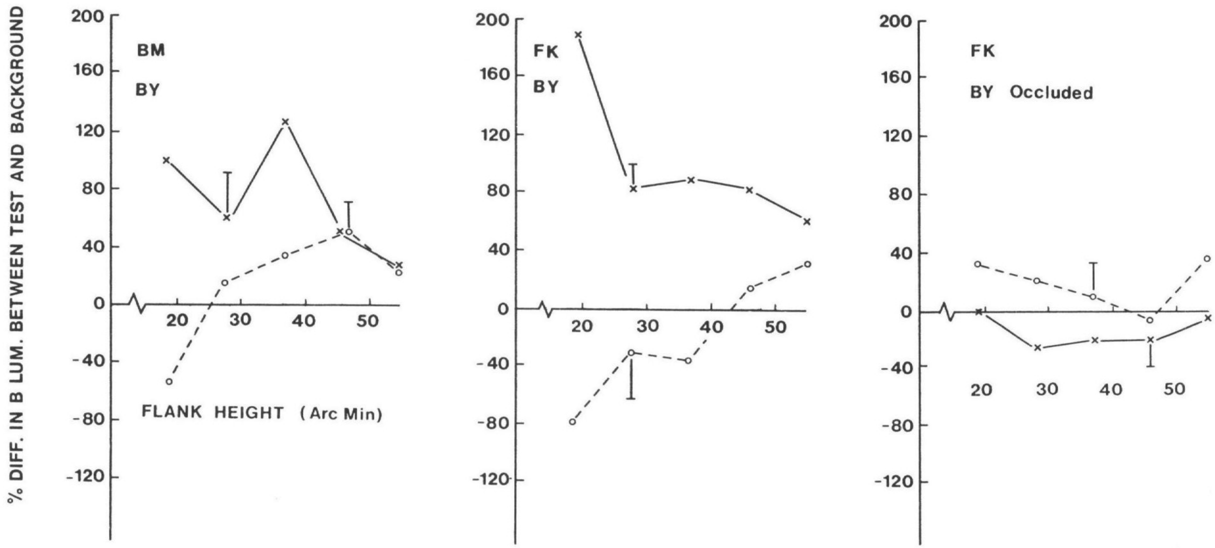


Figure 6. Results for the blue–yellow H patterns for both subjects, FK and BM. The ordinate represents the percentage difference in B luminance between the test patch and background. Continuous line = BYB condition, dashed line = YBY condition. Error bars give one standard error for the data point with the largest S.E., calculated from the 5 settings made for that condition. There is a substantial orientation anisotropy in the cruciform (left-most data point) condition.

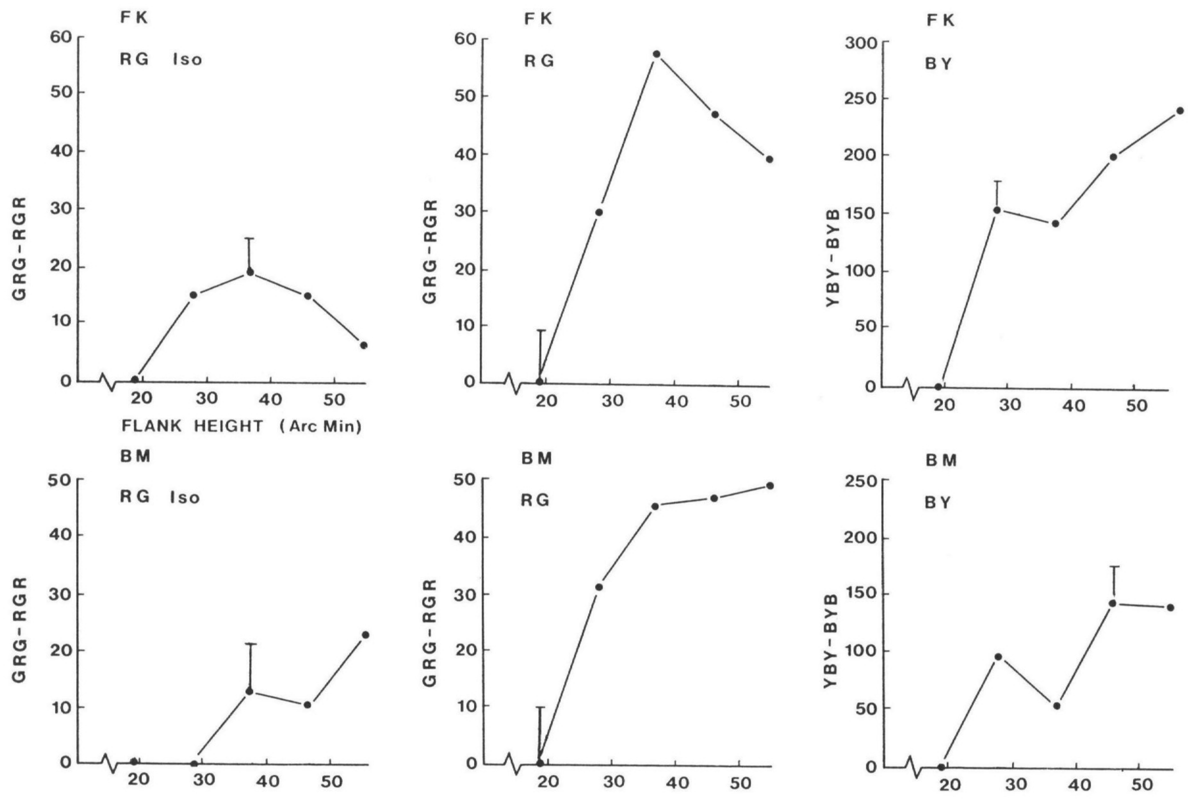


Figure 7. Difference between the values of each H pair that are shown individually in Figs. 5 and 6, normalized to eliminate the orientation anisotropies in the cruciform conditions. (a) RG isoluminant condition; (b) RG non-isoluminant condition; (c) BY condition. Error bars represent the largest value for each condition of the S.E. of the difference between the means.

asymptote is reached at a flank height of 36.2 arcmin, followed by a decline. In both subjects the isoluminant RG conditions produce less marked effects than the non-isoluminant RG conditions.

DISCUSSION

We have demonstrated a hue-induction effect in chromatic H patterns that is analogous to the brightness induction effect in achromatic H patterns demonstrated by Moulden and Kingdom (1989a). The grey patch in an RGR H pattern appears more reddish (or less greenish) than the same patch in a GRG H pattern, and the grey patch in a BYB H pattern appears more bluish (or less yellowish) than in a YBY H pattern. We have shown that this effect is due to the presence of the flanking bars which extend vertically above and below the component cruciform pattern.

We have shown that the effect occurs whether the stimuli are isoluminant (according to the criterion of minimum heterochromatic flicker), or non-isoluminant, that is containing both luminance and chromatic contrast. This illustrates the generality of the phenomenon. That the magnitude of the effect was greater in the non-isoluminant RG condition is what would be expected given the presence of the more intense green bars in that condition.

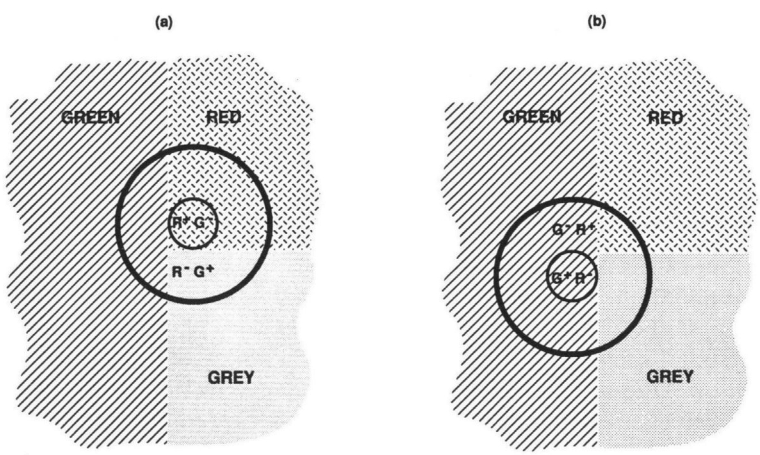
We described evidence in the introduction which supported the view that the effect in the achromatic H patterns occurred because of the presence of the corner intersections of the flank and coaxial bars with the test grey patches. Corners are powerful stimuli for retinal ganglion cells with concentric, centre-surround receptive fields. The effect of the corners, we argued, was to give the coaxial bars a disproportionate weighting in determining the brightness of the test patch through simultaneous contrast. We argue that the results of the experiment described here implicate the operation of an analogous mechanism in the chromatic domain. The neural filters that are responsible for simultaneous colour contrast are similarly sensitive to the corner intersections in the chromatic H patterns, giving extra weighting to the coaxial bar in determining the hue of the test grey patches.

In the same way that in the achromatic domain the effect implicates the operation of band-pass filters, that is, filters whose receptive field centres are stimulated by light energy, but whose surrounds are inhibited (or the reverse), so also does the effect in the chromatic H patterns implicate chromatic band-pass filters. Such filters would be insensitive to homogenous light of any wavelength covering their entire receptive field, and would be maximally stimulated by light of one wavelength falling in the receptive-field centre, together with light of a different wavelength falling in the receptive-field surround. This eliminates the simple color-opponent cell, presumably the principal carrier of colour information at the sub-cortical level, from mediating the pattern of induced hue shown here. These cells are low-pass in the chromatic domain (Ingling and Martinez-Uriegas, 1983; Morgan and Aiba, 1985). Their receptive field centres are excited by stimulation from one cone type, while their surrounds are inhibited by stimulation from another cone type. If one positioned, for example, a red on-centre, green off-surround simple opponent cell at the corner intersection of an isoluminant GRG cruciform pattern, and extended the green flanks to form the H pattern, the output of the cell would *diminish*, rather than increase as the flanks extended into the cell's receptive field surround. For the non-isoluminant stimuli, one need only consider the effect of the extended flank on that component of the cell's output which provides colour, rather than luminance information, since it is the hue and not brightness content of the stimuli which we are concerned with. This component is low-pass irrespective of the degree of luminance contrast in the stimulus (Ingling and Martinez-Uriegas, 1983) and the same argument therefore applies to the non-isoluminant as to the isoluminant case.

A type of chromatic band-pass filter, known as the double opponent cell, has been found to be relatively common in the monkey visual cortex (Gouras, 1974; Michael, 1978; Livingstone and Hubel, 1984). Such cells are characterized by possession of colour opponency within the receptive-field centre, and the opposite direction of colour opponency in the receptive-field surround. Moreover most are concentric. Double opponent cells would therefore be good candidates as mediators of the effects described here. An example of a concentric red–green double opponent cell is illustrated in Fig. 8. In this figure two such cells of opposite polarity are positioned in the two stimulus locations which, we argue, produce the critical difference in response magnitude that causes the effect. Similarly, blue–yellow double opponent cells (Livingstone and Hubel, 1984) could mediate the effect in the blue–yellow H patterns.

That hue induction phenomena implicate the operation of filters which are band-pass rather than low-pass in the chromatic domain has not escaped the notice of previous investigators. De Valois and De Valois (1975, pp. 156–162) were the first to point out that the form of spectral opponency found in the simple colour-opponent cells would not produce simultaneous colour contrast effects, but that the double opponent organization would. Recent investigations into the hue and perceived saturation of the illusory spots found at the intersections in coloured Hermann grids are also consistent with this position (Levine *et al.*, 1980; Oehler and Spillman, 1981).

Can one say anything regarding the size of the filters underlying the effect? In the introduction we suggested that the asymptote at which the flanking bar increment was maximal for the achromatic case (6–12 arcmin) was consistent with the size of foveal receptive fields. Inspection of Fig. 7 shows that in the red–green H patterns the asymptote is reached at a flank height of about 36 arcmin for FK, and perhaps higher for BM. A flank height of 36 arcmin means a flank increment of 9 arcmin, which is similar to the achromatic case. In the blue–yellow H patterns, the data as a whole



Figrue 8. Double-opponent cells in the two positions as in Fig. 3. As the flank extends into the surround of the cell in the corner position the output of the cell will increase.

suggest that the asymptote is reached later than in the red–green patterns. There is, therefore, a hint in the data that the filters mediating the effect in the blue–yellow H patterns have larger receptive fields than those involved in red–green H patterns. Neurophysiological recordings suggest that double opponent cells are generally quite large. In Michael's (1978) study, in which only red–green double opponent cells were isolated, the centres of the receptive fields varied between 10 arcmin and 1 deg, with overall receptive field width varying from 3–10 deg. With such large surrounds, one would not have predicted the asymptotic pattern that seems clear in FK's data with red–green H patterns. Clearly more precise data on the flank height at which this effect asymptotes needs to be gathered, but our results may imply smaller receptive fields in humans than those found in monkeys.

Moulden and Kingdom (1989a) have suggested that the 'corner effect' in the achromatic domain is in part responsible for White's (1979) effect, in which short grey bars replacing segments of the white phase of a square-wave grating appear markedly darker than identical bars replacing segments of the black phase of the grating. Kingdom and Moulden (1988), following a suggestion by Paola Bressan, have recently demonstrated an analogous effect with coloured gratings. Grey bars replacing segments of the green phase of a red–green square-wave grating appeared more reddish (or less greenish) than identical bars on the red phase. A corresponding effect was found with a blue–yellow grating. These colour grating effects are essentially versions of the phenomena orginally demonstrated by Wright (1969) that we described in the Introduction. The results of the experiments described here suggest that a local corner effect may play a part in the generation of the chromatic version of White's effect demonstrated by Wright and ourselves.

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