Separate Processing of Chromatic and Achromatic Contrast in Color Constancy

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Received 2 June 2003; revised 14 June 2004; accepted 10 August 2004

Abstract: In a preceding study we measured human color constancy in experimental conditions in which simulated illuminants and surface colors were varied in the chromatic domain only. Both illumination level and sample reflectance were fixed in that study. In the present study we focus on the achromatic dimension, both with respect to luminance contrast (Experiment 1) and overall illumination (Experiment 2). Sample-to-background contrast was varied over a two log unit range that covered both luminance decrements and increments. Illumination level was varied either for the short-wave-sensitive (S) cones only or for all three cone types simultaneously. Data predictions on the basis of a cone-specific response function, derived in our preceding study, indicate that this model has difficulty in accommodating the results obtained with varying luminance contrast. However, a modified version of the response function, incorporating separate processing of color and luminance contrast, correctly predicts the data from both the present and the previous study. We also show that over a limited stimulus range our earlier response function is mathematically equivalent to Jameson and Hurvich's model of brightness contrast. The latter model, cast into a trichromatic format, performs equally well or better than our original response function, but is less accurate than our modified model. © 2005 Wiley Periodicals, Inc. Col Res Appl, 30, 172–185, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20105

Key words: color constancy; cone-specific contrast; luminance contrast; luminance normalization; brightness model

INTRODUCTION

Reflected light conveys information about changes in both surface reflectance and ambient illumination. How the visual system keeps track of these two variables is a problem typically treated in the context of color constancy. However, the problem is not confined to the chromatic domain. It has also to be solved in monochromatic vision or by trichromats that are forced to operate in the monochromatic mode. These conditions can be encountered in daily life, for example, under illumination by sodium light, when seeing in the dark (scotopic vision) or when watching black-and-white TV or motion pictures. Despite the lack of spectral information under these circumstances, the visual system may nevertheless still be capable of recovering (achromatic) reflectance, as is also evidenced by studies on lightness constancy (e.g., Refs. [1–3]).

The functional analogy between color constancy and lightness constancy (both separating light from matter) invites a theoretical approach in which color constancy is treated as the trichromatic extension of lightness constancy (cf. Hurlbert[4]). That is, the processing of lightness within three cone-specific channels, as is also the basic principle underlying the well-known retinex model.[5,6] In the retinex model three cone-specific lightness values (so-called designators) are computed that register the perceived color as a point in a three-dimensional lightness space. Because these designators are resistant against changes in illumination they can provide a basis for color constancy. There is evidence showing that (local) contrast, rather than lightness, is the stimulus variable of interest[7–9] but that does not affect the rationale of the trichromatic lightness approach.

We have shown[10] that color constancy involves more than just the processing of (trichromatic) contrast. Contrary to the predictions of contrast or lightness models we found an effect of the *absolute* level of (cone-specific) illumination. This effect, which has also been noticed in the study of McCann, McKee, and Taylor,[11] could be quantified by assuming a cone-specific "response function" as follows:

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$$R = (Q_w)^r \log\left(k \frac{Q_j}{Q_w}\right), \quad (1)$$

where Q_j/Q_w represents the cone-specific contrast of samples (j) relative to a white background (w). The term $(Q_w)^r$, which varies in proportion with the illuminant, makes R dependent on absolute light level. With $r = 0.33$ and $k = 4.35$, Eq. (1) provides an accurate description (95% explained variance) of data obtained over a wide range of colored illuminants.[10] It could also be shown that Eq. (1) correctly predicts the breakdown of color constancy in conditions where the illuminant is spectrally impoverished.[12]

Equation (1) was derived from experiments in which color was the main stimulus variable of interest. The test illuminants and test samples varied in chromaticity but not in luminance (except for variations because of the interaction between samples and illuminant). Variations in cone-specific contrast (Q_j/Q_w) could thus be produced only by spectral modulation of illuminants and sample reflectances.

Here we address the question whether Eq. (1) may also accommodate the results from experiments in which cone contrast is modulated by luminance rather than color. Therefore we presented the same set of test samples Q_j on backgrounds Q_w that varied in reflectance. We also did the reverse experiment, by varying sample reflectance while keeping background reflectance fixed. Having already extensively studied the effect of illuminant color, we now only compared the samples under a fixed pair of illuminants, blue and yellow. This combination, which strongly modulates the short-wave-sensitive (S) cones, had been found to be most critical for testing the validity of Eq. (1).

In addition to studying the effect of contrast (Experiment 1) we also measured the effect of overall illumination level (Experiment 2). We did this for a single sample contrast (50% under white light) and used the same blue and yellow lights as in Experiment 1. In Experiment 2, however, these lights were not necessarily equi-luminant, but could be varied so as to produce sizable differences in (cone-specific) background luminance Q_w.

The experimental results we obtained are difficult to account for on the basis of Eq. (1). We searched for alternative ways of quantifying the data, thereby going back to some of the earlier studies on brightness contrast. We found that a trichromatic implementation of Jameson and Hurvich's[13] model for brightness contrast provided a reasonably good description of our data. This was quite unexpected, considering the different nature of the stimulus transformations involved. We show, however, that these functions are mathematically equivalent over a limited stimulus range. Beyond that range, the equivalence no longer holds.

Although the Jameson and Hurvich model (later to be referred to as JH model) provides a better description of our experimental data than Eq. (1), it still requires a rather complex adjustment of its adaptation constant k (to be discussed). We therefore decided to give the response function in Eq. (1) a second chance and searched for possible modifications. As a result we arrived at a normalized form of Eq. (1), giving a simpler and more accurate description of the data. The normalization takes place in the luminance domain, dividing the (cone) input variables (Q_j and Q_w) of the response function Eq. (1) by the associated luminance values (Y_j and Y_w). Such a normalization is also performed in the MacLeod–Boynton color space.[14] This implies deriving a luminance-free (i.e., purely chromatic) cone-specific contrast signal. Such a step would seem quite natural in view of the evidence for separate chromatic and achromatic postreceptoral mechanisms (e.g., Refs. [15–21]). The role of the luminance variable in color constancy (and color vision in general) has always been a difficult issue. We therefore decided not to lightly dismiss other approaches than our own and consequently present the data together with the predictions derived from both the modified version of Eq. (1) and those computed with the trichromatic version of the Jameson and Hurvich model.[13]

METHODS

Because the methods were essentially the same as in a preceding study,[10] we present only a brief summary of the general aspects that apply to both Experiment 1 and 2.

General

Equipment. The stimuli were generated on a daily calibrated Sony high-resolution color monitor (8-bit luminance resolution per channel), controlled by a Sun 3/260 computer. A recalibration algorithm was used that enabled color reproduction within an average error of 0.005 CIE x,y units.[22] Subjects adjusted colors with the mouse. Movements of the mouse were translated by the computer into movements in CIE x,y space. Two of the three mouse buttons were used for increasing or decreasing luminance; the third mouse button was pressed when a satisfactory match was obtained (of match to test sample), after which a new test sample was presented. A large box-shaped hood, fitted to the front of the display, restricted the field of view to the stimulus pattern, which subtended a visual angle of $14.3 \times 19.5°$ at the observation distance of 1 m. The two viewing holes in the box were alternately opened and closed by mechanical shutters, so that the "match" pattern was seen by one eye, then the "test" pattern was seen by the other eye.

Simulation of Object–Illuminant Interaction. We used the same trichromatic reflection paradigm as in two preceding studies.[9,10] It describes reflected light, L_r, in terms of display primary luminances (Y_R, Y_G, Y_B) that are independently modulated by surface-specific reflection coefficients (a_R, a_G, a_B) and illuminant-specific emission coefficients (b_R, b_G, b_B). So, for any sample-illuminant combination, the light reflected from the sample is given by the following:

$$L_r = a_R b_R Y_{R_w} + a_G b_G Y_{G_w} + a_B b_B Y_{B_w}, \quad (2)$$

where Y_{R_w}, Y_{G_w}, and Y_{B_w} are the primary luminances required for producing white light. This is the case for a white surface ($a_R = a_G = a_B = 1$) under white light ($b_R = b_G = b_B = 1$). The XYZ tristimulus values of the colors that are produced by the simulation described in Eq. (2) are the same XYZ values that are obtained when viewing real Munsell

TABLE I. CIE *x,y* chromaticities and luminance *Y* of the 35 samples and the background used, either under blue or yellow illumination.[a]

Sample number	Blue light			Yellow light		
	x	*y*	*Y* (cd/m^2)	*x*	*y*	*Y* (cd/m^2)
1	0.2981	0.2715	5.86	0.4421	0.4503	6.18
2*	0.2189	0.1859	6.39	0.3832	0.4461	5.66
3	0.2426	0.2390	6.02	0.3824	0.4758	5.93
4*	0.2410	0.1905	6.33	0.4285	0.4242	5.80
5*	0.2411	0.2666	5.91	0.3583	0.5006	5.97
6	0.2897	0.2813	5.83	0.4232	0.4647	6.16
7*	0.2091	0.1980	6.29	0.3452	0.4759	5.66
8	0.3695	0.2869	5.77	0.5090	0.4124	6.43
9	0.3875	0.4275	5.51	0.4361	0.4805	6.42
10	0.2590	0.2410	3.00	0.4100	0.4600	3.00
11	0.2609	0.2607	5.92	0.3965	0.4752	6.03
12	0.3141	0.2311	6.01	0.5000	0.4026	6.23
13	0.2590	0.2410	10.8	0.4100	0.4600	10.8
14	0.4091	0.3697	5.58	0.4851	0.4414	6.49
15	0.2743	0.3452	5.68	0.3613	0.5183	6.14
16*	0.2186	0.2283	6.09	0.3419	0.4951	5.80
17	0.2862	0.2461	5.96	0.4478	0.4390	6.12
18*	0.2590	0.2410	6.00	0.4100	0.4600	6.00
19	0.2320	0.2203	6.13	0.3779	0.4700	5.84
20*	0.3085	0.2459	5.95	0.4783	0.4206	6.21
21	0.2585	0.1883	6.33	0.4655	0.4023	5.90
22	0.1949	0.1724	6.54	0.3293	0.4639	5.44
23	0.2590	0.2410	1.20	0.4100	0.4600	1.20
24	0.2164	0.2565	5.96	0.3165	0.5227	5.85
25	0.2563	0.2152	6.14	0.4302	0.4370	5.95
26	0.2590	0.2410	9.00	0.4100	0.4600	9.00
27	0.2183	0.1668	6.58	0.4054	0.4184	5.56
28	0.1928	0.2003	6.29	0.2968	0.5048	5.58
29*	0.3397	0.2911	5.78	0.4758	0.4342	6.33
30	0.2414	0.2060	6.21	0.4117	0.4430	5.85
31*	0.2769	0.2166	6.12	0.4632	0.4185	6.05
32*	0.3053	0.3326	5.69	0.4077	0.4860	6.22
33	0.2727	0.2305	6.04	0.4424	0.4365	6.05
34*	0.3480	0.3416	5.65	0.4486	0.4612	6.34
35	0.2323	0.2090	6.20	0.3895	0.4573	5.81
Background	0.2590	0.2410	12.0	0.4100	0.4600	12.0

[a] In this particular condition, the background (shown in the last entry in the table) conveys the exact color and luminance of the illuminant (100% reflectance). The 11 test samples used for obtaining the color matches are indicated by an asterisk in the first column.

samples under a six-wavelength illuminant. These six wavelengths form three pairs of two wavelengths, with intensity ratios such that the *x,y* chromaticities of the two-wavelength mixtures are identical to the *x,y* chromaticities of the display primaries. For the CRT display used in our experiments, the three wavelength pairs are 604 and 492 nm (for Red), 563 and 503 nm (for Green), and 528 and 458 nm (for Blue).

Samples. In our simulations of surface colors we used 35 Munsell samples, 30 chromatic samples (10 from the 5/6 series, 10 from 5/4, and 10 from 5/2), and 5 achromatic samples (10, 25, 50, 75, and 90% luminous reflectance). All chromatic samples were presented at the same luminous reflectance (under white light). Eleven samples were selected as test samples, 10 from the Munsell 4/5 series and 1 neutral (of the same luminous reflectance as the others). These test samples are indicated by an asterisk in Table I, where the CIE *x,y* chromaticities of the simulated Munsell samples are shown under blue and yellow illumination. The latter two are the illuminants used in Experiment 1 and 2. Also shown in Table I are the luminances (*Y*) of the samples and the background of the stimulus patterns (to be discussed). These are the luminances found in the condition where the illuminants produce a luminance of 12 cd/m^2 (at 100% luminous reflectance) and where sample and background have luminous reflectances (under white light) of 50 and 100%, respectively. The simulated sample and background reflectances are varied in Experiment 1, hence their luminances vary accordingly.

Procedure. Three observers, the two authors and a naive subject, participated in the experiments. Their task was to match the color and brightness of a patch in the "match" pattern to the corresponding patch in the "test" pattern. The two patterns were seen successively by the left and right eye (haploscopic matching). From condition to condition, the role of the eyes (test or match) was interchanged to prevent possible long-term effects of chromatic adaptation. The test and match pattern were switched every 5 sec to keep both eyes equally exposed to their respective illuminant conditions. There was no time restriction; the observer could view the two illuminant conditions until completely satisfied with the match. The precision of the match, which is actually a short-term memory task, was quite satisfactory.[10] Average deviations in terms of CIE chromaticity coordinates ($\Delta\, xy$) are on the order of 1%.

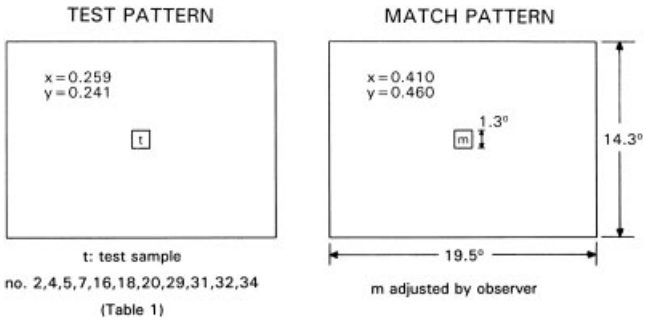

FIG. 1. Stimulus configuration (center-surround) of Experiment 1.

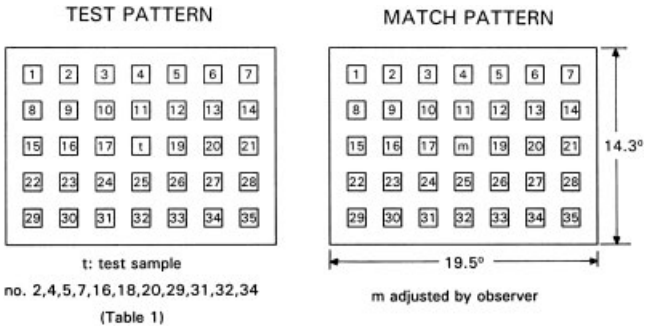

FIG. 3. Stimulus configuration (array) of Experiment 2.

Experiment 1: Varying Luminance Contrast

In Experiment 1, a simple center-surround stimulus was used, as shown in Fig. 1. It has been demonstrated in other studies[23,24] that the results obtained with the center-surround stimuli are not qualitatively different from those obtained with complex stimulus configurations. The test and match pattern were illuminated by blue ($x = 0.259$, $y = 0.241$) and yellow ($x = 0.410$, $y = 0.460$) light, respectively. The samples under blue light ("test" illuminant) had to be matched by samples under yellow light ("match" illuminant). In this way, the short-wave system (S-cones), which provides the most critical test for the validity of Eq. (1), receives a differential stimulation of about a factor 7, whereas the middle-wave-sensitive (M) and long-wave-sensitive (L) system remain at about the same level of activation. The *x,y* chromaticities of the test samples under blue light, presented in the center of the test pattern, and those of the backgrounds (surrounds), are given in Table I.

As shown in Fig. 2, the luminance contrast between sample (j) and (white) background (Y_j/Y_w) was varied by either manipulating the luminance of the test samples (upper panel) or the luminance of the background (lower panel). The range of contrasts in Fig. 2 may be related to reflectance in various ways depending on what reflectance is to be assigned to a particular luminance. In our previous study a (fixed) background luminance of 12 cd/m^2 was taken as representing 100% reflectance. Doing the same for the present stimuli would imply that luminances in excess of 12 cd/m^2 represent fluorescent stimuli, reflecting more than 100%. If, conversely, 100% reflectance is assigned to, say, 40 cd/m^2, then all stimuli can be considered as surface reflectances in the range from 1.5 to 90%. However, this reflectance interpretation is just as arbitrary as the former one, so we prefer to describe the stimulus in terms of contrast (Y_j/Y_w) rather than reflectance.

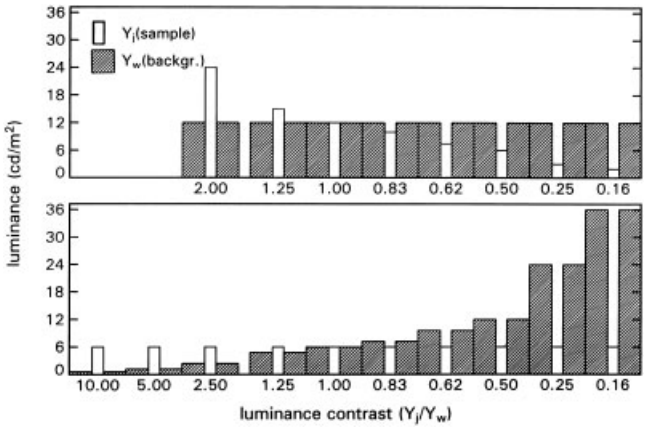

FIG. 2. Schematic overview of the two sets of luminance profiles (sample surrounded by the background) used in Experiment 1. A range of corresponding luminance contrasts (Y_j/Y_w) was obtained by either varying sample reflectance around a fixed background reflectance (upper panel) or vice versa (lower panel). The luminance values shown here apply to samples and background under white light. The actual values under blue or yellow light are listed in Table I.

Experiment 2: Varying Illumination Level

In Experiment 2, the stimulus pattern was a rectangular array consisting of 35 square samples on a homogeneous background (Fig. 3). This stimulus was also used in our preceding studies.[1,11,13] The numbers (1–35) of the samples shown in Fig. 3 correspond to the numbers in the first column of Table I, where the colors are specified under yellow and blue illumination. In contrast to Experiment 1, the reflectances of the samples and the background are now fixed at 50 and 100%, respectively, the standard configuration of our previous study.

Four illuminant conditions are used in Experiment 2, each with a different combination of test and match illuminant. The *x,y* chromaticities and luminance levels of these four illuminant combinations are listed in Table II, which is presented under Results. The different (cone-specific) illumination levels in test and match eye were implemented by either a color difference, a luminance difference, or both.

THEORETICAL PREAMBLE

Presentation of Models

In this section we discuss three different models, each one representing a different attempt at quantifying the data. These are, in "evolutionary" order, the original Lucassen and Walraven[10] model, the Jameson and Hurvich[12] model, and the modified Lucassen and Walraven model. For brevity, the models are respectively referred to as JH or LW

TABLE II. Specification of the four illuminant conditions used in Experiment 2.

Condition	Test illuminant	Match illuminant	Cone-specific ratios (test/match)
	Blue	Blue	
	$x = 0.2590$	$x = 0.2590$	
	$y = 0.2410$	$y = 0.2410$	
1	$Y = 12.0$ cd/m^2	$Y = 12.0$ cd/m^2	
	$L = 3.815$	$L = 3.815$	1.000
	$M = 4.204$	$M = 4.204$	1.000
	$S = 7.850$	$S = 7.850$	1.000
	Blue	Yellow	
	$x = 0.2590$	$x = 0.4100$	
	$y = 0.2410$	$y = 0.4600$	
2	$Y = 12.0$ cd/m^2	$Y = 12.0$ cd/m^2	
	$L = 3.815$	$L = 4.038$	0.945
	$M = 4.204$	$M = 3.911$	1.075
	$S = 7.850$	$S = 1.087$	7.221
	Blue	Blue	
	$x = 0.2590$	$x = 0.2590$	
	$y = 0.2410$	$y = 0.2410$	
3	$Y = 21.08$ cd/m^2	$Y = 2.92$ cd/m^2	
	$L = 6.710$	$L = 0.928$	7.221
	$M = 7.385$	$M = 1.023$	7.219
	$S = 13.79$	$S = 1.910$	7.220
	Blue	Yellow	
	$x = 0.2590$	$x = 0.4100$	
	$y = 0.2410$	$y = 0.4600$	
4	$Y = 21.08$ cd/m^2	$Y = 2.92$ cd/m^2	
	$L = 6.710$	$L = 0.983$	6.817
	$M = 7.385$	$M = 0.952$	7.757
	$S = 13.79$	$S = 0.264$	52.24

models, whereby the latter may represent the original as well as the modified version.

As already mentioned in the Introduction, the LW and JH model are mathematically equivalent over a limited stimulus range. This finding is of theoretical significance considering the radically different ways in which the test (Q_j) and background (Q_w) are treated by the JH and LW model. The JH model performs a subtractive operation, whereas the LW model is multiplicative in nature (taking ratios). As discussed henceforth, the reason for the mathematical equivalence can be traced to the fact that taking the logarithm of the ratio of two signals (as applies to the LW model) may not be that different from taking the difference of these signals after being transformed by a cube root transformation (as applies to the JH model).

Mathematical Equivalence of the JH and LW Model

Both the LW and JH model describe a response function in which test and surround stimulus (Q_j and Q_w) provide the input of a single channel. In case of the JH model this is the "brightness channel," but we use it here for describing the output of cone-specific pathways. Using our nomenclature, the JH response function takes the following form:

$$R_{JH} = \frac{c(Q_j^n - kQ_w^n)}{(1-k)^2}, \tag{3}$$

where k is a constant dependent on the particular stimulus configuration and the exponent n typically takes the value $n = 0.33$. As for the proportionality factor c, Jameson and Hurvich[12] could describe their results by simply assuming $c = 1$.

The LW response function is described by Eq. (1), with $r = 0.33$ and $k = 4.35$:

$$R_{LW} = (Q_w)^{0.33} \log\left(4.35\,\frac{Q_j}{Q_w}\right). \tag{4}$$

The mathematical equivalence of Eqs. (3) and (4) follows from the fact that, as is shown in Fig. 4, one may write:

$$\log(x) \approx x^{0.33} - 1. \tag{5}$$

Upon substitution of $x = 4.35Q_j/Q_w$ in Eq. (5) this equation reads as follows:

$$\log\left(4.35\,\frac{Q_j}{Q_w}\right) \approx \left(4.35\,\frac{Q_j}{Q_w}\right)^{0.33} - 1. \tag{6}$$

When rewriting the right-hand side of Eq. (6) this equation becomes the following:

$$\log\left(4.35\frac{Q_j}{Q_w}\right) \approx \left(4.35\frac{Q_j}{Q_w}\right)^{0.33} - \left(\frac{Q_w}{Q_w}\right)^{0.33}$$
$$= \left(\frac{1.624Q_j^{0.33} - Q_w^{0.33}}{Q_w^{0.33}}\right) = 1.624\left(\frac{Q_j^{0.33} - 0.617Q_w^{0.33}}{Q_w^{0.33}}\right). \tag{7}$$

Multiplying both sides of Eq. (7) with $Q_w^{0.33}$ yields the following:

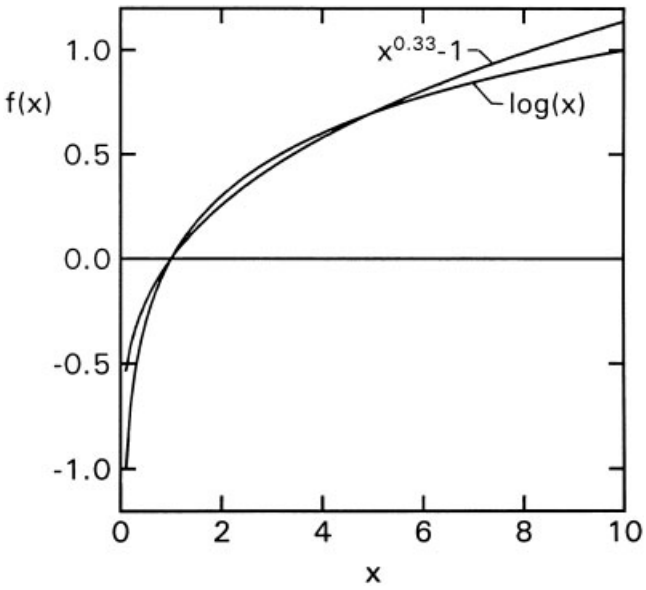

FIG. 4. Comparison of the functions log(x) and $x^{0.33} - 1$. Over a certain range of x, the two functions closely resemble each other.

$$Q_w^{0.33} \log\left(4.35 \frac{Q_j}{Q_w}\right) \approx 1.624(Q_j^{0.33} - 0.617 Q_w^{0.33}) \quad (8)$$

The left-hand side of Eq. (8) is the LW response function, whereas the right-hand side corresponds to the JH function, with $n = 0.33$, $k = 0.617$, and $c = 1.006$. These values closely correspond to the values cited by Jameson and Hurvich[13], who found $n = 0.33$, $k = 0.6$, and $c = 1$ to describe the data of the classical Hess and Pretori[25] experiments on brightness contrast.

The question that is raised by the above equivalence is whether the visual system encodes *differences* between center and surround (Jameson and Hurvich) or contrast *ratios* between center and surround (Lucassen and Walraven). The answer to this question cannot be given as long as the approximation in Eq. (5) holds. As shown in Fig. 4, this is the case for the range $0.5 \leq x \leq 6$. With 4.35 Q_j/Q_w substituted for x, this range is $0.23 \leq Q_j/Q_w \leq 1.38$, a range that comprises both increments and decrements. Within each cone class, the value of Q_j/Q_w is determined by the chromatic difference as well as the luminance difference between sample and background. However, the chromatic difference is more or less limited by the spectral compositions of the center and surround, whereas the luminance difference can be manipulated almost unrestrictedly. Therefore, a critical test for discriminating between the LW and JH model would require that the luminance contrast between sample and background is varied well outside the range $0.23 \leq Q_j/Q_w \leq 1.38$. This is what we did in our Experiment 1.

The Modified LW Model

As shown under Results, the LW response function, Eq. (1), is not well suited to describe the present data. We therefore tried to modify Eq. (1) and thereby arrived at a model in which the cone-specific inputs Q_j and Q_w are normalized for luminance. The modified response function can be written as follows:

$$\tilde{R}_{LW} = (\tilde{Q}_w)^{0.33} \log\left(2.6 \frac{\tilde{Q}_j}{\tilde{Q}_w}\right), \quad (9)$$

where $\tilde{Q}_w$ and $\tilde{Q}_j$ are the luminance-normalized cone inputs as follows:

$$\tilde{Q}_w = \frac{Q_w}{Y_w}; \quad \tilde{Q}_j = \frac{Q_j}{Y_j}. \quad (10)$$

The luminance normalization makes $\tilde{R}_{LW}$ unresponsive to variations in the cone input that result from changes in luminance. Any change in Y will cause a proportional change in Q, but because Y enters the denominator in Eq. (10), there will be no change in $\tilde{Q}$. Equation (9) can also be used to describe the data of our earlier study. The reason we arrived at Eq. (1) instead is addressed under Discussion.

Data Predictions

The data predictions can be derived by assuming that the subjects receive equal responses R from test and match samples, so that

$$R^m = R^t. \quad (11)$$

The superscripts m and t denote "match" and "test," respectively. For the original LW model, as described by Eq. (1), substitution of the latter into Eq. (11) yields the following:

$$(Q_w^m)^r \log\left(k \frac{Q_j^m}{Q_w^m}\right) = (Q_w^t)^r \log\left(k \frac{Q_j^t}{Q_w^t}\right). \quad (12)$$

From this equation the cone input of the matching sample, Q_j^m (for cone types L, M, and S), can be solved, that is:

$$Q_j^m = \frac{Q_w^m}{k}\left[k \frac{Q_j^t}{Q_w^t}\right]^{(Q_w^t/Q_w^m)^r}, \quad (13)$$

with $k = 4.35$ and $r = 0.33$. For the modified version of the LW model the prediction is the same, but now in terms of luminance normalized cone inputs $\tilde{Q}$, so that

$$\tilde{Q}_j^m = \frac{\tilde{Q}_w^m}{k}\left[k \frac{\tilde{Q}_j^t}{\tilde{Q}_w^t}\right]^{(\tilde{Q}_w^t/\tilde{Q}_w^m)^r}, \quad (14)$$

with $k = 2.6$ and $r = 0.33$. Note that $\tilde{Q}_j^m$ is a luminance-normalized cone input, in accordance with Eq. (10). To compute the absolute cone input Q_j^m, one has to multiply $\tilde{Q}_j^m$ by Y_j^m. However, Y_j^m is an unknown variable (to be set by the subject). This problem is addressed when discussing the results. It is shown that the data indicate a relationship between Y_j^m and the other (known) luminance variables (Y_w^m, Y_j^t, Y_w^t) from which Y_j^m can be solved.

For the JH model, we follow the same procedure, substitution of Eq. (3) into Eq. (11), and thus obtain the following:

$$Q_j^m = [(Q_j^t)^n - k((Q_w^t)^n - (Q_w^m)^n)]^{1/n}, \quad (15)$$

with $k = 0.617$ and $n = 0.33$. Because $Q_j^m \geq 0$, the term inside the brackets on the right-hand side of Eq. (15) should also be ≥ 0.

All predictions will be expressed in terms of Q_j^m, the cone input (per receptor system) required for matching the test stimulus (Q_j^t). The quantity Q has the dimension of Candelas per square meter per receptor system. It can be derived from the CIE x,y,Y specifications of the stimuli for a given set of cone spectral sensitivities.[26,27] A discussion of the Q unit, and the procedures for deriving Q from the CIE x,y,Y specifications, is presented in Appendices C and D of Ref. 1.

RESULTS

Experiment 1: Varying Luminance Contrast

In Experiment 1 the test/background contrast (Q_j/Q_w) was varied by changing the luminance of either the test field (Y_j) or the background (Y_w). Figure 5 shows a comparison of predictions and results, as obtained with variable test and fixed background (see the top panel in Fig. 2). The left three panels relate to the original unnormalized LW model predictions (for L-, M-, and S-cones, respectively), whereas the three right panels show the same for the JH model.

When comparing the predictions of the LW and JH model in Fig. 5, it is clear that these only differ for the S-cones. The reason for that is that the blue (test) and yellow (match) illuminant produce a differential effect in the S-cones only. The L- and M-cones hardly register a difference in illumination when changing from the yellow to the (equi-luminant) blue background. Consequently, the LW and JH model will concur in their predictions, that is, interocular identity matches (but not without some scatter) for both the L- and M-cone systems. Therefore, different predictions only show up in the S-cone data, as is also apparent from the data obtained with fixed sample luminance and varying background. The latter are shown in Fig. 6. The data plotted in Fig. 6 show the same pattern as those presented in Fig. 5 and for the same reason. Here again the difference in model predictions are found only for the S-cones, the latter being strongly modulated when switching between blue and yellow light.

When comparing the performance of the LW and JH model, it is clear that the latter can better account for the (S-cone) data. The problem with the LW model is that it does not correctly predict the results from samples that are much brighter than the background ($Y_j > Y_w$). This is shown in Fig. 7, where we plotted ΔQ_j^m, the error in predicting Q_j^m, as a function of Y_j/Y_w, the sample/background contrast (in the test pattern). These are the pooled data from Figs. 5 and 6, so increasing values of Y_j/Y_w may be because of either an increase in Y_j or a decrease in Y_w. Figure 7 shows that for decrements ($\log(Y_j/Y_w) < 0$) the LW model performs slightly better than the JH model. However, for increments the LW model shows increasing mispredictions with increasing contrast, whereas the JH model does not show that

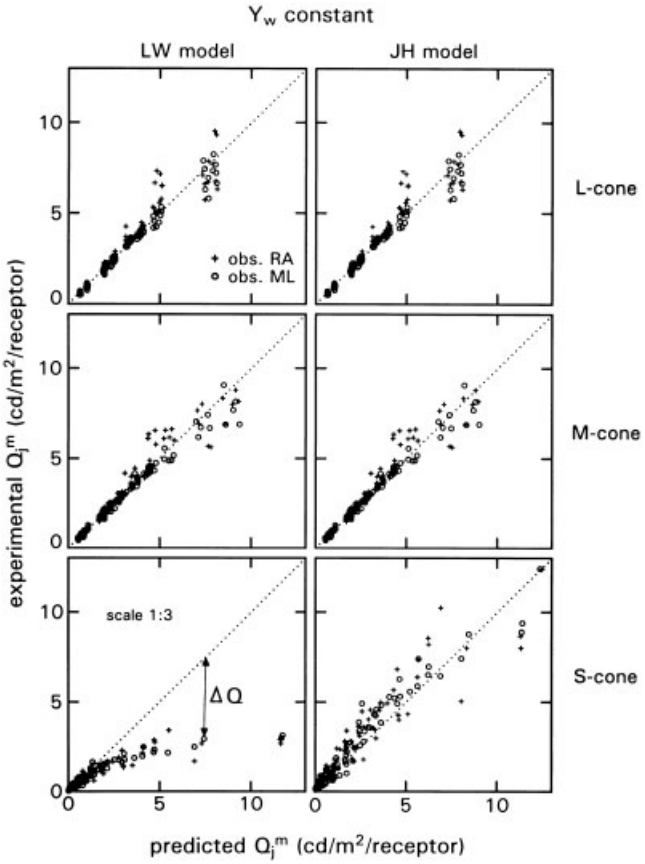

FIG. 5. Results of Experiment 1, for conditions with fixed background luminance (Y_w). Comparisons of predicted and experimentally obtained cone inputs of the color matches, shown separately for the L-, M-, and S-cones (top to bottom). Graphs on the left relate to the predictions obtained with the original unnormalized Lucassen and Walraven (1993) model; graphs on the right relate to those obtained with the Jameson and Hurvich (1964) model. Computations were performed with Eq. (13) and Eq. (15), respectively. Note the different scale for the lower left graph, where a value of 10 along the axes corresponds to a value of 30 in reality.

tendency. Clearly, the LW model, as described by Eq. (1), has to be modified to be applicable over the whole two-log-unit contrast range investigated here.

Experiment 2: Varying Illumination

In Experiment 1 we studied only the effect of relative luminance variation (contrast). The absolute level of (simulated) illumination was not varied when switching between the blue test and yellow match illuminant condition. In Experiment 2 we focus on varying the illumination, thereby testing the four conditions mentioned under Methods. The specifications of the four combinations of test (Q_w^t) and match (Q_w^m) illuminant are shown in Table II. These are given in terms of the luminance of the background (Y_w, cd/m^2) and the associated L-, M-, and S-cone inputs (Q_j, Candelas per square meter per receptor). In all conditions the sample/background contrast was $Y_j/Y_w = 0.50$, corresponding with 100% reflectance of the background and 50%

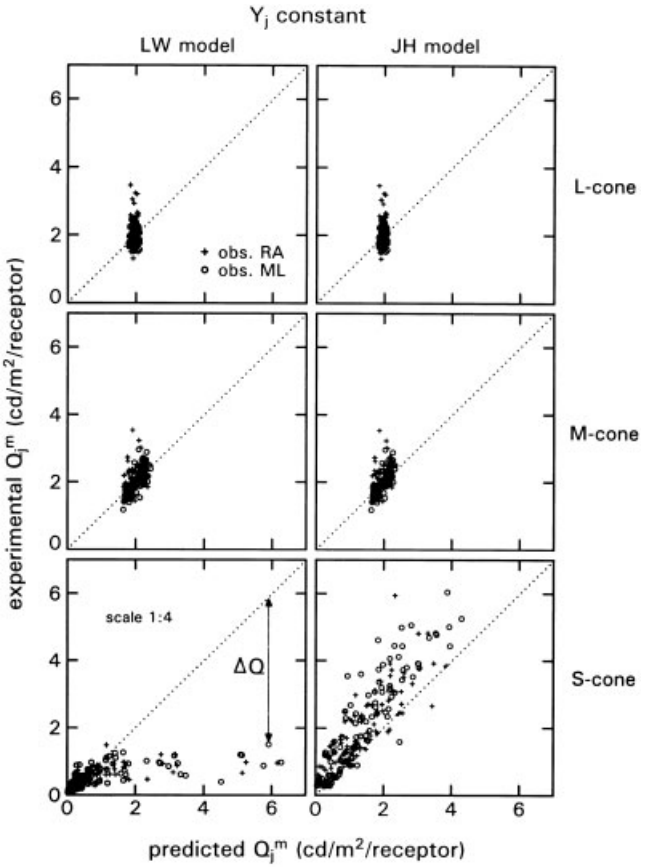

FIG. 6. Same as Fig. 5, but now for the conditions with fixed sample luminance (Y_j). Note the different scale for the lower left graph, where a value of 6 along the axes corresponds to a value of 24 in reality.

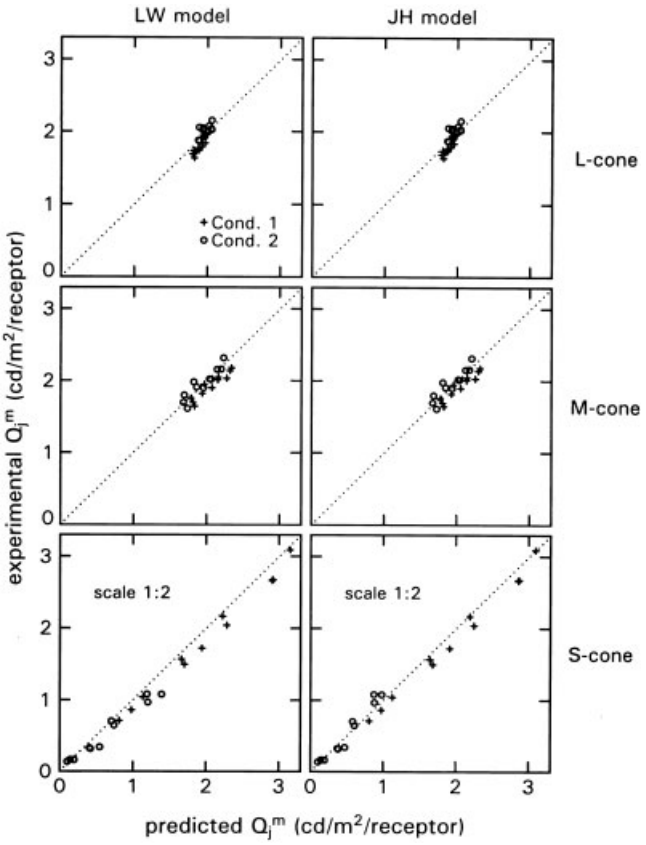

FIG. 8. Results of Conditions 1 and 2 of Experiment 2 (mean data of three observers). Comparisons of predicted and experimentally obtained cone inputs of the color matches, shown separately for the L-, M-, and S-cones (top to bottom). Graphs on the left relate to the predictions with the LW model; graphs on the right relate to those with the JH model. Computations were performed with Eq. (13) and Eq. (15), respectively. Note the different scale for the S-cone graphs.

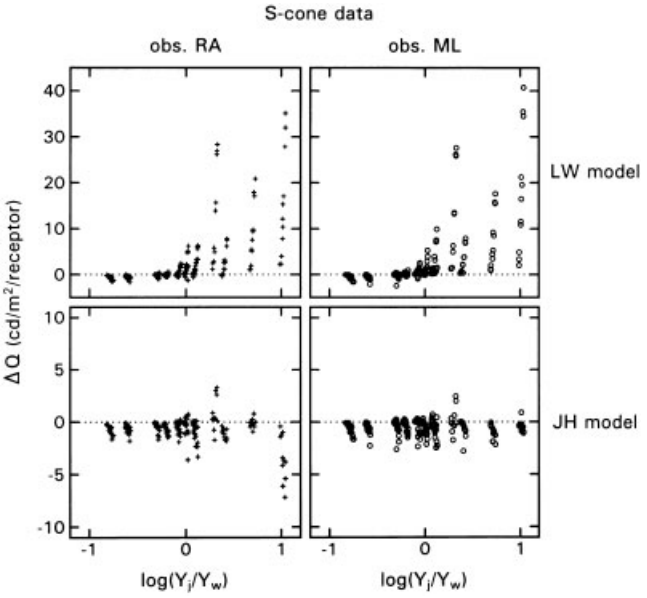

FIG. 7. Mispredictions, ΔQ, of the LW (top) and JH (bottom) models as a function of sample-to-background luminance contrast (Y_j/Y_w). Pooled S-cone data from Figs. 5 and 6. The dotted lines indicate perfect model predictions.

reflectance of the test sample (under white light). All experiments were performed with the 5×7 array configuration. The conditions shown in Table II were so chosen to introduce predetermined changes in cone activation (test/match ratio) by just a color change (Condition 2), a luminance change (Condition 3), or both (Condition 4). For the sake of completeness, there was also a "no-change" condition (Condition 1), which tests the absence of any effects when both eyes see the same stimulus. This condition also allows an estimate of the precision of making (haploscopic) identity matches. Note that in Conditions 3 and 4, the same factor of increase in cone input (about a factor 7) is achieved but by different means (a change in luminance and color respectively).

Because the results of the three observers participating in Experiment 2 were not systematically different, the averaged data were used for the analysis. For Conditions 1 and 2, these data and their model predictions are compared in Fig. 8. As can be seen from the close correspondence between obtained and predicted data, both the LW and JH model have no difficulty predicting the results of these two conditions. Recalling that in Experiment 2 the samples were

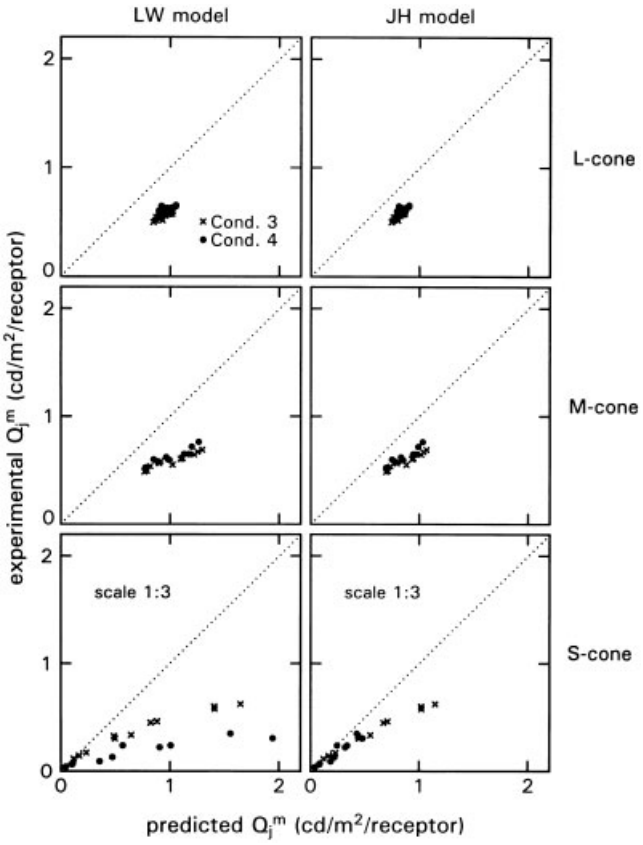

FIG. 9. Same as for Fig. 8, but now for Conditions 3 and 4.

always presented as decrements ($Y_j/Y_w = 0.50$), this was the expected outcome. We already found in Experiment 1 that mispredictions, as were obtained before with the LW model, occur only for incremental stimuli ($Y_j > Y_w$).

In Conditions 1 and 2 the change from test to match pattern was not accompanied by a change in the level of illumination ($Y_w^t = Y_w^m = 12$ cd/m^2). In Conditions 3 and 4, however, the levels of test ($Y_w^t = 21.08$ cd/m^2) and match ($Y_w^m = 2.92$ cd/m^2) illumination differed by about a factor 7. As can be seen in Fig. 9, which plots the results for Conditions 3 and 4, this poses a problem for both the LW and JH models. The predictions from both models fall below the identity diagonal in Fig. 9, which implies that the models overestimated the cone inputs required for matching the test samples. The failure of the two models might be possibly attributed to different pupil sizes (the match eye received less illumination). However, this possibility is ruled out, because control experiments with 4-mm artificial pupils for both eyes, yielded the same results. (The 4-mm pupil is smaller than the natural pupil at the illumination levels in question.)

The variables tested in Experiments 1 and 2, luminance contrast (Y_j/Y_w) and absolute illumination level (Q_w), clearly pose a problem for our model. This problem was not encountered in the study from which we derived the model,[10] because these were exactly the variables that were kept constant in that study. Consequently, the effect of these variables was reduced to a constant, a constant probably hidden somewhere within the constants of Eq. (1). Taking that as a starting point, we now take a closer look at the constants of Eq. (1).

Modifying Equation (1): Evidence for Luminance-Normalized Cone Signals

The results of Experiment 1 suggest that luminance contrast (Y_j/Y_w) is a variable that somehow must enter Eq. (1) to be able to better predict the results that we found for increments ($Y_j > Y_w$). In Eq. (1) the constant k acts as a multiplier on the cone-specific contrast (Q_j/Q_w), so this would make it a likely vehicle for implementing the effect of luminance contrast. That is, k should no longer be constant but instead depend on luminance contrast, according to the (unknown) function as follows:

$$k = f\left(\frac{Y_j}{Y_w}\right). \tag{16}$$

To derive the function relating k to Y_j/Y_w, we need to know what value of k would yield correct predictions on the basis of Eq. (1). Therefore we have to return to Eq. (13), which is used for computing the predicted Q_j^m. Using Eq. (13) and substituting $r = 0.33$ it can be shown that k must satisfy the following:

$$k_{LW} = \left(\frac{Q_j^t}{Q_w^t}\right)^{[(Q_w^m/Q_w^t)^{0.33}-1]^{-1}} \left(\frac{Q_j^m}{Q_w^m}\right)^{[(Q_w^t/Q_w^m)^{0.33}-1]^{-1}}, \tag{17}$$

where we labeled k with subscript LW for denoting the LW model. The same procedure, but now applied to Eq. (15), can be followed for the constant k_{JH} of the JH model as follows:

$$k_{JH} = \frac{(Q_j^t)^{0.33} - (Q_j^m)^{0.33}}{(Q_w^t)^{0.33} - (Q_w^m)^{0.33}}. \tag{18}$$

Both k_{LW} and k_{JH} depend on Q_j^m, an experimentally obtained value. If the model predictions would be perfect, then the obtained values of Q_j^m would show k to be constant. However, in reality we may expect k to depend on luminance contrast. Note that for $Q_w^t = Q_w^m$, that is, no illuminant change (for the receptor system in question), the JH model and the LW model predict k_{JH} and k_{LW} to reach infinity, respectively. As mentioned before, the condition $Q_w^t = Q_w^m$ more or less applies to the L- and M-cones in our experiment, so only the S-cone data are of interest for getting information on the function $k = f(Y_j/Y_w)$.

The S-cone data obtained in Experiment 1, the experiment in which Y_j/Y_w was varied, were used for computing both k_{LW} and k_{JH}. In Fig. 10, the values of k_{LW} and k_{JH}, averaged over the 11 samples per condition, are shown as a function of the inverse luminance contrast Y_w/Y_j, also averaged per condition. The left panel shows the result for k_{LW} computed with Eq. (17), the right panel the result for k_{JH} computed on the basis of Eq. (18). The two different data symbols used in Fig. 10 relate to the conditions where either the background luminance (Y_w) was fixed (upper panel in Fig. 2) or the sample luminance (Y_j) was fixed (lower panel in Fig. 2).

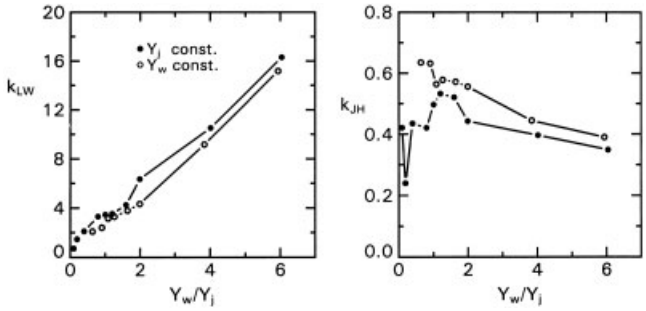

FIG. 10. Value of k_{LW} (left panel) and k_{JH} (right panel), computed with Eq. (17) and Eq. (18), respectively, as a function of the background-to-sample luminance contrast (Y_w/Y_j). Data points represent averages over 11 samples per condition (S-cone data from Experiment 1). Open and closed circles relate to conditions with fixed background and fixed sample luminance, respectively.

The results for the JH model show a rather complex relationship between k_{JH} and Y_w/Y_j, which does not lend itself to a simple mechanistic interpretation. The behavior of k_{LW} is better behaved in this respect. It linearly increases with Y_w/Y_j for both the conditions where Y_w = constant and Y_j = constant. We fitted these data points with the following:

$$k_{LW} = 2.6\,\frac{Y_w}{Y_j} \tag{19}$$

The significance of this result becomes immediately clear when substituting Eq. (19) into Eq. (1). The response function now becomes the following:

$$R_{LW} = (Q_w)^r \log\left(2.6\,\frac{Y_w Q_j}{Y_j Q_w}\right) = (Q_w)^r \log\left(2.6\,\frac{Q_j/Y_j}{Q_w/Y_w}\right) \tag{20}$$

and thus shows the cone contrast Q_j/Q_w to be normalized for luminance. This implies that R_{LW} responds only to contrast changes that are because of a change in chromaticity. Any change in luminance contrast (Y_j/Y_w) is negated because of the normalizing factor Y_w/Y_j.

When we tried to predict the data on the basis of Eq. (20), we still found this to be unsatisfactory for the data obtained in Conditions 3 and 4. These are the conditions in which we employed different illumination levels (Q_w) for the test and match eye. It turned out that also Q_w had to be normalized to fit the data. So, the cone inputs to Eq. (1) all have to be converted from absolute (Q) to luminance-normalized inputs as follows:

$$\tilde{Q} = \frac{Q}{Y}. \tag{21}$$

Consequently, Eq. (1) can now be rewritten as follows:

$$\tilde{R} = (\tilde{Q}_w)^r \log\left(k\,\frac{\tilde{Q}_j}{\tilde{Q}_w}\right) \tag{22}$$

with $r = 0.33$ and $k = 2.6$.

Because Eq. (22) applies to luminance-normalized contrast $\tilde{Q}_j/\tilde{Q}_w$, its predictions with respect to the predicted input of the match sample (j) are in the same terms. That is, in analogy to Eq. (13),

$$\tilde{Q}_j^m = \frac{\tilde{Q}_w^m}{k}\left[k\,\frac{\tilde{Q}_j^t}{\tilde{Q}_w^t}\right]^{(\tilde{Q}_w^t/\tilde{Q}_w^m)^r}. \tag{23}$$

On the basis of Eq. (23) we can predict $\tilde{Q}_j^m$ for each cone system, but not Q_j^m. Therefore we have to know Y_j^m so as to "denormalize" $\tilde{Q}_j^m$ according to the following:

$$Q_j^m = Y_j^m \tilde{Q}_j^m, \tag{24}$$

in which $\tilde{Q}_j^m$ can be predicted with Eq. (23). However, for Y_j^m, the luminance variable, we need a separate predictor.

Intuitively, one might expect that matching the achromatic aspect of test and match sample would involve the matching of luminance contrast ($Y_j^m/Y_w^m = Y_j^t/Y_w^t$). However, in our earlier study,[10] we already noted that in the (few) experiments in which we used different illumination levels for the test and match illuminant, there were deviations from strict proportionality between test and match contrast. This is also shown in Fig. 11(a), in which we plotted the data from conditions with unequal background luminances ($Y_w^t = Y_w^m$), both from our earlier study and the present one (Conditions 3 and 4). We found that the relatively low correlation between test and match contrast, shown in Fig. 11(a), could be improved by redefining luminance contrast (C_Y) according to the following:

$$C_Y = \frac{Y_j}{(Y_w)^{0.88}}. \tag{25}$$

The improved correlation is shown in Fig. 11(b). The exponent for compressing Y_w was found by minimizing data variance as a function of the power of Y_w. The implication of this result is that the response to a given luminance contrast increases with illumination level, an effect to be addressed under Discussion.

From Eq. (25) it follows that

$$Y_j^m = Y_j^t\left(\frac{Y_w^m}{Y_w^t}\right)^{0.88}, \tag{26}$$

which, on substitution in Eq. (24), allows Q_j^m to be calculated once $\tilde{Q}_j^m$ has been computed with Eq. (23). Predictions

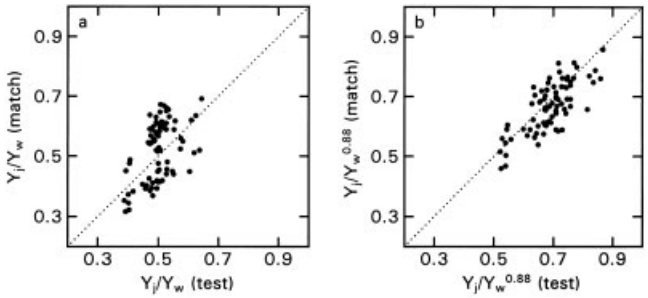

FIG. 11. Comparison of luminance contrast in the test and macth pattern. Luminance contrast is defined as either Y_j/Y_w (a) or $Y_j/Y_w^{0.88}$ (b). Shown are pooled data from a previous study (Lucassen and Walraven, 1993) and Conditions 3 and 4 of Experiment 2. All data relate to conditions with asymmetric test and match illumination.

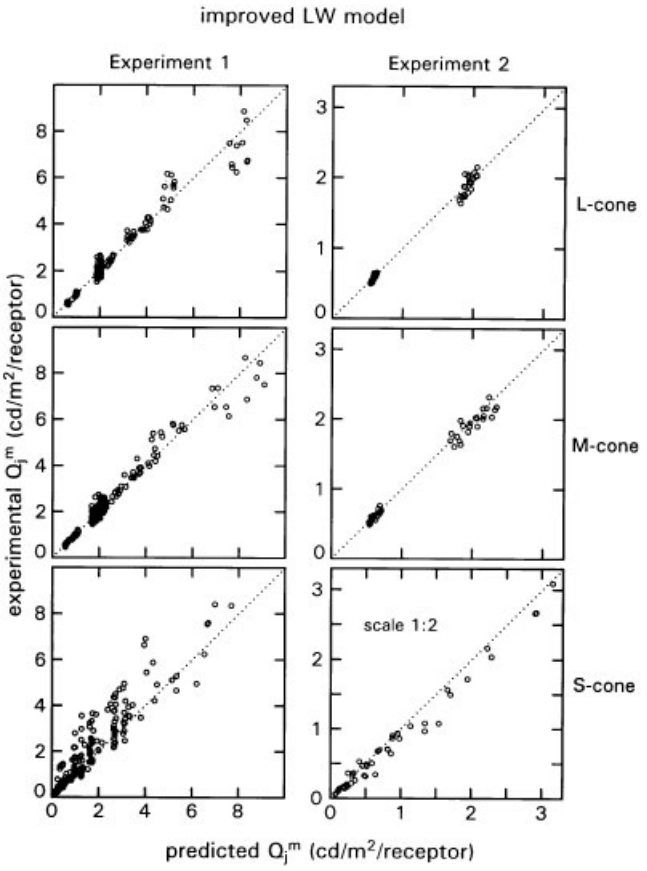

FIG. 12. Predictions with the improved LW model. The left graphs relate to the (mean) data of Experiment 1; those on the right to Experiment 2.

of Q_j^m, as based on the modified response function, are shown in Fig. 12. The left panels in Fig. 12 relate to the pooled data of Experiment 1, the panels on the right to the pooled data of Experiment 2. The predictions shown here are for the data averaged over the observers.

Although the predictions show some scattering around the identity line, the overall result is quite satisfactory, as is confirmed by the high correlation coefficients between prediction and experiment that we obtained. The correlation coefficients for the graphs on the left in Fig. 12 (Experiment 1) are 0.979, 0.981, and 0.929, for the L-, M-, and S-cone data, respectively. For the graphs on the right (Experiment 2) they are 0.995, 0.994, and 0.991, respectively.

The data of our previous study[10] are also described by the modified response function. The correlation coefficients for the comparisons of the experimentally obtained cone inputs for the match and those obtained by prediction on the basis of the modified response function are 0.972, 0.970, and 0.961, respectively, for that particular set of data.

DISCUSSION

Luminance-Free Cone Signals

We have shown that color constancy is not independent of the achromatic stimulus variable, contrast, and illumination level. It is for that reason that we had to modify Eq. (1), the response function that so accurately described the results of our earlier study.[10] That it did so is not surprising, because the experimental variable of interest in that study was the color of the illuminant; contrast was fixed at $Y_j/Y_w = 0.50$ and so was illumination level (except for small variations in a few pilot experiments).

The modification of Eq. (1) involves replacing the cone-specific sample and background inputs (Q_j and Q_w) by their luminance-normalized values ($\tilde{Q}_j = Q_j/Y_j$ and $\tilde{Q}_w = Q_w/Y_w$). This normalization removes an ambiguity of the cone-specific contrast input (Q_j/Q_w). That is, a change in cone contrast may result from a change in luminance contrast, chromaticity contrast, or both. For example, if the L-cones signal a dark sample on a light background, this could represent a gray sample on a white background but also a green sample on a red background. The luminance normalization makes the contrast signal insensitive to luminance changes, so what is left only reflects changes in chromaticity.

The effect of luminance normalization may not be very conspicuous when the spectral sensitivities of the luminance channel and a receptor channel are largely overlapping. In the extreme case, complete overlap (a monochromat), Q and Y will be equal and vary in tandem, resulting in a constant (chromatic) output of unity. As a matter of fact, both the L- and M-cones have spectral sensitivities that are largely overlapping, both with respect to each other and with respect to V_λ. Consequently, the chromatic contrast signalled by the L- and M-cones varies over a relatively small range. This explains why in Experiment 2, where luminance contrast was fixed, the variation in Q_j^m (which here reflects only the variation in the color of the test samples), is so much smaller for the L- and M-cones than for the S-cones (see Figs. 8 and 9). The latter, therefore, are the most critical for testing models of color constancy. It is for that reason that our experimental conditions were designed for maximally exploring the chromatic signal range of the S-cones.

Luminance normalization of cone contrast implies that the activity generated within a cone system is put into relationship to that generated by other cone systems. The latter activity, the luminance signal (Y), represents the activities of the three cone systems[26,28] according to $Y = 2L + M + 0.02S$. A more straightforward way for normalizing the L, M, and S signals would be to use the unweighted L, M, and S sum in the way this is done in the CIE XYZ domain, where chromaticity coordinates x, y, and z are defined according to $x = X/(X + Y + Z)$, and so on. In the same way, one might also define receptor coordinates l, m, and s according to $l = L/(L + M + S)$, and so on. (see also Fairchild[29]). The associated l,m diagram[30,31] (analogous to the CIE x,y diagram) turned out to be a useful tool for analytical purposes. When analyzing the data on the basis of $(L + M + S)$ normalization, the predictions were not much different from those using luminance $(2L + M + 0.02S)$ normalization. We nevertheless chose the latter approach, because it might be the more relevant choice from the physiological point of view. We think in this respect of the

well-established notion of a "luminance channel," with its spectral sensitivity (V_λ) matching the combination $2L + M + 0.02S$ rather than $L + M + S$. Why the visual system chose for unequal weighing of the three cone systems is an interesting question, but one that is outside the scope of this study.

Luminance and Luminance Contrast

A visual system that encodes color in terms of luminance-free cone signals pays the penalty of losing information about luminance contrast and absolute luminance level. The possession of a luminance channel allows the separate processing of these variables, of course, but it is not that self-evident how the visual system extracts a contrast signal without losing information about absolute light level. A contrast signal, in our nomenclature Y_j/Y_w, remains nearly invariant under varying illumination because the light reflected from sample (j) and background (w), increases in the same proportion. So, a mechanism for extracting contrast implies eliminating absolute light level.

A way out of this problem is to process the approximate rather than the exact luminance ratio. This may explain why we found that the (interocular) contrast matches showed a better correlation when expressed as $Y_j/Y_w^{0.88}$ instead of Y_j/Y_w (see Fig. 11). This means that (apparent) contrast is not independent of illumination but gradually increases with illumination, in proportion with $Y_w^{0.12}$. For the moment we consider this to be more of an empirical than a mechanistic description of how the visual system resolves the dilemma of encoding both relative and absolute luminance information. Probably, a more detailed model is necessary, possibly involving considerations regarding "noise" or "dark light."

Comparison with Models for Achromatic Vision

As discussed in the Introduction, color constancy may be analyzed in terms of a trichromatic extension of achromatic signal processing. A point in case is our finding that the brightness contrast model of Jameson and Hurvich,[13] applied to cone-specific contrast, can be used for describing at least part of our data (Figs. 5 and 8). It is of interest that this model, which treats contrast in terms of a *difference* signal, may yield similar results as our model, in which contrast is defined as a *ratio.* We have shown that this can be understood because of the equivalence (over a limited range) of $f(x) = x^{0.33}$ and $f(x) = \log(x) + 1$. So, the difference $Q_j^{0.33} - Q_w^{0.33}$ may yield approximately the same result as $\log(Q_j) - \log(Q_w) = \log(Q_j/Q_w)$.

A system that operates like a logarithmic analyzer will exhibit lightness constancy, because it will transmit a ratio (a reflectance) as a luminance invariant signal. It also has the advantage that it can easily remove (by subtractive filtering) the multiplicative noise introduced into the retinal image by the overlay of blood vessels and neural tissue.[32] A plausible physiological mechanism for implementing the logarithmic transformation is a fast gain control that aims at a fixed output.[32] Such a mechanism, essentially Rushton's[33] "automatic gain control," can account for a great variety of psychophysical data.[32,34,35] It is for that reason that we prefer to analyze our data in terms that are compatible with a logarithmic rather than a cube root transformation.

In addition to the model of Jameson and Hurvich[13] we tried various other models from the achromatic domain for describing our results. These include models by Burkhardt *et al.,*[36] Georgeson,[37] Kingdom and Moulden,[38] Semmelroth,[39] Stevens and Stevens,[40] and Whittle.[41] However, none of these gave better data predictions than our own equations, even when optimizing free parameters that are incorporated in some of those models.

Other Quantitative Accounts of Color Constancy

There are not many studies on color constancy in which experimental data are confronted with model predictions. Best known is the study of McCann, McKee, and Taylor,[11] which tested the validity of the (early) Retinex model.[5] Although the Retinex model(s) may be considered as the first analytical (rather than empirical) attempts at quantifying color constancy, we have shown that it performed less well than our own model.[10] The main shortcoming of the Retinex model, even in its most recent version,[42] is that it is too relativistic. It makes no allowance for the absolute illumination level.

Using asymmetric color matching, Brainard and Wandell[43] showed that their data can be described by assuming cone-specific sensitivity adjustments, consistent with the von Kries coefficient law.[44] Moreover, the coefficients (gain factors) were found to be proportional with the change in illumination. In that sense the predictions would not be different from the Retinex model, which is essentially a von Kries model, as has been pointed out already by various authors.[9,23,45,46] Similar results with respect to von Kries adjustment were obtained in more recent studies,[47–50] but the data predictions on the basis of the von Kries model were never perfect. Bäuml[50] also confirms our earlier findings[1] that deviations from perfect color constancy are mainly because of failures in the adjustment of the S-cone signals.

A von Kries type of adaptation that varies in proportion with illumination changes would result in perfectly discounting illuminant level. This is contrary to our daily experience and is also contradicted by laboratory experiments on brightness or lightness constancy.[3,51] Our own results, showing that the matching of luminance contrast (Y_j/Y_w) between test and match image is not independent of illumination level, also argues against gain adjustment in proportion with stimulus intensity. In our opinion the proportionality found by Brainard and coworkers[43,47,48] and Bäuml[48,50] is probably because of small range linearity. When analyzing the illuminants they used we noted that these produced cone inputs that varied by a factor 2–3 at most.

Model Implications

The present data, and those of our earlier studies (covering a wide gamut of illuminants), can be quantitatively accounted for. The correlation coefficients of predicted and experimentally obtained cone inputs for our match samples (Q_j^m) are in excess of $\rho = 0.9$ for all three cone classes. We do not think, however, that this already allows strong conclusions about the mechanisms subserving color constancy (as manifested in our experiments). All we can say is that the data are consistent with separate processing of luminance contrast (Y_j/Y_w) and chromatic contrast ($\tilde{Q}_j/\tilde{Q}_w$). The latter information may be conceived of as being captured by subtraction of the logarithmically transformed inputs $\tilde{Q}_j$ and $\tilde{Q}_w$ (*i.e.*, $\log(\tilde{Q}_j/\tilde{Q}_w) = \log(\tilde{Q}_j) - \log(\tilde{Q}_w)$. Furthermore, within this context, the color signal $\tilde{R}$ as defined by Eq. (22) is not only determined by this difference signal but also by the overall chromatic response, as represented by the cube power of the input from the background ($\tilde{Q}_w^{0.33}$).

According to our data luminance contrast is not signaled on a completely relative basis. As indicated by Eq. (25), the contrast signal may result from incomplete subtraction of the log-transformed background signal (Y_w) [*i.e.*, $\log(Y_j/Y_w^{0.88}) = \log(Y_j) - 0.88\log(Y_w)$]. In terms of the "Weber-machine" of Koenderink *et al.*[32] this would imply that the gain control does not aim at complete removal of the background signal.

An important consideration in all analyses of color processing in the visual system, is the transformation from cone outputs into chromatic opponent channels. This stage of signal processing, which may serve the decorrelation and optimal processing of the cone signals,[52] has been recognized in most models of color vision.[53–56] Our results can be cast into an opponent-color system in the same way as this has been done by Worthey[46] in his analysis of the data of McCann *et al.*[11] However, because the data predictions do not necessitate this step this could mean that processes underlying color constancy (as isolated in our experiments) operate prior to the transformation of cone signals into opponent signals. A similar conclusion, based on the same argument, was reached by Brainard and Wandell,[43] who explicitly tested whether a more complex transformation than just a von Kries transformation, was necessary for predicting the data.

ACKNOWLEDGEMENT

This study was supported by the Netherlands Organization for Scientific Research (NWO) through the Foundation for Biophysics.

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