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Color appearance of spatial pattern: the role of increments and decrements

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Abstract

In a number of recent adaptational studies evidence for a different processing of incremental and decremental cone signals has been reported. The present study examined whether such asymmetries occur in spatial pattern as well. Subjects set color matches between a uniform, 2° matching box and bars within squarewave patterns. The squarewaves varied in spatial frequency, color direction, and contrast. For all three cone signals the asymmetric matches showed clear evidence for increment–decrement asymmetries: Although both incremental and decremental matches scaled roughly linearly with pattern contrast, in general, the scalings for the two types of color signals differed. This difference in scaling increased with spatial frequency, thus leading to an increase in the size of the increment–decrement asymmetry with spatial frequency. The matches were well described by means of two-stage models, consisting of a color transformation in the first stage and a pattern-dependent scaling in the second stage. Analyses based on these pattern–color separable models suggest that the asymmetries are mediated mainly through a white–black mechanism and much less, if at all, through a red–green and yellow–blue mechanism. © 2002 Published by Elsevier Science Ltd.

1. Introduction

The color appearance of light varies with spatial pattern. This basic finding has been demonstrated numerous times by using isolated sinewaves or squarewaves as experimental stimuli. Both the spatial frequency and the color direction and contrast of the patterns was varied and the appearance of the single bars in the patterns was measured using variants of the method of asymmetric color matching: Observers had to adjust a uniform matching box until it matched in appearance with one of the bars in the gratings. Typically, considerable effects of spatial frequency were found in the yellow–blue and red–green direction but only moderate effects were found in the white–black direction, indicating that, above all, the color appearance of patterns becomes progressively desaturated as the spatial frequency of the stimulus increases (Bäuml & Wandell, 1996; Elsner, Burns, & Pokorny, 1987; Ingling, Scheibner, & Boynton, 1970; Middleton & Holmes, 1949; Poirson & Wandell, 1993).

Poirson and Wandell (1993) captured this qualitative observation of the frequency effect and modeled the phenomenon quantitatively (Fig. 1). Their pattern–color separable model assumes that, in the first stage, the mean rate of cone absorptions from the grating's bar and the uniform matching box undergo a linear transformation into an intermediate color representation. Then, in the second stage, the intermediate color representation values are scaled by an amount that depends on the local spatial pattern. The grating bar and the uniform box appear to match when the final, scaled representations are equal. As the results from previous studies showed, the model can serve as a useful first-order approximation of the spatial frequency effect, both when using isolated squarewaves (Poirson & Wandell, 1993) and when using mixture gratings that consist of the sum of squarewaves (Bäuml & Wandell, 1996). Poirson, Wandell, and Bäuml also estimated the color and pattern responsivity functions of the three putative pathways of the intermediate color representation. Consistent with prior work, they found that the effects of spatial pattern are mediated by two color-opponent pathways, one red–green and one yellow–blue pathway,

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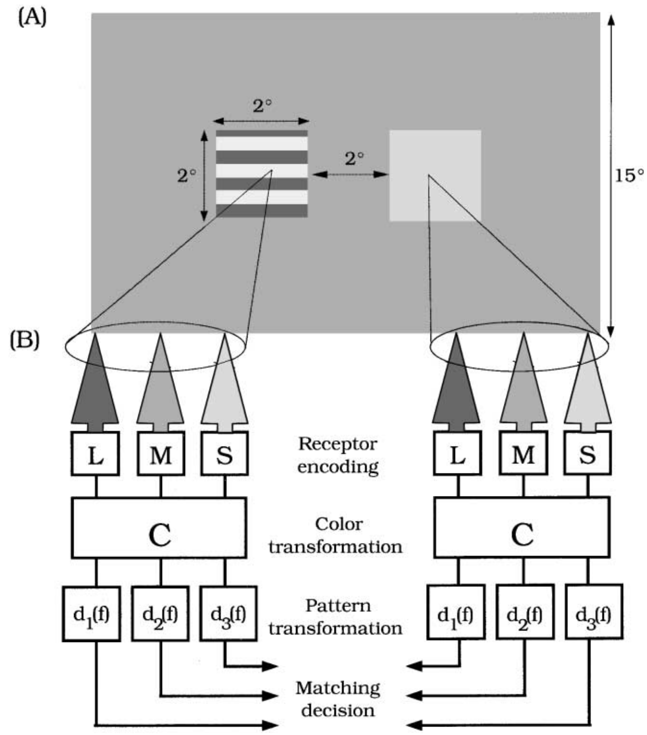

Fig. 1. The linear pattern–color separable model: (A) Subjects set color appearance matches between a bar in the squarewave grating and a uniform field. (B) In the first stage of the model, the mean rate of cone absorptions caused by the bar and the uniform matching box undergo a linear color transformation into an intermediate color representation. In the second stage, the intermediate color representation values are each scaled by an amount that depends on the local spatial pattern (*f*). The squarewave bar and the uniform box match when the final, scaled representations are equal.

and one all-positive white–black pathway. Also consistent with prior research, they found that, at least up to 8 cpd, the white–black pathway is not much affected by frequency, whereas the two opponent pathways show a considerable loss of contrast information as the frequency is increased (see also Bäuml, Zhang, & Wandell, 2001).

The pattern–color separable model is a linear model and thus uses the same transformations to describe the frequency effect for cone signals that are incremental and cone signals that are decremental relative to the uniform background field. This linearity property of the model contrasts with recent findings from the adaptation literature. In these studies evidence has been reported that the visual system processes lights which are incremental relative to a uniform background field differently than lights which are decremental. With respect to color appearance Mausfeld and Niederee (1993), for instance, showed that red–green equilibria do not fall on a single straight line in color space but rather fall on two straight lines bent at some point close to the color coordinates of the background field. Chichilnisky and Wandell (1996, 1999) observed analogous asymmetries with respect to the achromatic locus and the red–green and yellow–blue dimension in color space as well. Moreover, the difference in processing between incremental and decremental lights was found to be regular to some degree: Decrements showed more responsiveness to changes in background color than increments (Chichilnisky & Wandell, 1996; for related results in recent color-constancy research see Bäuml, 2001; Delahunt & Brainard, 2000; Schirillo 1999a,b).

Both Poirson and Wandell (1993) and Bäuml and Wandell (1996) noticed evidence for increment–decrement asymmetries in spatial pattern as well. For instance, for some squarewave patterns the matches to incremental lights scaled differently with pattern contrast than the matches to decremental lights, indicating that incremental and decremental cone signals are not processed symmetrically. Such increment–decrement asymmetries, however, were neither numerous nor strong and thus were hardly measurable. As a result, they were ignored in the first modeling step. This study re-examines the issue of increments and decrements in spatial pattern, examining whether the increment–decrement asymmetries observed in the two previous studies are real, and, if they are, how they vary with pattern.

Subjects set color appearance matches between the bars in squarewave gratings and a uniform patch for a number of different color directions, contrasts, and spatial frequencies (1, 2, 4, and 8 cpd). For each color direction and spatial frequency it was examined whether the matches to incremental cone signals scaled equally with pattern contrast as the matches to decremental cone signals, or whether the scalings for incremental and decremental signals differed. If asymmetries between incremental and decremental lights were found, it was examined how these asymmetries varied with spatial frequency. Three results emerged: First, for all three cone signals the asymmetric matches showed clear evidence for increment–decrement asymmetries. Although both incremental and decremental matches scaled roughly linearly with pattern contrast, in general, the scalings for the two types of color signals differed. Second, for all three cone types the matches often showed a smaller effect of spatial frequency on the decremental signals than on the incremental ones. This difference was regular and led to an increase in the size of the increment–decrement asymmetry with spatial frequency. Third, the matches were well described by means of two-stage models, consisting of a color transformation in the first stage and a pattern-dependent scaling in the second stage. Analyses based on these pattern–color separable models suggest that the asymmetries are mediated mainly through a white–black mechanism and much less, if at all, through a red–green and yellow–blue mechanism.

2. Method

The methods used in this study were similar to those used by Poirson and Wandell (1993) and Bäuml and Wandell (1996).

2.1. Visual display

The visual stimuli were presented on a CRT monitor. Throughout the experiment the monitor displayed a neutral, 15° uniform background. The test patterns were horizontal squarewave gratings subtending 2° and were superimposed upon the uniform background. The matching box also subtended 2° and was presented to the right of the test pattern, separated from it by 2° of visual angle (see Fig. 1). The subjects viewed the screen from a distance of about 2 m. The stimuli were steadily presented.

The patterns were displayed on a computer-controlled color monitor (BARCO calibrator) using a refresh rate of 71 Hz in noninterlaced video mode. The three channels of the monitor were controlled by an 8-bit digital-to-analog converter. The signals of the color channels could be varied in 256 steps from zero to maximal intensity for each pixel. Software was used to control the monitor's input signal in order to correct for nonlinearities in the tube's response function. The luminance of each color channel was measured with a high precision photometer (Fa. Lichtmesstechnik, Modell L 1003). The CIE xy-coordinates of the phosphors were provided by the manufacturer. The programming was done by using PXL subroutines (Irtel, 1997). The test pattern and matching box were presented at different locations on the screen. To compensate for local variations in the gamma curves, the above measurements were done separately for the screen locations where the test pattern and matching box were presented. Gamma curves measured at the center of the test pattern, or matching box, were used to control the stimuli.

2.2. Color and pattern representation

The representation of the physical stimulus was based on the use of the Smith and Pokorny (1975) cone fundamentals. A version of the cone fundamentals that is normalized to a peak value of 1.0 was used. The LMS coordinates of the uniform background were $L = 6.60$, $M = 5.62$, and $S = 3.71$. The matching box and the gratings are represented as deviations from the uniform background, $s = (\Delta L, \Delta M, \Delta S)$. The color direction of a stimulus is defined to be the unit length vector $(1/\|s\|)s$, where $\|s\|$ is the length of the cone-difference vector, s. I constructed squarewave gratings of 1, 2, 4, and 8 cpd. The squarewaves were created in one of four color directions. The complementary bars in the gratings appeared either white–black, yellow–blue, orange–light blue, or purple–bright green. The color directions of these squarewave patterns are shown in Table 1.

Table 1
Squarewave color pairs

Squarewave	L	M	S	Appearance
S-W1	0.700	0.596	0.394	White
	−0.700	−0.596	−0.394	Black
S-W2	0.747	0.577	−0.330	Yellow
	−0.747	−0.577	0.330	Blue
S-W3	0.351	0.671	−0.653	Orange
	−0.351	−0.671	0.653	Light blue
S-W4	0.393	0.691	0.607	Purple
	−0.393	−0.691	−0.607	Bright green

Unit length vectors of LMS cone differences of the squarewave color pairs used in the experiment. In addition, the appearance description of each squarewave is given. Spatial pattern is a uniform, square, 2° field (S-W: squarewave, L: L cone coordinate, M: M cone coordinate, S: S cone coordinate).

2.3. Subjects

Two observers (TK, male; KK, female) served as subjects. They had normal color vision as assessed with the Farnsworth–Munsell 100-Hue Test. Both subjects were naive about the purpose of the experiment.

2.4. Procedure

Subjects set matches to the two differently colored bars of a squarewave grating. They looked back and forth between the test pattern and matching box, adjusting the phosphor intensities to obtain an appearance match, i. e., to create the same hue, saturation, and brightness in the matching box as the test stimulus. Both subjects made adjustments to three different color directions. Both made matches to the white–black and the yellow–blue direction, subject TK additionally made matches to the purple–bright green direction, and subject KK additionally made matches to the orange–light blue direction. Each of the two subjects' data include 96 different spatial frequency and color conditions, with eight matches for TK and four matches for KK in each condition.

2.5. Data analysis

Tests of several models of the asymmetric matching data are reported. To choose the best parameters for each model, the difference between theoretically predicted and empirically observed matches were minimized using an error term that was normalized by the estimated covariance matrix of the match settings (Mahalanobis metric). The observed difference between prediction and observation was normalized using a single covariance matrix, Λ, derived by combining the subject's matches from all the single experimental conditions (see Anderson, 1958). Suppose the column vector, e_i, denotes the difference between the predicted match vector, p_i, and the observed match vector, m_i. Then, the model parameters were estimated subject to the minimization of the quantity

$$\frac{1}{n}\sum_{i=1}^{n}(e_i^{t}\Lambda^{-1}e_i)^{1/2},$$

where n denotes number of stimulus conditions $\times$ number of match replications. Intuitively, this error measure is equivalent to (a) transforming the model deviations in a new coordinate frame where the distribution of errors are independent and have unit variance, and (b) using the Euclidean distance in that coordinate frame as the error measure. This approach to model fitting was also used in the studies by Poirson and Wandell (1993) and Bäuml and Wandell (1996). It is used here in order to provide a as direct as possible comparison in model errors across studies. [1]

3. Results

3.1. Increment–decrement asymmetries

Fig. 2A and B show some typical data on how subjects' matches to the squarewaves varied with the cone contrast of the gratings. [2] The three panels within each figure refer to the three different cone types. The horizontal axis of each panel is the cone contrast of the squarewave; the vertical axis is the cone contrast of the matching box. The panel origin represents the mean background. Fig. 2A shows matches of subject TK to a pattern of 4 cpd in the white–black direction, Fig. 2B shows matches of subject KK to a pattern of 4 cpd in the orange–light blue direction. Matches were made to both bars at four contrast levels. Each data point represents the average of eight matches (TK) or four matches (KK) to a single bar. To the extent that the measurements deviate from a line of unit slope, the matches show an effect of pattern on color appearance.

Within each quadrant, the match contrast scales roughly linearly with the squarewave contrast, which holds true for all three cone types. The matches from the two quadrants, however, are not odd symmetric through the origin, indicating a different processing of signals which are incremental relative to the background field and signals which are decremental. In particular, the incremental matches deviate clearly from physical matches, whereas the decremental matches show relatively small effects of pattern. Again these observations hold true for all three cone types. The two straight lines within each graph represent the fit of an increment–decrement model (see below). The dashed lines extend the solid lines to demonstrate that incremental and decremental matches differ.

Fig. 3A and B show mean matches of subject TK set for the white–black and the yellow–blue direction, Fig. 3C and D show mean matches of subject KK set for the white–black and the purple–bright green direction. Each figure shows matches for the three spatial frequencies of 1, 4, and 8 cpd. Again each data point represents the average of eight matches (TK) or four matches (KK) to a single bar. As can be seen, for many of the combinations of color direction and spatial frequency the figure shows evidence for an increment–decrement asymmetry: Both incremental and decremental matches scale roughly linearly with pattern contrast, the scalings for the incremental and decremental matches, however, differ. Moreover, in many cases the increase in spatial frequency has a smaller effect on the matches to decremental lights than on the matches to incremental lights. As a result, the size of the increment–decrement asymmetry increases with spatial frequency. This tendency for an increase in the increment–decrement asymmetry with spatial frequency can be observed for all three cone types. Obviously, it is more clear-cut for the matches of subject TK than for the matches of subject KK.

3.2. Modeling analysis

3.2.1. Separable linear model

I fitted Poirson and Wandell's (1993) linear pattern–color separable model to the matches of each subject. The model describes a subject's matches for a spatial frequency f through the equation

$$m = (C^{-1}D_fC)s,$$

where C is a 3×3 matrix which maps the cone difference signals for the test and matching box, m and s, into an intermediate color representation, and D_f is a 3×3 diagonal matrix which scales the output of the three putative color pathways as a function of the pattern (see Fig. 1). Thus, C captures the effect of color, whereas D_f captures the effect of pattern. This model includes 21 $(9 + 4 \times 3)$ parameters to describe each subject's entire set of matches. When fitting this model to the data of the two subjects, I found a residual error of 3.08 units for subject TK, compared to a precision of 1.35 units, and a residual error of 3.01 units for subject KK, compared to

[1] Poirson and Wandell (1993) computed error scores using both the Mahalanobis metric and the CIELUV metric. The two types of error measures revealed a high degree of correspondence, both in pattern and in size.

[2] The squarewave and matching box contrasts were computed from the positive and negative cone differences by dividing the difference coordinates by the respective cone coordinates of the background field.

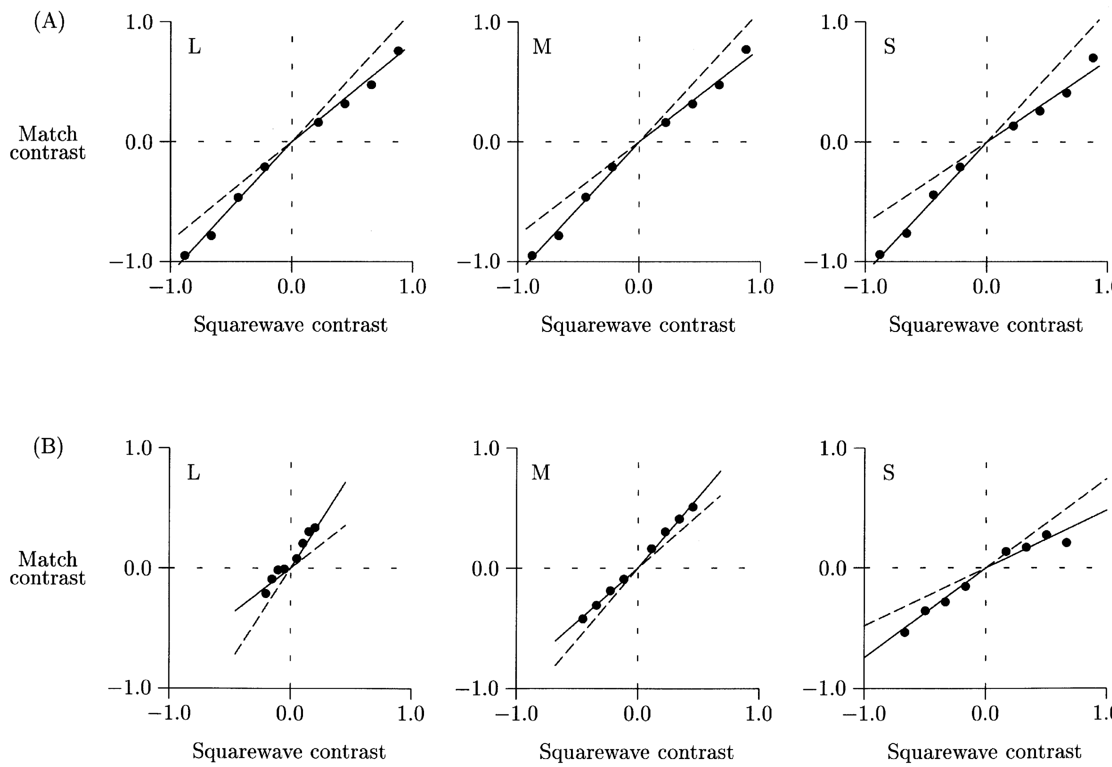

Fig. 2. Asymmetric color matches: (A) *LMS* coordinates of the asymmetric matches of subject TK to a white–black squarewave pattern of varying contrast and a spatial frequency of 4 cpd; (B) *LMS* coordinates of the asymmetric matches of subject KK to an orange–light blue squarewave pattern of varying contrast and a spatial frequency of 4 cpd. The horizontal axis of each panel is the cone contrast of the squarewave's bars; the vertical axis is the cone contrast of the matching box; the panel origin represents the mean background. The solid lines within each graph represent the fit of the pattern–color separable CID model (see text). The dashed lines extend the solid lines to demonstrate that incremental and decremental matches differ. (*L*: L cone coordinate, *M*: M cone coordinate, *S*: S cone coordinate).

a precision of 1.61 units. This result replicates those reported by Poirson and Wandell (1993) and Bäuml and Wandell (1996), who found the model to describe their subjects' data to within a tolerance of twice the precision of the matches.

For each of the two subjects Table 2 (Panel A) shows the parameter estimates for matrix C. Each row in this matrix defines the spectral responsivity of a putative color pathway that is a weighted sum of the three cone coordinates. The resulting new coordinate frame is consistent with a general opponent-colors organization of color appearance: The first row of matrix C specifies a mechanism similar to a white–black pathway, the second row a mechanism similar to a red–green pathway, and the third row a mechanism similar to a yellow–blue pathway. Table 2 (Panel B) shows, separately for each of the two subjects, the parameter estimates for matrix D_f which defines the pattern sensitivities of the three putative pathways. The estimated coefficients suggest the white–black pathway to be bandpass and the two opponent pathways to be lowpass. Both the coefficients estimated for matrix C and the coefficients estimated for matrix D_f are close to those found in the prior studies by Poirson and Wandell (1993) and Bäuml and Wandell (1996). [3]

3.2.2. Separable C(olor)ID model

Figs. 2 and 3 shown above suggest that we can get a better description of the data by using a model which incorporates an increment–decrement asymmetry. On the basis of the separable linear model at least two possibilities arise on how to incorporate increment–decrement asymmetries. A first possibility is to generalize the linear model by allowing for different color transformations depending on whether the single cone signals of the test lights are incremental or decremental. This dependence of the color transformation on the signs of

[3] I also used the parameter values for matrix C that Poirson and Wandell (1993) estimated for their two subjects and fitted the separable linear model to the data of the two subjects in the present study. When using the Poirson and Wandell rather than the best fitting parameters, the residual errors increased only slightly (TK: 3.18 vs. 3.08 units, KK: 3.11 vs. 3.01 units). This small increase in error indicates that the parameter values for matrix C are roughly the same across subjects and studies (for further evidence on this point see Bäuml et al., 2001).

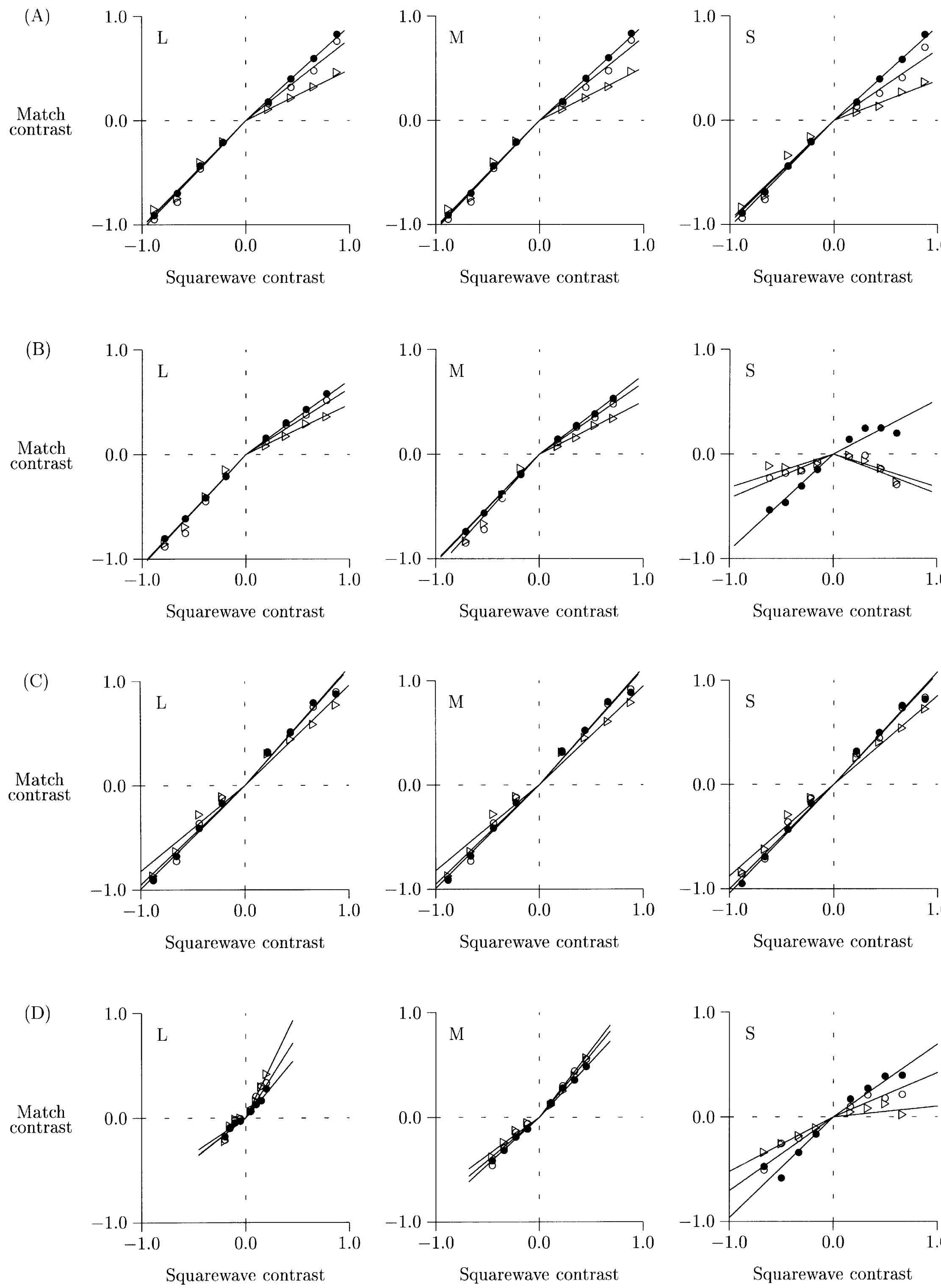

Fig. 3. Asymmetric color matches: (A) *LMS* coordinates of the asymmetric matches of subject TK to white–black squarewave patterns of varying contrast and varying spatial frequency; (B) *LMS* coordinates of the asymmetric matches of subject TK to yellow–blue squarewave patterns of varying contrast and varying spatial frequency; (C) *LMS* coordinates of the asymmetric matches of subject KK to white–black squarewave patterns of varying contrast and varying spatial frequency; (D) *LMS* coordinates of the asymmetric matches of subject KK to orange–light blue squarewave patterns of varying contrast and varying spatial frequency (•—1 cpd, ∘—4 cpd, ▷—8 cpd). The horizontal axis of each panel is the cone contrast of the squarewave's bars; the vertical axis is the cone contrast of the matching box; the panel origin represents the mean background. The solid lines within each graph represent the fit of the pattern–color separable CID model (see text; *L*: L cone coordinate, *M*: M cone coordinate, *S*: S cone coordinate).

Table 2
Fit of the linear pattern–color separable model

Panel A	Subject TK			Subject KK		
Function	L	M	S	L	M	S
W–B	0.968	0.050	0.243	0.990	0.104	−0.095
R–G	0.658	−0.752	−0.015	0.716	−0.696	−0.094
Y–B	−0.700	0.562	0.440	0.440	−0.515	0.736
Panel B						
Frequency (cpd)	W–B	R–G	Y–B	W–B	R–G	Y–B
1	0.969	0.889	0.869	1.039	0.990	0.968
2	0.975	0.844	0.774	1.072	1.005	0.887
4	0.914	0.676	0.576	1.052	0.960	0.837
8	0.762	0.434	0.395	0.918	0.755	0.624

Panel A: parameter estimates for color matrix C.
Panel B: parameter estimates for the pattern sensitivity matrix D_f (see Fig. 1 and text for details; L: L cone coordinate, M: M cone coordinate, S: S cone coordinate, W–B: white–black coordinate, R–G: red–green coordinate, Y–B: yellow–blue coordinate, cpd: cycles per degree).

the stimulus cone signals doubles the number of parameters for the color transformation, because there is one set of parameters for the positive cone signals and a second set for the negative cone signals. As a result, the model comes up with 30 ($2 \times 9 + 4 \times 3$) parameters to describe each subject's matches.

Based on this (nonlinear) separable C(olor)ID model each subject's matches for a spatial frequency f are described by the equation

$$m = (C_{\mathrm{ID}}^{-1} D_f C_{\mathrm{ID}})s,$$

where C_{ID} is a 3×3 matrix which maps the incremental and decremental cone signals for the test and matching box, s and m, into an intermediate color representation, and D_f is a 3×3 diagonal matrix which scales the output of the three putative color pathways. In this model, the columns of C_{ID} depend on the signs of the cone signals, with one set of columns (nine parameters) for the positive cone signals and a second set of columns (nine parameters) for the negative cone signals. In the case of mixed signs (for instance, $L+M-S+$), matrix C_{ID} thus consists of some columns from the set of columns for the positive cone signals (L column, S column) and some columns from the set of columns for the negative cone signals (M column). Again, C_{ID} captures the effect of color and D_f captures the effect of pattern. When fitting this model to the data of the two subjects, I found a residual error of 1.89 units for subject TK and a residual error of 2.41 units for subject KK. Thus, for both subjects the model leads to a considerable reduction in residual error compared to the separable linear model.

For each of the two subjects Table 3 (Panel A and B) show the parameter estimates for matrix C_{ID}: Table 3 (Panel A) shows the estimates for the incremental cone

Table 3
Fit of the pattern–color separable CID model

Panel A	Subject TK			Subject KK		
Function	$L+$	$M+$	$S+$	$L+$	$M+$	$S+$
W–B	0.154	−0.741	0.653	−0.084	0.485	0.871
R–G	0.849	−0.506	0.150	0.678	−0.733	0.056
Y–B	−0.252	−0.113	0.961	0.458	−0.566	0.686
Panel B						
Function	$L-$	$M-$	$S-$	$L-$	$M-$	$S-$
W–B	0.496	0.846	0.195	0.916	0.390	−0.088
R–G	0.575	−0.793	0.203	0.654	−0.755	0.058
Y–B	0.073	−0.587	0.806	0.512	−0.477	0.714
Panel C						
Frequency (cpd)	W–B	R–G	Y–B	W–B	R–G	Y–B
1	1.038	0.899	0.813	1.044	1.021	0.937
2	1.080	0.875	0.740	1.062	1.019	0.882
4	1.100	0.765	0.514	1.056	0.930	0.782
8	0.975	0.562	0.284	0.918	0.731	0.585

Panel A: parameter estimates for color matrix C_{ID} for the incremental cone signals.
Panel B: parameter estimates for color matrix C_{ID} for the decremental cone signals.
Panel C: parameter estimates for the pattern sensitivity matrix D_f (see text for details; L: L cone coordinate, M: M cone coordinate, S: S cone coordinate, $+$: incremental coordinate, $-$: decremental coordinate, W–B: white–black coordinate, R–G: red–green coordinate, Y–B: yellow–blue coordinate, cpd: cycles per degree).

signals, Table 3 (Panel B) shows the estimates for the decremental cone signals. In the case of decremental cone coordinates the rows of matrix C_{ID} are again consistent with a general opponent-colors organization, suggesting a white–black, a red–green, and a yellow–blue pathway. In the case of incremental cone coordinates things are different. Whereas the second and third row of the matrix still suggest a red–green and a yellow–blue pathway, the first row differs from what we actually expect from a white–black mechanism. The most obvious difference lies in the relatively small contribution of the L cone signal and the relatively large contribution of the S cone signal to this putative pathway. Table 3 (Panel C) shows the parameter estimates for matrix D_f which defines the pattern sensitivities of the three putative pathways. Consistent with the results from the separable linear model the estimated coefficients suggest one pathway to be bandpass and the other two to be lowpass.

On the basis of the CID model I examined whether all three pathways of the intermediate color representation show different cone weights for increments and decrements, or whether the asymmetry exists mainly for one or two of the three pathways. I started with the restriction that the cone weights for the red–green pathway show no increment–decrement asymmetry and then added the restriction that the cone weights for the yellow–blue pathway show no asymmetry as well. Imposing these two restrictions on the general form of the CID model increased the error for both subjects only slightly (TK: from 1.89 to 2.01 to 2.14 units; KK: from 2.41 to 2.52 to 2.57 units). However, imposing as a third restriction the assumption that also the cone weights for the white–black pathway show no increment–decrement asymmetry increased the error of the model quite a lot (TK: 3.08 vs. 2.14 units, KK: 3.01 vs. 2.57 units). These results suggest that the increment–decrement asymmetry found in the present data exists mainly in the cone weights for the putative white–black pathway and much less, if at all, in the cone weights for the putative red–green and yellow–blue pathway.

3.2.3. Separable P(attern)ID model

A second possibility to incorporate increment–decrement asymmetries into the separable linear model is to allow for different pattern sensitivities for increments and decrements at the stage of the intermediate color representation. Such a dependence of pattern sensitivity on the sign of the signals of the three putative pathways doubles the number of parameters for pattern scaling. As a result, the model comes up with 33 ($9 + 2 \times 4 \times 3$) parameters to describe each subject's matches.

Based on this (nonlinear) separable P(attern)ID model each subject's matches for a spatial frequency f are described by the equation

$$m = (C^{-1} D_{f\mathrm{ID}} C)s,$$

where C is a 3×3 matrix which maps the cone difference signals for the test and matching box, m and s, into an intermediate color representation. $D_{f\mathrm{ID}}$ is a 3×3 diagonal matrix which scales the output of the three putative pathways with different scalings for a pathway's incremental and decremental signals. When fitting this model to the data of the two subjects, I found a residual error of 1.84 units for subject TK and a residual error of 2.48 units for subject KK. Thus, for both subjects the model leads to roughly the same errors as the separable CID model.

For each of the two subjects Table 4 (Panel A) shows the parameter estimates for matrix C. Again the rows of matrix C are consistent with a general opponent-colors organization, suggesting a white–black, a red–green, and a yellow–blue pathway. Table 4 (Panel B and C) show the parameter estimates for matrix $D_{f\mathrm{ID}}$ which defines the pattern sensitivities of the three putative pathways in the case of incremental (Table 4, Panel B) and decremental (Table 4, Panel C) signals. In both cases the estimated coefficients suggest the white–black pathway to be bandpass and the red–green and yellow–blue pathway to be lowpass.

On the basis of the PID model I examined whether all three putative pathways show different pattern sensitivities for incremental and decremental signals, or whether the asymmetry exists mainly for one or two of the three pathways. I started with the restriction that only the white–black pathway but not the red–green and yellow–blue pathway show different scalings for increments and decrements. In agreement with the analysis of the CID model, this restriction increased the error of the PID model only slightly (TK: 2.05 vs. 1.84 units, KK: 2.60 vs. 2.41 units). However, additionally imposing the restriction that the white–black pathway shows no asymmetry as well led to a substantial increase in error (TK: 3.08 vs. 2.05 units; KK: 3.01 vs. 2.60 units). These results indicate that the increment–decrement asymmetry is reflected mainly in the pattern sensitivity of the white–black pathway and much less, if at all, in the pattern sensitivities of the red–green and yellow–blue pathway.

3.2.4. Comparison of models

Fig. 4 shows scatterplots for the separable linear model (A), the separable CID model (B), and the separable PID model (C). The graphs show the mean matches of subject TK for all 96 combinations of color and frequency and compare them with the predictions of the three models. To the extent that, for each of the three cone types, the data points fall on the diagonal line, they indicate that the model holds perfectly. The visual impression confirms the results from the above analyses. There are some clear differences between

Table 4
Fit of the pattern–color separable PID model

Panel A	Subject TK			Subject KK		
Function	*L*	*M*	*S*	*L*	*M*	*S*
W–B	0.392	0.900	−0.192	−0.397	0.915	0.079
R–G	0.627	−0.777	0.054	0.658	−0.753	0.004
Y–B	−0.623	0.290	0.727	0.528	−0.664	0.530
Panel B						
Frequency (cpd)	(W–B)+	(R–G)+	(Y–B)+	(W–B)+	(R–G)+	(Y–B)+
1	0.806	0.884	0.821	1.035	0.995	0.999
2	0.833	0.796	0.685	1.053	0.913	0.894
4	0.697	0.609	0.444	1.030	0.819	0.777
8	0.472	0.415	0.339	0.873	0.610	0.548
Panel C						
Frequency (cpd)	(W–B)−	(R–G)−	(Y–B)−	(W–B)−	(R–G)−	(Y–B)−
1	1.037	0.944	0.817	1.095	1.054	0.950
2	1.079	0.903	0.827	1.122	1.049	0.906
4	1.108	0.818	0.624	1.125	1.017	0.862
8	1.011	0.567	0.347	0.959	0.800	0.664

Panel A: parameter estimates for color matrix *C*.
Panel B: parameter estimates for the pattern sensitivity matrix $D_{f\mathrm{ID}}$ if the three pathways' signals are incremental.
Panel C: parameter estimates for the pattern sensitivity matrix $D_{f\mathrm{ID}}$ if the three pathways' signals are decremental (see text for details; *L*: L cone coordinate, *M*: M cone coordinate, *S*: S cone coordinate, W–B: white–black coordinate, R–G: red–green coordinate, Y–B: yellow–blue coordinate, +: incremental coordinate, −: decremental coordinate, cpd: cycles per degree).

matches and predictions in the case of the linear model, whereas matches and predictions agree well in the case of both the CID and PID model. Consistent with the analyses above, the two ID models, therefore, provide a reasonable description of the subject's matches. The results for subject KK show an analogous pattern, although, as expected from the residual errors reported above, the difference between the linear model and the two ID models is smaller than for subject TK. [4]

4. Discussion

In previous studies the effect of pattern on the color appearance of light was described by means of a linear pattern–color separable model (Bäuml & Wandell, 1996; Poirson & Wandell, 1993). According to this model the mean rate of cone absorptions from a grating's bar undergoes a linear transformation into an intermediate color representation and the resulting color values are then scaled by an amount that depends on the local spatial pattern. As a corollary, this model predicts that incremental and decremental cone signals undergo the same transformations and thus are processed symmetrically. Although the results from the present experiment confirm those from the previous studies by demonstrating that this linear model provides a useful first-order account of the pattern effect, the results do also show that increments and decrements are not processed symmetrically. Indeed, the subjects' matches reveal systematic differences between the processing of lights which are incremental relative to the uniform background field and the processing of lights which are decremental. This asymmetry between incremental and decremental signals can be found for all three types of cone signals.

For each spatial frequency, both the matches to incremental and the matches to decremental cone signals scale roughly linearly with pattern contrast. The effect of spatial frequency on these scalings, however, is often larger for the incremental signals than for the decremental ones. Indeed, there is a tendency in the matches of both subjects that with increasing spatial frequency the incremental matches deviate more from physical matches than the decremental ones. The size of the increment–decrement asymmetry, therefore, increases with spatial frequency. The present results demonstrating increment–decrement asymmetries in spatial pattern

[4] I also evaluated the question of whether the predictions of the matches would improve if we did not use a representation based purely on cone contrasts. The cone contrast representation does not include any color appearance contribution from the background and thus corresponds to a complete discounting of the background. Several reports in the literature, however, suggest that, at least under certain conditions, the background may not be discounted completely (e.g., Chichilnisky & Wandell, 1999; Shevell, 1978). For both the CID and the PID model, this hypothesis adds 3 new parameters corresponding to an additive color appearance effect from the background. For none of the two models this generalization led to a substantial improvement in model fit. In both cases the reduction in residual error was only on the order of 0.10–0.20 units. An analogous picture arose when no longer including separability into the models and fitting a more general pattern-dependent ID model to the data.

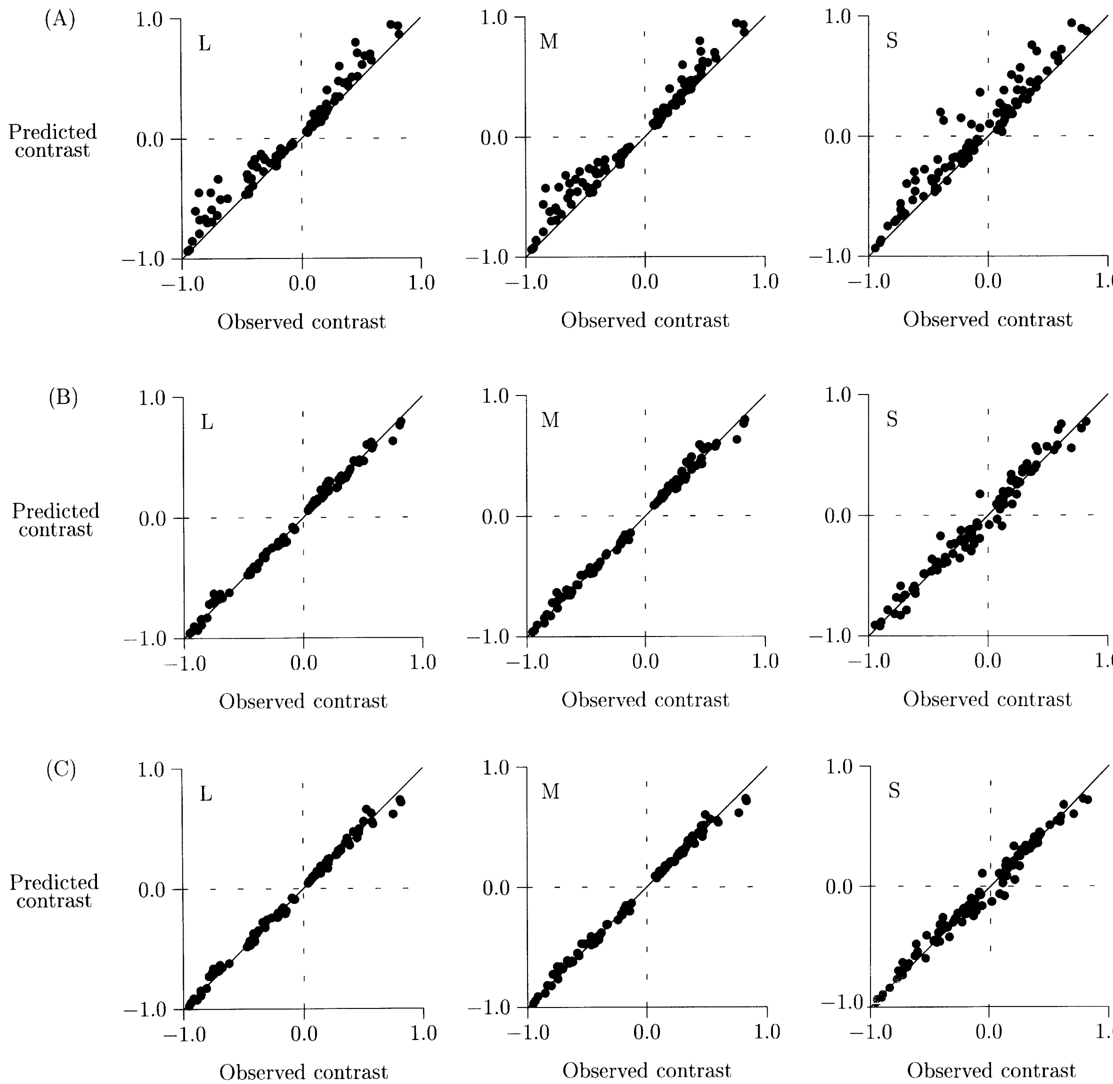

Fig. 4. Scatterplots of model fit: (A) Fit of the linear pattern–color separable model; (B) Fit of the pattern–color separable CID model; (C) Fit of the pattern–color separable PID model. The *LMS* coordinates of subject TK's mean matches are compared with the predictions of these matches which are based on the three models.

complement those from recent adaptational studies, in which evidence for increment–decrement asymmetries has been reported as well (Chichilnisky & Wandell, 1996, 1999; Mausfeld & Niederee, 1993). They show that increment–decrement asymmetries are not restricted to uniform lights but rather occur in spatial pattern as well. They additionally show that decrements are not only more responsive to changes in background color than increments (Chichilnisky & Wandell, 1996) but are also less influenced by pattern than increments. Taken together these findings suggest that the color appearance of decremental objects is generally less influenced by changes in viewing context than the color appearance of incremental objects (see also Bäuml, 2001; Burton, Nagshineh, & Ruddock, 1977; Delahunt & Brainard, 2000; Schirillo, 1999a,b; Schirillo & Shevell, 1996).

The existence of the increment–decrement asymmetry necessitates a generalization of the linear pattern–color separable model. The linear pattern–color separable model is a two-stage model, consisting of a linear color transformation in the first stage and a pattern-dependent linear scaling in the second stage. To incorporate an asymmetric processing of incremental and decremental color signals, two possible generalizations of the model arise. As a first generalization, the model's first processing stage is modified and it is assumed that the color transformation depends on the signs of the cone signals, thus leading to different weights for incremental and decremental cone signals (CID model). As a second generalization, the model's second processing stage is modified and it is assumed that pattern scaling depends on the signs of the pathway signals of the intermediate color representation (PID model). Both generalizations in fact improve the description of the data considerably and lead to a reasonable account of the subjects' matches. Because both models describe the data about equally well, the present data do not come up with a preference for one of the two models. The question of whether the increment–decrement asymmetry is caused by asymmetric weighting of incremental and decremental cone signals or by asymmetric pattern scaling of incremental and decremental postreceptoral signals thus must remain open in this first step. The present data, however, do come up with an indication about which mechanism carries most of the asymmetry. Analyses on the basis of both models suggest that the increment–decrement asymmetry in spatial pattern is caused mainly through an asymmetric processing of a white–black mechanism and much less, if at all, through an asymmetric processing of a red–green and yellow–blue mechanism.

As mentioned above, evidence for increment–decrement asymmetries in spatial pattern was seen in prior work as well (Bäuml & Wandell, 1996; Poirson & Wandell, 1993). The effect, however, was small and hardly measurable. In the present study the asymmetries were more clear-cut and less hard to measure. At least two reasons may have contributed to this difference between the present and prior studies. As a first reason, in the present study we obtained four (KK) or even eight (TK) matches for each stimulus condition, so that quite reliable estimates of the matching values could be obtained. In the prior studies only two matches were obtained for each stimulus condition, a fact which might have obscured the increment–decrement asymmetry to some extent. As a second reason, the size of the asymmetry seems to vary somewhat with subject. Evidence for such a variation is seen in the present data, in which particularly the matches of subject TK show clear asymmetries, whereas the matches of subject KK reveal smaller asymmetries. Evidence for such a variation has also been reported from the adaptational literature (Chichilnisky & Wandell, 1999). Obviously, the chances to find substantial increment–decrement asymmetries can vary with subject.

The emphasis of the present study has been on the question of whether increment–decrement asymmetries also exist in spatial pattern and, if they do, how they vary with pattern. Having demonstrated that such asymmetries exist and that they increase with spatial frequency, in the next step the question arises of whether the asymmetries occur through asymmetric weighting of incremental and decremental cone signals or through asymmetric pattern scaling of incremental and decremental postreceptoral signals. To come up with a definitive answer on this point matches for a larger range of spatial frequencies and possibly also a larger number of color directions will be necessary than has been available in the present study. Such a larger data base will also permit further tests of the hypothesis that increment–decrement asymmetries in spatial pattern are mediated mainly through a white–black mechanism.

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