Increments and decrements in color constancy

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The present study examines whether increment–decrement asymmetries reported in a number of recent center–surround situations occur in more complex images as well. Subjects saw the CRT simulation of a whole uniformly illuminated array of foreground surfaces presented against a large background surface and, for a number of different viewing contexts, made achromatic settings over a wide range of luminance values. Three results emerged. First, subjects' achromatic loci did not fall on a single straight line in color space but rather fell on two separate lines intersecting at some point in this space. Second, the intersection points were not identical to but dependent largely on background color and showed only small effects of foreground colors. Third, cone signals that were decremental relative to the intersection point were more responsive to illuminant changes than cone signals that were incremental, the latter additionally showing some variation with foreground colors. The results are interpreted in terms of increment–decrement asymmetries. They suggest that these asymmetries occur in more complex images as well. © 2001 Optical Society of America

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1. INTRODUCTION

To assign constant colors to objects the visual system must compensate against illuminant changes and maintain object color appearance in spite of possible variations in the color of neighboring surfaces. The results from a number of experimental studies have shown that the visual system indeed compensates against the effect of illumination. In some of these studies the amount of compensation was found to be only moderate,[1–3] in others it was high.[4–6] In none of these studies was the adjustment complete, however, suggesting that illuminant changes have at least some effect on the color appearance of objects. Changes in the color of surrounding surfaces have been shown to influence the color appearance of objects as well. Again, these effects were relatively small in some studies[5] and more substantial in others.[2] Understanding which factors determine the degree to which illumination and image surfaces affect color appearance is an important task in color constancy research.

One possible source for the variation in amount of illuminant adjustment and effect of surrounding surfaces observed in previous studies might be the fact that in some of the studies CRT simulations of illuminated objects were presented to the observers, whereas in others real objects rendered under real illuminants were employed.[7] High degrees of illuminant adjustment, for instance, were found mostly in studies using nearly natural images,[4,5] whereas moderate degrees of illuminant adjustment were found mostly in studies using CRT simulations.[1–3,8] On the other hand, high degrees of illuminant adjustment are not restricted to experimental images with a high degree of naturalness but have been found in CRT studies as well.[6] Another possible source for the variation in effects of illumination and surrounding surfaces across studies might be the test object employed. The results from a number of previous center–surround studies indicate that our visual system processes lights that are incremental relative to a surround color than lights that are decremental.[9–11] With respect to color appearance Mausfeld and Niederee,[12] 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 surround field. Analogous observations were made by Chichilnisky and Wandell[13,14] with respect to both red–green and yellow–blue equilibria and achromatic settings. In the achromatic domain Whittle[15,16] reported evidence for a different processing of increments and decrements.

To account for the differences in the processing of increments and decrements in the center–surround situation, Mausfeld and Niederee[12] proposed that the visual system distinguishes between cone signals that are incremental and cone signals that are decremental relative to the surround field and scales the two types of cone signals differently as a function of surround color. Changes in the surround color therefore should cause different von Kries scalings for incremental and decremental cone signals.[13,14,17] The question arises of whether increment–decrement asymmetries exist only in center–surround situations or occur in more complex images as well. Whereas in the center–surround situation a quite natural and precise definition of incremental and decremental cone signals arises, no such straightforward definition is available for complex displays. Indeed, *a priori* several options arise about which reference(s) the visual system might choose in order to distinguish between effective increments and decrements: Increments and decrements might be computed relative to some internal illumination code, relative to some internal surface code, or relative to the whole incoming light array. Moreover, there might even be different increment–decrement distinctions at various stages of internal color coding that subserve different purposes and that are interwoven in complex ways.

In view of a lack of clear empirical support for any of these approaches, in the present paper the most simple of

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these approaches is preferred. It is assumed that for each viewing context the visual system computes some level from the incoming light array and uses this level to distinguish between cone signals that are effective increments and cone signals that are effective decrements. The resulting incremental and decremental cone signals are then supposed to be scaled as a function of viewing context, with different von Kries scalings for increments and decrements. Two aspects make this approach appear reasonable in a first approximation to the problem. First, the approach provides a straightforward generalization of the Mausfeld and Niederee account by incorporating level as a parameter into the original model. Indeed, Mausfeld and Niederee's original account may be regarded a special case of the present one, with level being identical to the color coordinates of the surround field. Second, the approach is consistent with the results from a recent study by Delahunt and Brainard,[18] who found that the von Kries description of asymmetric color matches in more complex images is improved if it is assumed that the visual system distinguishes between effective increments and decrements and scales the two types of cone signals differently as a function of the illumination in the image. On the negative side, the present approach does not provide an *a priori* specification of how exactly level is determined by the incoming light array. Examining how the level parameter varies with viewing context, however, should provide insights into how an image's color information is integrated for the computation of level.

If the visual system distinguishes between cone signals that are increments and cone signals that are decrements relative to some level, the question arises of what the role of increments and decrements in color constancy might be. Following a functionalistic intuition,[12,13] the different processing of effective increments and decrements might contribute to the slicing up of the incoming light array into an internal illumination and an internal surface color code. According to this view, one might expect that decrements (surface code) are more responsive to illuminant changes and show less variation with changes in surrounding surfaces than increments, an expectation also reminiscent of the classical Judd–Helson effect.[19,20] Right or not, discovering regularities in the different processing of effective increments and decrements will improve our understanding of color constancy and contribute to the explanation of why the amount of illuminant adjustment and the effect of surrounding surfaces varied so much across previous studies.

This study reports the results of two experiments in which it was examined how subjects' achromatic settings vary with luminance level and context in Mondrian-style images. Subjects saw the CRT simulation of a whole uniformly illuminated array of foreground surfaces presented against a large background surface. For a number of simulated illuminants and surface conditions, subjects made achromatic settings over a wide range of luminance levels. Three results emerged. First, consistent with the proposal that the visual system computes some level from the incoming light array and processes effective increments and decrements differently, subjects' achromatic loci did not fall on a single straight line in color space but rather on two separate lines intersecting at some point in this space. Second, although the points at which the two lines intersect were generally not identical to the color coordinates of the illuminated background field, they showed a strong dependence on background color and were hardly influenced by the color coordinates of the foreground surfaces, thus suggesting simple ways of how level is determined in the present experiment. Third, effective incremental and decremental cone signals differed in the amount of illuminant adjustment they showed, with a high amount of adjustment for the decremental and only a moderate amount of adjustment for the incremental cone signals. Variations in the color of the surrounding surfaces affected the increment–decrement asymmetry only to a minor degree.

2. EXPERIMENT 1

A. Method

The methods used in this study are similar to those used in previous studies.[1,2,6] The visual stimuli were presented on a CRT monitor. The stimulus was a simulation of an array of 24 flat matte foreground surfaces presented against a large background surface, and a test object. The array of foreground surfaces and the background surface were rendered under the same spatially uniform illumination. The subjects pressed buttons to adjust the appearance of the test object until it appeared achromatic. For each luminance level subjects were instructed to adjust the test light so that it appeared neither reddish nor greenish and neither yellowish nor bluish. Both the simulated illuminant and the simulated surfaces remained constant during the adjustment process. However, during this process the local positions of a quarter of the stimuli were changed every 3 s, including the test object. This was done to minimize local effects, like local adaptation, and to isolate the effect of changing the illuminant from other variables (see Brainard and Wandell[1] for the rationale). Apart from the 25% movement every 3 s the lights were steady.

1. *Visual Display*

The visual display was identical to that used in previous studies[2,6] (see Fig. 1). It consisted of 25 small foreground regions against a large background region. The foreground regions consisted of 24 rectangular regions (simulation of illuminated foreground surfaces) and one circular region (test object). They subtended 2 deg of visual angle, both vertically and horizontally, and were separated by 1 deg, again both vertically and horizontally. The whole background region subtended 24 vertical by 38 horizontal degrees of visual angle. Subjects saw the screen without head restraints from a distance of approximately 0.5 m in an otherwise dark room. The simulated images were displayed on a computer-controlled color monitor (BARCO Calibrator CCID 7651) using a refresh rate of 71 Hz in noninterlaced video mode. The monitor's input signal was controlled with the use of software in order to correct nonlinearities in the tube's response function. The luminance of each color channel was measured with a high-precision photometer (Fa. Lichtmesstechnik,

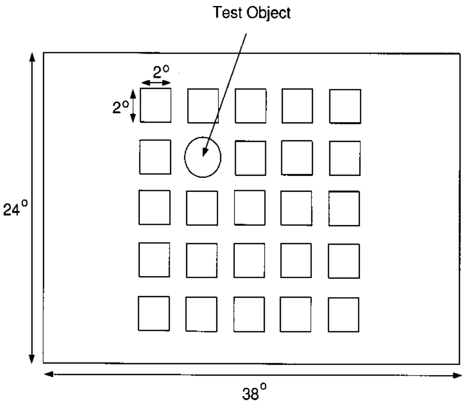

Fig. 1. Visual display. Subjects saw CRT simulations of a collection of 24 flat matte foreground surfaces (rectangular regions) and a test object (circular region), both presented against a large background surface. The array of foreground surfaces and the background surface were rendered under the same spatially uniform illumination. The subjects pressed buttons to adjust the appearance of the test object.

Modell L 1003). The CIE *xy* chromaticity coordinates of the phosphors were provided by the manufacturer (for further details see Bäuml[6]).

2. *Experimental Illuminants and Surfaces*

Three simulated illuminants were used in this experiment. They were drawn from the CIE daylight locus[21] and are typical for natural daylight. One of them was neutral looking, one bluish, and one yellowish. The CIE xyY coordinates of the three lights are $x = 0.326$, $y = 0.339$, and $Y = 57.84$ for the neutral illuminant; $x = 0.249$, $y = 0.249$, and $Y = 29.76$ for the blue illuminant; and $x = 0.402$, $y = 0.394$, and $Y = 70.0$ for the yellow illuminant, where chromaticity (x, y) is specified with respect to the CIE 1931 colorimetric system and luminance (Y) is specified as candelas per square meter. All three experimental illuminants were already used in a previous study.[6]

One collection of experimental surfaces was constructed to be used as foreground surfaces in the image. This collection (C_N) consisted of 24 surface reflectances and contained surfaces from the whole gamut of hues. The collection's mean chromaticity coordinates were $x = 0.343$ and $y = 0.302$ and the mean luminance coordinate was $Y = 11.83$. The collection's surfaces showed considerable variation in terms of chromaticity and luminance. It was identical to a collection used in a previous study.[6] Finally, two neutral background surfaces were used in this experiment. They varied only in their luminance value. Their chromaticity coordinates were $x = 0.326$ and $y = 0.339$, their luminance values were $Y = 19.61$ (B_L) and $Y = 39.22$ (B_H).

3. *Subjects*

Two male subjects (TE and KHB) took part in the experiment. They had normal color vision. One of the subjects was completely naïve about the purpose of the experiment; the other subject was the author. Each of the two subjects made achromatic settings under all six combinations of illumination and background surface with approximately 18 settings for each combination.

4. *Procedure*

In each experimental session, three combinations of illumination, image surfaces, and background surface were presented to the subject. For each combination, the subject made between 8 and 12 settings during a session. Each combination was presented in two different sessions. Each subject began an experimental session with one minute of dark adaptation. Then a collection of simulated surfaces rendered under a simulated illuminant was presented to the subject. The test object was not yet visible. After two minutes of adaptation to these illuminated surfaces the test object appeared, and the subject made a number of settings for this condition, readapting between the settings for 30 s. Using CIE 1931 color-matching functions, each setting was done on an isoluminant plane in color space. About half of the settings were done at luminance levels below that of the background color, the other half at luminance levels above it. The settings covered the luminance range from approximately 2 to 75 cd/m^2. After these settings for a viewing context were completed, the next combination of illumination, image surfaces, and background surface was presented. The same procedure was used as for the first combination. The subjects made adjustments by pressing the buttons on a mouse. They were instructed to adjust the test object so that it appeared neither reddish nor greenish and neither yellowish nor bluish, i.e., achromatic to them.

B. Results

1. *Achromatic Settings*

For two viewing contexts, Figs. 2(A) and 2(B) show the Smith–Pokorny[22] LMS cone coordinates that subjects

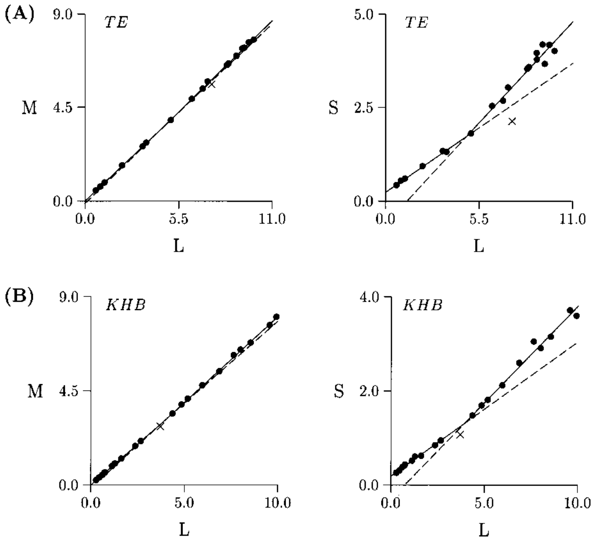

Fig. 2. Achromatic settings (Experiment 1). (A) Settings of subject TE (collection C_N, yellow illuminant, background surface B_H). (B) Settings of subject KHB (collection C_N, yellow illuminant, background surface B_L). L and M (left panels) coordinates and L and S (right panels) coordinates of the single settings are compared. Solid lines represent the predictions of these settings, which are based on the ID model. Dashed lines extend the solid lines to demonstrate that the settings do not fall on a single straight line. (x, coordinates of the illuminated background field; see also Fig. 3 below.)

TE and KHB adjusted to create achromatic targets at different luminance levels. The graphs compare the long- and medium-wavelength-sensitive (L and M) coordinates and the L and short-wavelength-sensitive (S) coordinates of the single settings. For subject TE measurements are shown for the brighter background B_H; for subject KHB measurements are shown for the darker background B_L. In both cases the illuminant is yellowish. The graphs indicate that in general the settings for a viewing context do not fall on a single straight line in cone space. Rather, they seem to fall on two straight lines that are bent at some point in this space. Such bends are particularly obvious when comparing the L and S coordinates of the settings, but are fairly weak when comparing the L and M coordinates (see also Table 1 below).

According to the increment–decrement model introduced above (Section 1), for each viewing context the visual system computes a level from the incoming light array and uses this level to conduct a different context-dependent von Kries scaling of the resulting incremental and decremental cone signals. I fitted a version of this model, henceforth referred to as the ID model, to the data of each subject and viewing context, assuming that both incremental and decremental achromatic settings fall on a straight line in color space.[13] For each viewing context this model has seven parameters, three for the estimate of the level coordinates and four for the estimates of the cone ratios for the effective increments and decrements. The fit of this model is exemplified in Figs. 2(A) and 2(B), which show the estimated level coordinates and the two best fitting straight lines for each data set. In addition, dashed lines are shown in each graph that extend the solid lines to demonstrate that incremental and decremental cone absorptions differ. The fit of the model to the data is good. On average, I found a mean CIELUV error of 2.49 units for subject TE and 2.08 units for subject KHB.[23] I also fitted a more restrictive model to the data that ignores increment–decrement asymmetries and assumes that all the settings for each subject and context fall on one single straight line. This model resulted in a mean CIELUV error of 5.33 units for subject TE and 5.67 units for subject KHB. This deterioration in fit reflects the visual impression from Fig. 2 that, in general, the achromatic settings fall on two straight lines rather than one.

For each viewing context, Table 1 compares the cone ratios that I estimated for the incremental settings with the cone ratios that I estimated for the decremental ones. The table actually shows how the decremental cone ratios that I estimated on the basis of the ID model have to be scaled to get the incremental cone ratios estimated from this model.[24] A scale factor of 1.0 indicates that there is no difference between incremental and decremental ratios. The table reflects the features already seen in Fig. 2. Particularly for S/L and S/M there is generally a clear difference between incremental and decremental cone ratios.

2. *Level Estimates*

Separately for each subject and viewing context, Fig. 3 shows the level chromaticity (A) and luminance (B) coordinates that I estimated on the basis of the ID model and compares these coordinates with those of the illuminated background surface. Two results emerge. First, for each illumination and background condition, the chromaticity coordinates of the level estimate agree well with those of the illuminated background surface. Second, although in some conditions the luminance coordinates of the level estimate and those of the illuminated background surface agree quite well, there are also cases in which we see substantial differences between the two. This holds particularly if the background luminance is quite high. In these cases the level coordinates show a tendency to be smaller than those of the background field.

The ID model does not provide a specification of how level depends on the incoming light array. In order to come up with a first-order specification of level I included an assumption into the ID model according to which level (a) agrees with the illuminated background field with respect to chromaticity and (b) with respect to luminance is related in a nonlinear way to the illuminated background field. To account for the nonlinearity that is induced through the smaller level coordinates in the case of higher background coordinates, I chose a power function to re-

Table 1. Scale Factors Used to Compute the Incremental M/L, S/L, and S/M Cone Ratios from the Respective Decremental Cone Ratios in Experiment 1[a]

	Subject					
	TE			KHB		
Viewing Context	M/L	S/L	S/M	M/L	S/L	S/M
(C_N, N, B_L)	1.03	1.23	1.20	1.02	1.10	1.08
(C_N, N, B_H)	1.03	1.37	1.33	1.01	1.08	1.08
(C_N, B, B_L)	1.01	1.11	1.10	0.99	0.97	0.98
(C_N, B, B_H)	0.96	0.97	0.99	0.97	0.71	0.74
(C_N, Y, B_L)	1.05	1.54	1.47	1.04	1.43	1.37
(C_N, Y, B_H)	1.03	1.56	1.54	1.08	1.35	1.27

[a] The extent to which the single scale factors differ from 1.0 indicates that different cone ratios underlie achromatic appearance for incremental lights and decremental lights. For each subject and viewing context, cone ratios were estimated by fitting the ID model to the subject's data (C_i = surface collection i; N = neutral illuminant, B = blue illuminant, Y = yellow illuminant; B_i = background surface i; see Subsection 2.A.)

late level and background luminance. I fitted this more restrictive ID model to the data of each subject. The model resulted in a mean CIELUV error of 3.48 units for subject TE and 3.29 units for subject KHB. Compared with the error of the more general ID model, in which level is left unspecified, the error increases only moderately, thus indicating that this restrictive version of the ID model provides a reasonable first-order specification of level. For both subjects Fig. 4 shows the power functions that resulted when fitting the more restrictive ID model to the two subjects' data. The function reflects the tendency for level luminance to fall below that of the illuminated background field if background luminance is high.

3. *Effect of Illuminant Changes on Increments and Decrements*

I finally examined whether the settings with cone coordinates that are incremental relative to the level estimate and the settings with cone coordinates that are decremental are differently responsive to illuminant changes. Figure 5 shows, for both the bluish and the yellowish illuminant, the L and S coordinates and the M and S coordinates for the achromatic settings of subject TE (background B_H) and subject KHB (background B_L), together with the predictions of these settings that are based on the general ID model. The coordinates are plotted as differences from the level estimates, i.e., in terms of effective increments and decrements. In addition, within each graph two theoretical dashed lines are shown that represent the settings that the subjects would have made if they had adjusted perfectly to the yellowish and bluish illuminant.[25]

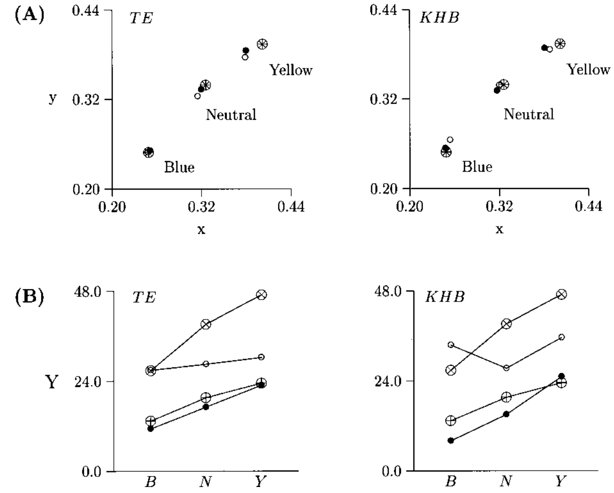

Fig. 3. Level estimates (Experiment 1). Chromaticity (A) and luminance (B) coordinates of the level estimates are shown and compared with the respective coordinates of the illuminated background surface (⊗, coordinates of the bright background field; ⊕, coordinates of the dark background field; ○, level coordinates for the bright background condition; ●, level coordinates for the dark background condition; B = blue illumination; N = neutral illumination; Y = yellow illumination).

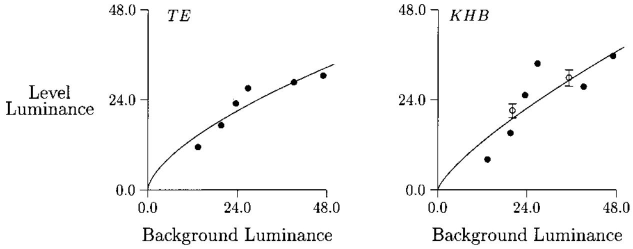

Fig. 4. Relating level luminance and background luminance. A power function fit is shown relating the two variables for each of the two subjects (●, data of Experiment 1; ○, data of Experiment 2).

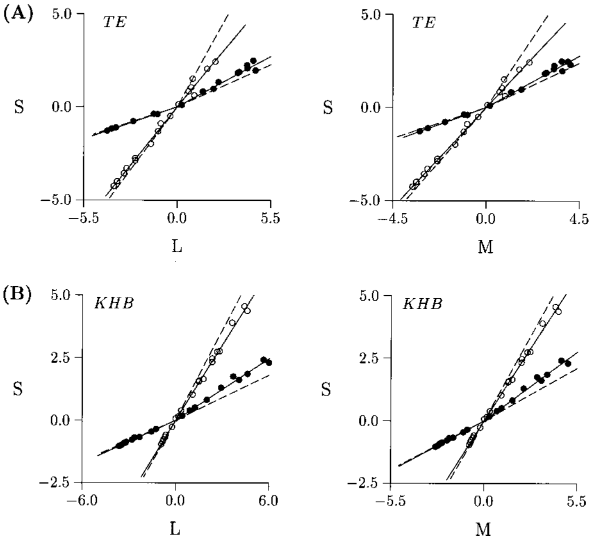

Fig. 5. Effect of illuminant changes (Experiment 1). L and S coordinates (left panel) and M and S coordinates (right panel) of the achromatic settings of subjects TE and KHB under the blue (○) and the yellow (●) illuminant are shown. The settings are plotted as differences from the estimated neutral points. Solid lines represent the predictions of the settings that are based on the ID model. Dashed lines represent the settings that the subject would have made if he had adjusted perfectly to the illuminant changes. (A) Subject TE (collection C_N, background surface B_H). (B) Subject KHB (collection C_N, background surface B_L).

As can be seen from the figure, for both the bluish and the yellowish illuminant the decremental settings show a high level of adjustment to the illuminant changes. Indeed, the settings are quite close to the locations that represent perfectly constant matches. The incremental settings show a lesser degree of adjustment and deviate clearly from perfectly constant settings. I used the method proposed by Arend *et al.*[27,28] to quantify the degree of constancy shown by the two subjects. Typically this method results in a constancy index between 0 and 1, whereby 0 reflects no adjustment to the illuminant and 1 reflects perfect adjustment. For incremental lights I found a mean constancy index of 0.61 for subject TE and 0.54 for subject KHB; for decremental lights I found a mean constancy index of 0.90 for subject TE and 0.87 for subject KHB. These numbers indicate a high degree of adjustment for the subjects' decremental settings, but only a moderate degree for the subjects' incremental settings.

3. EXPERIMENT 2

Experiment 1 examined how subjects' achromatic settings vary with luminance level and the illumination in the image. In the present Experiment 2 it is examined how subjects' achromatic settings vary with the color of the foreground surfaces in the image. To address this issue subjects made achromatic settings for all combinations of two illuminants and seven foreground conditions.

A. Method

The same methods were used as in Experiment 1. Both the visual display and the procedure were identical to Experiment 1. The two experiments differed only in experimental illuminants and surface collections and in subjects.

1. *Experimental Illuminants and Surfaces*

Two of the three experimental illuminants employed in Experiment 1 were also used in this Experiment 2. These are the bluish illuminant and the yellowish illuminant. The neutral illuminant was not used. Three collections of experimental surfaces were constructed to be used as foreground surfaces in the image, each collection consisting of 24 surface reflectances. Collection C_B contained mostly bluish surfaces, C_G mostly yellowish-greenish surfaces, and C_R mostly yellowish-reddish surfaces. Collection C_B had mean chromaticity coordinates $x = 0.289$ and $y = 0.266$ and mean luminance coordinate $Y = 12.26$; collection C_G mean chromaticity coordinates $x = 0.371$ and $y = 0.377$, and mean luminance coordinate $Y = 13.67$; and C_R mean chromaticity coordinates $x = 0.413$ and $y = 0.314$ and mean luminance coordinate $Y = 8.84$. Each collection's surfaces showed considerable variation in terms of chromaticity and luminance. All three collections of image surfaces are identical to collections used in a previous study.[6]

Out of each of the three surface collections one additional surface collection was created (C_{B_M},C_{G_M},C_{R_M}), consisting of 24 identical surfaces with CIE *xy* and luminance coordinates equal to the mean coordinates of the original set of image surfaces. A seventh collection of image surfaces, C_U, was created. Just like collections C_{B_M}, C_{G_M}, and C_{R_M}, this collection consisted of 24 identical surfaces. The color coordinates of these surfaces when rendered under the neutral illumination were $x = 0.326$ and $y = 0.339$, and their luminance value was $Y = 29.41$. Finally, one neutral background surface was used in this experiment. Its chromaticity coordinates were $x = 0.326$ and $y = 0.339$, and its luminance value was $Y = 29.41$ (B_M). In the context of this background surface collection C_U thus induced a homogeneous background condition.

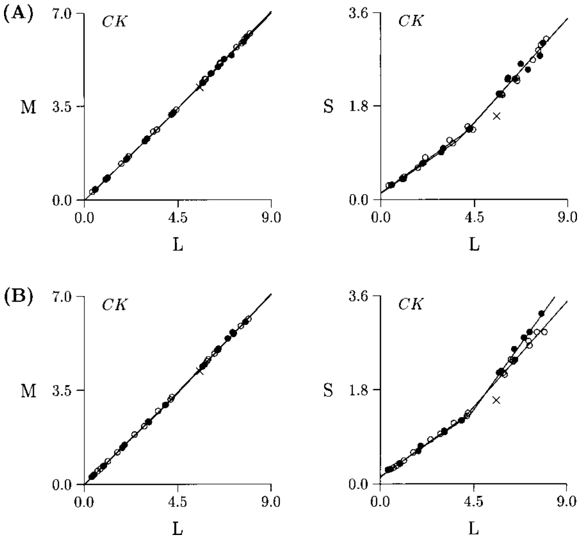

Fig. 6. Achromatic settings (Experiment 2). L and M coordinates (left panels) and L and S coordinates (right panels) of achromatic settings of subject CK under the yellow illuminant are shown. (A) Settings for surface conditions C_U (●) and C_G (○). (B) Settings for surface conditions C_{B_M} (●) and C_B (○). Solid lines represent the predictions of the settings that are based on the ID model. (x, coordinates of the illuminated background field; see also Fig. 7.)

2. *Subjects*

Two male subjects took part in the experiment. One of them (CK) was completely naive about the purpose of the experiment; the other (KHB) was the author. Both subjects had normal color vision. They made achromatic settings under all combinations of the two illuminants and the seven surface conditions. On average, each of the two subjects made approximately 16 settings for each combination of illumination and image surfaces.

B. Results

1. *Achromatic Settings*

Figure 6(A) shows the Smith–Pokorny[22] LMS cone coordinates of subject CK's achromatic settings for the greenish surface collection C_G and the surface collection C_U, which induces a homogeneous background condition. Figure 6(B) shows the coordinates of the subject's settings for the two bluish collections, C_B and C_{B_M}. In both cases the settings were done under the yellowish illuminant. The figure replicates results already seen in Experiment 1: The graphs show clear evidence for increment–decrement asymmetries, with the settings for a viewing context falling on two lines rather than a single straight line in color space. Also, the asymmetries are present mainly when comparing the settings' L and S coordinates and much less when comparing the settings' L and M coordinates (see also Table 2).

Again, I fitted both the general ID model and a restrictive ID model, in which it is assumed that all the settings for a viewing context fall on one single straight line in color space, to the data of each subject. Consistent with the results from Experiment 1, the fit of the general model to the data is much better than the fit of the more restrictive model, indicating that increment–decrement asymmetries exist: For subject CK the mean CIELUV error of the general model was 2.08 units and of the restrictive model 4.98 units; for subject KHB the error of the general model was 2.04 units and of the restrictive model 6.69 units. The good fit of the general ID model is exemplified in Figs. 6(A) and 6(B), which show the estimated level coordinates and the two best-fitting straight lines for each data set. For each viewing context, Table 2 again compares the cone ratios that I estimated for the incremental settings with the cone ratios that I estimated for the decremental ones.[24] Particularly for S/L and S/M, incremental and decremental cone ratios differ, which is in agreement with the results of Experiment 1.

Table 2. Scale Factors Used to Compute the Incremental M/L, S/L, and S/M Cone Ratios from the Respective Decremental Cone Ratios in Experiment 2[a]

	Subject					
	CK			KHB		
Viewing Context	M/L	S/L	S/M	M/L	S/L	S/M
(C_U, B, B_M)	0.99	1.02	1.03	1.01	0.78	0.77
(C_B, B, B_M)	0.96	0.86	0.90	1.02	0.87	0.85
(C_{B_M}, B, B_M)	1.01	1.10	1.09	1.03	0.80	0.78
(C_G, B, B_M)	1.04	0.98	0.95	1.04	0.94	0.90
(C_{G_M}, B, B_M)	0.97	0.85	0.87	1.00	0.83	0.83
(C_R, B, B_M)	0.98	0.92	0.93	1.02	0.84	0.82
(C_{R_M}, B, B_M)	0.97	1.09	1.13	1.00	0.83	0.82
(C_U, Y, B_M)	1.06	1.72	1.62	1.08	1.28	1.18
(C_B, Y, B_M)	1.05	1.63	1.55	1.06	1.05	0.99
(C_{B_M}, Y, B_M)	1.06	1.57	1.48	1.08	1.16	1.08
(C_G, Y, B_M)	1.09	2.02	1.85	1.10	1.42	1.29
(C_{G_M}, Y, B_M)	1.08	2.02	1.87	1.10	1.24	1.13
(C_R, Y, B_M)	1.09	2.02	1.86	1.09	1.25	1.14
(C_{R_M}, Y, B_M)	1.06	1.76	1.66	1.12	1.28	1.15

[a] The extent to which the single scale factors differ from 1.0 indicates that different cone ratios underlie achromatic appearance for incremental lights and decremental lights. For each subject and viewing context, cone ratios were estimated by fitting the ID model to the subject's data (C_i = surface collection i; B = blue illuminant, Y = yellow illuminant; B_i = background surface i; see Subsection 2.A.)

2. *Level Estimates*

Separately for each subject and viewing context, Fig. 7 shows the level chromaticity [Fig. 7(A)] and luminance [Fig. 7(B)] coordinates that I estimated on the basis of the general ID model and compares these coordinates with those of the illuminated background surface. For each illumination, the chromaticity coordinates of the level estimate agree well with those of the illuminated background surface and show only minor variation with image surfaces. At the same time, surface condition appears to have an effect on level luminance. This effect occurs both for the lower (blue illuminant) and the higher (yellow illuminant) luminance value of the illuminated background field. This effect of surface condition, however, shows considerable variation between the two subjects, which suggests that at least some amount of the effect might be random, having to do with difficulties in the exact estimation of the level luminance. To address this issue a version of the ID model was fitted to the data of each subject, in which it was assumed that both level chromaticity and level luminance do not vary with image surfaces. Such a model led to mean CIELUV errors of 2.36 units for subject CK and 2.47 units for subject KHB. These errors are only slightly larger than those for the general ID model in which level is permitted to vary with surface condition, thus indicating that most of the variation in level luminance seen in Fig. 7(B) is due to difficulties in the exact determination of level.

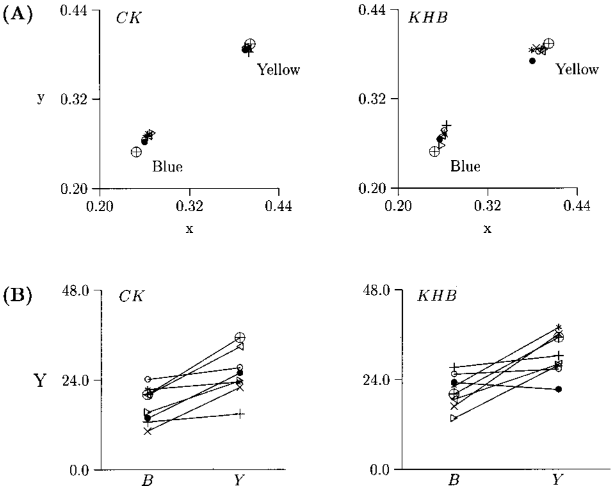

Fig. 7. Level estimates (Experiment 2). Chromaticity (A) and luminance (B) coordinates of the level estimates are shown and compared to the respective coordinates of the illuminated background surface (⊕, coordinates of the background field; ●, level coordinates for surface collection C_B; ○, level coordinates for surface collection C_{B_M}; ◁, level coordinates for surface collection C_G; ▷, level coordinates for surface collection C_{G_M}; x, level coordinates for surface collection C_R; +, level coordinates for surface collection C_{R_M}; *, level coordinates for surface collection C_U; B = blue illumination; Y = yellow illumination).

For each subject I used the estimates of level luminance for the single surface conditions to compute the mean level luminance for each of the two illumination conditions. I compared these means with the respective luminance values of the illuminated background surface. For subject CK mean level luminance was $Y = 16.8$ for the blue and $Y = 23.6$ for the yellow illuminant; for subject KHB mean level luminance was $Y = 21.06$ for the blue and $Y = 29.8$ for the yellow illuminant. Compared with the corresponding luminance values of the illuminated background surface ($Y = 20.1$ und $Y = 35.3$), these values show a tendency already observed in Experiment 1: As the background luminance increases level luminance does not increase to the same extent and, particularly for higher luminance values, may fall substantially below that of the illuminated background field. Subject

KHB served as a subject in both Experiment 1 and the present Experiment 2. For his data the mean level luminance that results for the two illumination conditions employed in Experiment 2 can be compared with the predictions that result on the basis of the power function estimated in Experiment 1. Figure 4 shows the results. For both conditions the mean level luminance agrees well with the predictions of the power function, which suggests that just as in Experiment 1 level is largely dependent on the illuminated background surface.

3. *Effect of Variations in Image Surfaces on Increments and Decrements*

Since variations in image surfaces have only a minor effect on level in this experiment, one might expect that variations in image surfaces have only a small effect on the incremental and decremental cone ratios as well. The settings shown in Fig. 6(A) first of all support this expectation. The settings show hardly any variation with surface condition. Figure 6(B), on the other hand, shows a moderate but systematic effect of surface condition. Interestingly, this effect occurs mainly for the incremental settings and less, if at all, for the decremental ones. As a side result, Figs. 6(A) and 6(B) provide further demonstrations of the fact that the mean in the image does not determine color appearance.[2,29,30]

The influence of image surfaces shown in Fig. 6(B) is among the most clear-cut effects of image surfaces observed in the whole experiment. Indeed, under many conditions the effect of image surfaces is relatively small or even nonexistent (see Table 2). This aspect of the data is well captured through analyses in which I used the ID model to quantify the effect of image surfaces on incremental and decremental cone ratios. I calculated the error that results when the additional restriction was imposed on the ID model that image surfaces not only have no effect on level but have no effect on incremental and decremental cone ratios, as well. This additional restriction increased the mean CIELUV error from 2.36 units to 3.47 units for subject CK and from 2.47 units to 3.33 units for subject KHB. This increase in error of about 1 unit is moderate and reasonably consistent with the expectation formulated above that image surfaces not only have small effects on level but have small effects on incremental and decremental cone ratios as well. Figure 8 supports the results from these analyses. It compares the subjects' achromatic settings across the seven different surface conditions. The settings are shown for the yellowish [Fig. 6(A)] and the bluish [Fig 6(B)] illuminant. We see relatively small effects of image surfaces, which, if they exist, occur more for the higher (incremental) luminance levels than for the lower (decremental) ones.

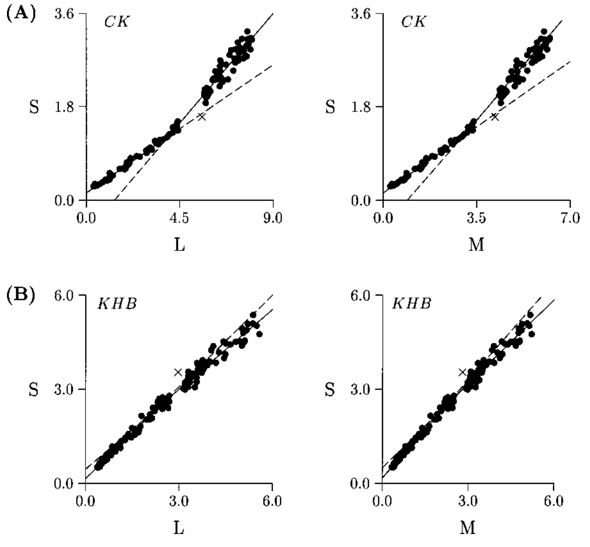

Fig. 8. Achromatic settings (Experiment 2). (A) Settings of subject CK for the yellowish illuminant, (B) settings of subject KHB for the bluish illuminant. L and S coordinates (left panels) and M and S coordinates (right panels) of the settings of all seven surface conditions are shown. Solid lines represent the predictions of these settings, which are based on a variant of the ID model, in which it is assumed that image surfaces do not affect the settings (see text). Dashed lines extend the solid lines to demonstrate that the settings do not fall on a single straight line. (x, coordinates of the illuminated background field; see also Fig. 7.)

4. DISCUSSION

A. Increment–Decrement Asymmetry

The present study addresses the issue of whether the evidence for a different processing of increments and decrements found in previous center–surround studies generalizes to more complex images. I started out with the assumption that for each viewing context the visual system computes a level from the incoming light array and distinguishes between cone signals that are incremental and cone signals that are decremental relative to this level. Incremental cone signals are then assumed to underlie different von Kries scalings than decremental signals. The results from the present experiments are consistent with this approach. They show that subjects' achromatic settings for a viewing context do not fall on a single straight line in color space but rather fall on two separate lines intersecting at some point in this space. If the point at which the two lines intersect is interpreted as the system's level estimate, then the fact that incremental and decremental settings fall on two different lines suggests that they are subject to different von Kries scalings. This interpretation of the results agrees with recent findings by Delahunt and Brainard,[18] who found that the von Kries description of asymmetric color matches was improved if it is assumed that the visual system distinguishes between effective increments and decrements and scales the two types of cone signals differently as a function of changes in illumination.

The assumption that for each viewing context the visual system computes some level from the incoming light array does not provide an *a priori* specification of how exactly level is determined. Fortunately, the results of the present experiments lead to some first-order suggestions, indicating that level is determined in a relatively simple way in the present context. Indeed, whereas the data show that level is generally not identical to the color coordinates of the illuminated background surface, they also demonstrate that level is largely dependent on background color and is influenced only to a minor degree by the foreground surfaces. This dependence on background color is reflected by the fact that level and background agree well with respect to chromaticity and are related in a regular, nonlinear way with respect to luminace. Although this specification of level is not perfect, owing to its simplicity it may serve as a useful first-order account of how level is determined in the present experiments.

One of the main issues of the present study was the question of which role effective increments and decrements might play in color constancy. In particular, the question was raised of whether increments and decrements respond differently to illuminant changes and/or changes in image surfaces. The results first of all showed that variations in image surfaces not only have small effects on level but have small effects on the incremental and decremental cone ratios as well. Although there were cases in which changes in image surfaces induced moderate and systematic effects on the subjects' achromatic settings [Fig. 6(B)], in most cases the effect of image surfaces was small or even nonexistent. These cases of a small or null effect of image surfaces even occurred when the effect of differently colored foreground surfaces was compared with the effect of a homogeneous background condition [Fig. 6(A)]. Interestingly, in the cases in which an image-surfaces effect occurred, the slight tendency emerged that the effect was present primarily in the incremental part of the settings and hardly in the decremental one.

As opposed to the relatively small effect of image surfaces, changes in illumination had a huge effect on the achromatic settings. This effect was stronger for the decremental part of the settings than for the incremental part. Indeed, decrements showed a fairly complete amount of illuminant adjustment, with the subjects' achromatic settings being close to the coordinates of perfectly color constant settings. Increments, instead, showed only a moderate amount of illuminant adjustment with clear differences between the subjects' settings and perfectly color constant settings. This result mimics the pattern observed in Chichilnisky and Wandell's[13] center–surround study, in which more adjustment for decrements than for increments was found in response to a change in the surround color. It is also reminiscent of the classical Judd–Helson effect,[19,20] according to which the appearance of lights that are substantially less intense than some (effective) background is roughly maintained across background changes, while lights that are substantially more intense than the background take on the color of the background.

B. Relation to Previous Color-Constancy Studies

In a number of previous color constancy studies amount of illuminant adjustment was measured. On the basis of the results from the present experiments one might expect that quite different degrees of illuminant adjustment should have been found, depending on whether decremental or incremental test objects were used. Indeed, in a number of studies only moderate degrees of illuminant adjustment were found [between 50% and 60% (Refs. 1–3 and 8)], whereas others reported much higher amounts of adjustment [between 80% and 90% (Refs. 4–6)]. Although these studies differed in a number of features, including whether they used CRT simulations of illuminated objects or real objects rendered under real illumination, the differences in amount of adjustment across studies might have to do with the increment–decrement asymmetry as well.

This view is in agreement with some informal observations that I made. Using the same experimental display and the same experimental illuminants as in the present Experiment 1, I asked one new female subject to make achromatic settings for several viewing contexts. In contrast to Experiment 1, the large background field was dark ($<.01\ \mathrm{cd/m^2}$), a feature that might make the test surface incremental. Just as in the present experiment the achromatic settings showed clear effects of illumination. However, there was no evidence for any increment–decrement asymmetry. Moreover, the degree of illuminant adjustment was below 60% and thus well comparable with the degree of adjustment the subjects in the present experiment showed in their incremental settings. This agreement in results indicates that the dark background field made the settings incremental in nature. This finding is interesting, because several of the previous CRT studies reporting only moderate amounts of illuminant adjustment used dark background fields as well.[1,2,8] Presumably they studied the behavior of increments only.

Previous studies did not only vary in the amount of illuminant adjustment they found but in the size of the effect of image surfaces as well. Whereas some studies found only small effects of image surfaces on the chromaticity coordinates of achromatic settings,[5,6] others found quite substantial effects.[2] Interestingly, there is a pattern in these studies, which is that a high amount of illuminant adjustment is accompanied by a low effect of image surfaces, and a moderate amount of illuminant adjustment is accompanied by a more substantial effect of image surfaces.[7] This pattern might have to do with the increment–decrement asymmetry. Indeed, in a recent brightness constancy study Schirillo[31] investigated how brightness varies with articulation, i.e., the addition of equally spaced incremental and decremental patches within a surround. He found clear evidence for increment–decrement asymmetries, a larger amount of illuminant adjustment for decrements than for increments, and a smaller effect of articulation for decrements than for increments. The present results show a similar pattern, although here the effect of image surfaces is generally smaller.

C. Role of Background and Foreground Surfaces

If our visual system adjusted to changes in the image's arithmetic or geometric mean[32,33] or used some other simple rule for integrating color information from the entire image, then a major effect of image surfaces should have been seen in the present experiment. As the results show, however, image surfaces had only a minor effect on the subjects' settings. When compared to the results of Schirillo's[31] brightness study the smallness of the image-surfaces effect observed in the present study might indicate that image surfaces affect mainly the luminance part of subjects' settings and to a much lesser degree their chromaticity part. Such a conclusion would be consistent with prior research, in which, using roughly the same experimental display as employed in the present study, image surfaces in fact were found to influence mainly the luminance part of subjects' settings.[6]

However, there are at least two further factors that might have contributed to the present results. One of these factors is the presence of the constant, neutral background surface in the display; the other is the fact that image surfaces were mostly decremental with respect to the neutral background field.[34] That these two factors might have influenced the present results is suggested through the results of a previous study.[2] That study used an experimental display and procedure similar to those used in the present study. As opposed to the present study, however, the background region was tripartite and consisted of three nonneutral surfaces, which changed their local position randomly. Also, the stimuli were presented against a relatively dark background region, which made most of the foreground surfaces incremental relative to the background field. Indeed, contrary to the present results considerable effects of variations in image surfaces were found, indicating that the effect of foreground surfaces may vary with background color and the relationship between background and foreground colors. Discovering exactly what these relationships are would mark an important step towards a more complete understanding of how the visual system integrates color information from an image.

D. Generalizability of Results

This study examined the existence of increments and decrements in more complex images by using a certain type of Mondrian display and asking subjects to make achromatic settings for a number of different viewing contexts. The question arises of whether the results obtained are specific to the experimental conditions employed or generalize to other experimental conditions as well. Three lines of generalizability are finally discussed.

First, the present data indicate that increment–decrement asymmetries not only exist in center–surround situations but also occur in Mondrian-style images with a well-defined background surface. In both natural and manmade scenes objects are often seen against nonhomogeneous surrounds so that they may be decrements with respect to one surround field and increments with respect to the other. There is evidence that increment–decrement asymmetries occur in situations with nonhomogeneous surrounds as well. In fact, results by both Delahunt and Brainard[18] concerning asymmetric color matches and Schirillo[31] concerning asymmetric brightness matches point to this direction. A well-defined background thus does not appear crucial for the occurrence of increment–decrement asymmetries.

Second, achromatic settings are a special case of increments and decrements in the sense that each setting is either an increment in all three cone coordinates or a decrement in all three cone coordinates. In general, however, an object may be an increment with respect to one cone type and a decrement with respect to another. Results from previous studies, in which increment–decrement asymmetries have been ignored, suggest that achromatic settings may be regarded a variant of asymmetric color matching and, for instance, underlie the same von Kries transformations as chromatic stimuli.[8,35] On the basis of these results it seems likely that results found for achromatic settings generalize to chromatic ones and results found for pure increments and pure decrements therefore generalize to stimuli that are incremental with respect to one cone type and decremental with respect to another.[12–14,18]

Third, achromatic settings serve to measure the color appearance of lights. It has repeatedly been shown, however, that we may have access not only to the color appearance of lights but also to their surface color.[27,36,37] A question that arises from this observation is whether the results found in the present study generalize to surface color perception. Such a generalizability would be interesting, because recently a number of parallels between color appearance and surface color matching have been found.[37] There is some initial evidence from the achromatic domain that such a generalizability might hold. Schirillo[31,38] reported increment–decrement asymmetries for both brightness and lightness matches with a similar pattern of results for the two types of matches. If analogous results were found in the chromatic domain, the claim would be strengthened that, in many respects, color appearance and surface color matches differ quantitatively and not qualitatively.

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23. When using the CIELUV metric[21] one has to define a nominally white light for a given context. For this white light I used the color coordinates of the respective illuminated background surface. Additionally, I repeated the analyses using other definitions of the nominally white light. Although the absolute error values varied with the choice of the nominally white light, the pattern of results remained the same. The pattern of results did not even change when the analyses were run in cone space.
24. For the computation of the cone ratios, incremental and decremental cone signals were coded as differences relative to the level estimate. The incremental cone signals thus were assigned positive coordinates, and the decremental ones were assigned negative coordinates.
25. Both the experimental illuminants and the experimental surfaces were described by three-dimensional linear models. On the basis of this type of modeling, for each illuminant ϵ a so-called light transformation matrix, Δ_ϵ, can be defined. This 3×3 matrix provides a mapping from each 3×1 column vector ρ, which represents a surface, to the cone absorptions that result from this surface when rendered under illuminant ϵ. I computed the light transformation matrix for each of the three experimental illuminants and used these matrices to compute perfectly color constant settings (see Wandell,[26] pp. 306–308).
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