Color constancy: the role of image surfaces in illuminant adjustment

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Previous studies on color constancy have found that the color appearance of a test surface varies both as a function of the illumination in the image and as a function of the image surfaces. To what extent these two effects interact is investigated here. To address this issue theoretically, a restrictive von Kries model is formulated that assumes that the scaling of the cone signals in response to an illuminant change does not depend on image surfaces. Subjects saw CRT simulations of illuminated surfaces and, for a number of different illuminants and surface collections, adjusted a test light so that it appeared achromatic and had a certain brightness. Consistent with previous studies, the settings showed a high degree of illuminant adjustment and also showed an adjustment to the surfaces in the image. The proposed von Kries model provided a good, although not perfect, description of the data, thus indicating that the illuminant adjustment was largely the same under the different surface collections. These results together with those from several previous studies suggest that image surfaces play only a minor role in the illuminant adjustment of our visual system. © 1999 Optical Society of America [S0740-3232(99)02307-8]

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1. INTRODUCTION

In our daily lives we regard color as a more or less inherent property of objects. We talk about a blue shirt, a red car, etc. What appears so natural from our experience is rather surprising from a scientific point of view because the light that enters our eyes from an illuminated object depends not only on the object, i.e., the reflectance properties of the object's surface, but also on the illumination that renders the object visible. The illumination conditions for an object, however, can vary drastically. Daylight is much brighter on a sunny day than on a cloudy day; it can be fairly yellowish-reddish in the evening and fairly bluish at noon. Although these changes in illumination have a great effect on the light that is reflected from a surface, the colors of objects remain roughly constant for us.

There is growing evidence that the color of objects is maintained across illuminant changes through an adjustment of the visual system that occurs largely in terms of the three cone signals, a principle often called von Kries adaptation.[1–8] According to the von Kries principle, the cone signals that result from an illuminated object are scaled as a function of the illumination in the scene. For instance, if an illuminant emits light mainly in the long-wavelength part of the spectrum, then it is mainly the L-cone signal that is scaled; if an illuminant emits light mainly in the short-wavelength part of the spectrum, it is mainly the S-cone signal that is scaled. Because of this scaling, a large part of the illuminant effect that is originally present in the cone signals can be discounted.

Illuminant changes, however, are not the only source of variations in the color of objects: Changes in the surface collection in the image are another. In a number of recent CRT studies it has been shown that the color of a light may vary considerably as the image surfaces vary. For instance, a light that appears achromatic in an image that consists largely of reddish surfaces usually no longer appears achromatic in an image that consists largely of bluish surfaces.[1,9] Although these effects of surface collection are interesting on their own, they raise another, more fundamental question: To what extent do the adjustment to illuminant changes and the adjustment to the image surfaces interact with each other? In particular, to what extent does the same illuminant effect induce a different illuminant adjustment of our visual system in different surface collections?

Many approaches to color constancy have assumed that the visual system adjusts to changes in the image's arithmetic or geometric mean or to changes in its maximum excitation of one of the three cone types.[10–13] Thus they have assumed that the system reacts to illuminant changes only through its responsivity to changes in one of these image statistics and thus adjusts differently to an illuminant change depending on what the surfaces in the image are. Meanwhile, several studies have demonstrated that, to compensate for changes in the viewing context, the visual system does not rely on this type of image statistics.[9,14–17] These studies, however, did not examine to what extent the illuminant adjustment depends on the surface collection at all. This question is important, because it addresses the extent to which the visual system is able to separate the effects of changes in illumination and changes in the image surfaces.

The present study reports an experiment in which the role of image surfaces in illuminant adjustment was examined. Subjects saw CRT simulations of illuminated surfaces and, for a number of different illuminants and surface collections, adjusted a test light so that it appeared achromatic—i.e., appeared neither reddish nor greenish and neither yellowish nor bluish—and had a certain brightness.[1,8,9,18,19] Consistent with the results from previous CRT studies, the settings showed a considerable amount of illuminant adjustment and also showed an adjustment to the surfaces in the image. As it turned out, however, there was not much interaction between the two adjustments. The adjustment to an illuminant change was largely the same under the different surface collections.

2. METHOD

The methods used in this study are similar to those used by the author in previous studies.[1,9] The visual stimuli were presented on a CRT monitor. The stimulus was a test surface and a simulation of an array of flat matte foreground surfaces 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 surface until it appeared achromatic and had a certain brightness. 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, including the test surface, were changed every three seconds. This was done to minimize local effects (see Brainard and Wandell[3] for the rationale).

A. Visual Display

Figure 1 shows the visual display. 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 oval region (test surface). 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 deg of visual angle. Subjects saw the screen without head restraints from a distance of ~0.5 m in an otherwise dark room.

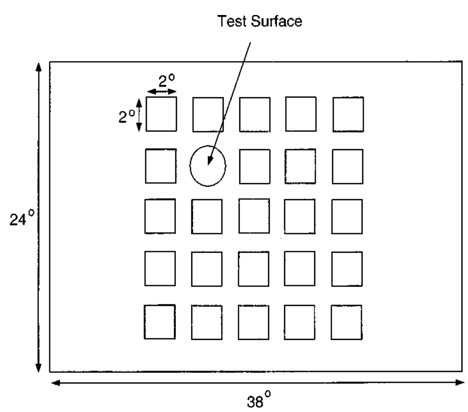

Fig. 1. Visual display. Subjects saw CRT simulations of a collection of 24 flat matte foreground surfaces (rectangular regions) and a test surface (circular region), both presented against a large background surface. The array of foreground surfaces and the background surface were rendered under the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

The simulated images were displayed on a computer-controlled color monitor (BARCO Calibrator CCID 7651) with a refresh rate of 71 Hz in noninterlaced video mode. The three channels of the monitor were controlled by an 8-bit digital-to-analog converter. The signals of the color channels could be varied in 256 steps from zero to maximal intensity for each pixel. 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, Model L 1003). The CIE xy coordinates of the phosphors were provided by the manufacturer. The programming was done by using PXL subroutines[20] (see Bäuml[1,9] for details).

B. Experimental Illuminants and Surfaces

Three experimental 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 $x = 0.326$, $y = 0.339$, $Y = 57.84$ for the neutral illuminant; $x = 0.249$, $y = 0.249$, $Y = 29.76$ for the blue illuminant; and $x = 0.402$, $y = 0.394$, $Y = 70.0$ for the yellow illuminant, where chromaticity (x, y) is specified with respect to the CIE 1931 colorimetric system and luminance (Y) is specified in candelas per square meters. All three experimental illuminants were constructed from the three-dimensional linear model of natural daylights proposed by Judd *et al.*[22]

Five sets of 24 surfaces (C_1–C_5) were drawn from the large set of simulated Munsell papers used by Brainard and Wandell.[3] These surfaces are approximations of Munsell papers, based on the three-dimensional linear model of Munsell papers by Maloney.[23] These papers define the foreground regions within the visual display. Figure 2 shows the xy chromaticity coordinates of the five collections when the surfaces are rendered under the neutral illuminant. As can be seen from the figure, the five collections differ largely in their surfaces' chromaticity coordinates. Whereas collections C_1 and C_2 contain surfaces from nearly the whole hue gamut, collection C_3 contains mostly bluish surfaces, C_4 mostly yellowish-reddish surfaces, and C_5 mostly yellowish-greenish surfaces. The collections' surfaces also span a considerable range of different luminance values. When rendered under the neutral illuminant, the surfaces' luminance values range from $Y = 2$ to $Y = 36$.[24] The mean luminance values are $Y = 11.83$ for C_1, $Y = 22.33$ for C_2, $Y = 12.26$ for C_3, $Y = 13.67$ for C_4, and $Y = 8.84$ for C_5. Two additional, neutral surfaces (B_1, B_2) of different luminance levels were used as background surfaces in the image. When rendered under the neutral illuminant, their CIE chromaticity values are $x = 0.326$, $y = 0.339$, and their luminance values are $Y = 19.61$ and $Y = 39.22$. The three experimental illuminants and three of the five experimental surface collections had already been used in previous studies.[1,2]

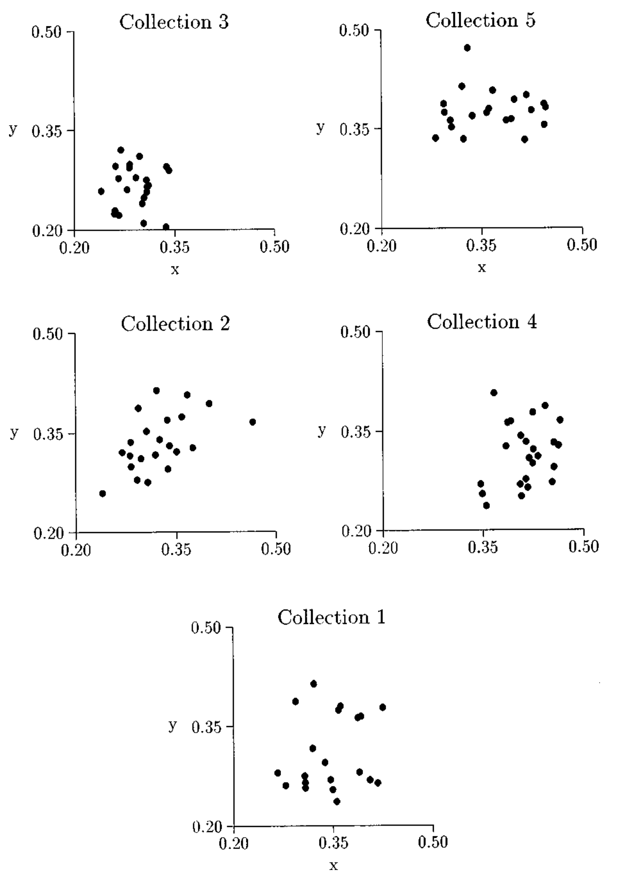

Fig. 2. Experimental surface collections. Each panel shows the CIE *xy* chromaticity coordinates of one of the five collections of foreground surfaces (C_1–C_5) that were used in the experiment. The coordinates of the surfaces that result when the surfaces are rendered under the neutral illuminant (see text) are shown.

Both the experimental illuminants and the experimental surfaces are 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 depends on the illuminant ϵ and 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 (see Wandell,[25] pp. 306–308). I computed the light transformation matrix for each of the three experimental illuminants and used these matrices to compute for each experimental surface the Smith–Pokorny[26] cone coordinates that result when the surface is rendered under one of the illuminants. These coordinates were used to simulate the illuminated surfaces on the monitor. In addition, the coordinates were used to determine for each illuminant change the matches that a perfectly color-constant observer would have set. Comparing these theoretical matches with the matches that a subject really sets provides information on the degree of the subject's illuminant adjustment.

C. Subjects

Two female subjects (AS and GR) took part in the experiment. Both had normal color vision and were completely naïve about the purpose of the experiment. They did settings under all combinations of the two background surfaces, the five foreground collections, and the three illuminants. Each of them adjusted one achromatic light of a certain brightness under each viewing context.

D. Procedure

In each experimental session, three combinations of surface collection and illuminant were presented to the subject. For each combination the subject did four or five settings during one session. Each combination of surface collection and illuminant was presented in two different sessions to each subject, resulting in eight to ten settings for each of them. Each subject began an experimental session with one min of dark adaptation. Then a collection of simulated surfaces rendered under a simulated illuminant was presented to the subject. The test surface was not yet visible. After two min of adaptation to these illuminated surfaces the test surface appeared, and the subjects did settings for this condition, readapting between the settings for 30 s. The subjects made adjustments by pressing the buttons on a mouse. They were instructed to adjust the test surface so that it appeared neither reddish nor greenish and neither yellowish nor bluish, i.e., achromatic to them. In addition, they had to adjust the luminance of the stimulus so that it had a certain brightness. Subjects were instructed to set a brightness level that they believed they could most easily memorize and set in later sessions.[1,27] Thus for each subject there was one brightness memory standard across the whole set of experimental conditions. Each subject took part in five practice sessions before the experiment was started. During the whole experiment each of the two subjects did approximately 300 settings.

3. RESULTS

A. Adjustments to Illumination and Image Surfaces

For each of the five foreground collections under each of the two background surfaces, Fig. 3 compares the Smith–Pokorny[26] long-, medium-, and short- (LMS) wavelength-sensitive-cone absorptions (cone coordinates) of the settings that subjects AS and GR made under the neutral illuminant with those they made under the bluish (AS) or the yellowish (GR) illuminant. The graphs also include the theoretical settings that the two subjects would have made if they had adjusted perfectly to the change from neutral to bluish or yellowish illumination.

As expected, the subjects' settings vary with illumination. They show considerable adjustments to the illuminant change and in many cases are quite close to perfectly color-constant settings. I used the method proposed by Arend *et al.*[28] to quantify the degree of constancy the subjects showed. In this method the distance between the settings under the neutral illuminant and perfectly color-constant settings is compared with the distance between perfectly color-constant settings and the settings under the changed illumination. Typically this method results in a constancy index between 0 and 1, whereby 0.0 reflects no adjustment at all to the illuminant change and 1.0 reflects complete adjustment.[29] On average I found a constancy index of 0.79 for subject AS and 0.84 for subject GR. These indices indicate a considerable degree of illuminant adjustment.

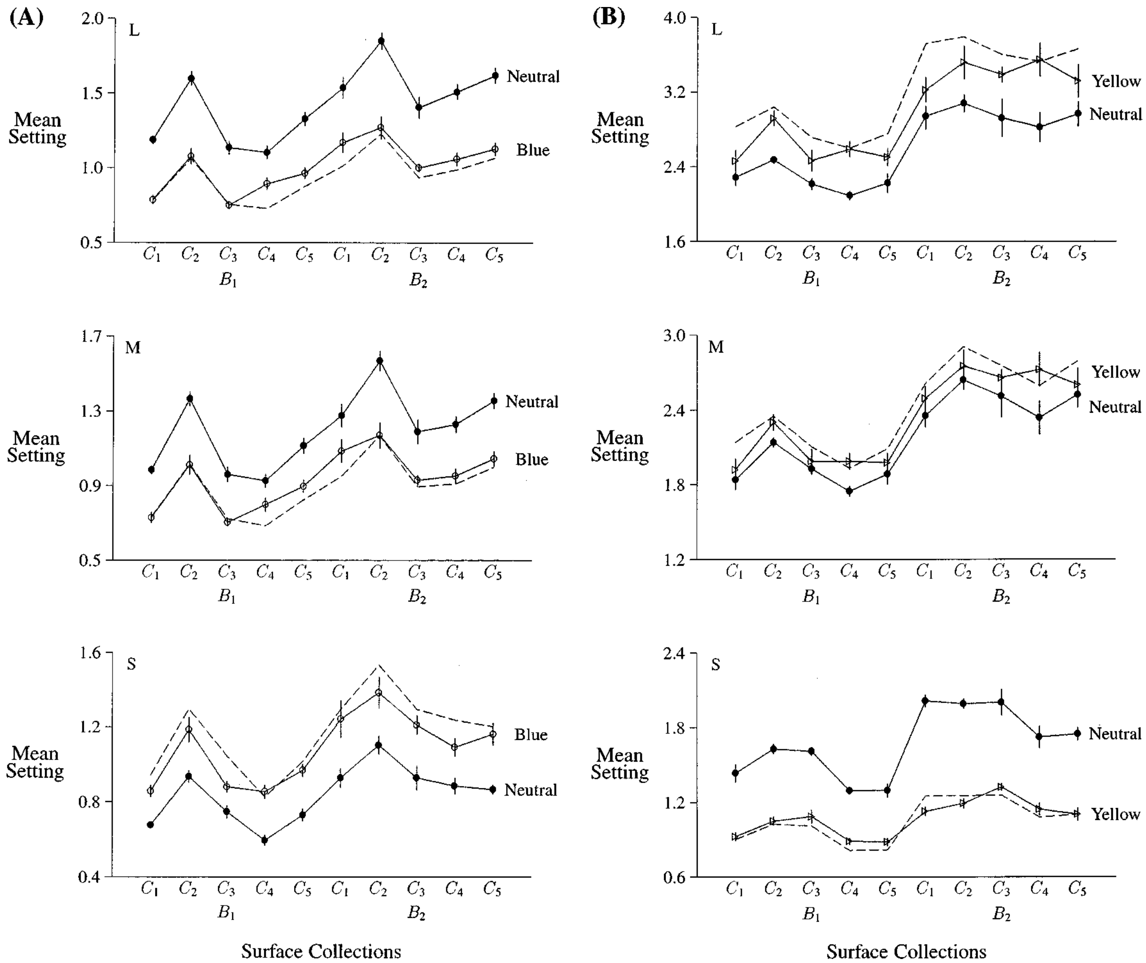

Fig. 3. Mean achromatic settings as a function of illumination and image surfaces. The Smith–Pokorny[26] LMS cone coordinates of the two subjects' achromatic settings as a function of the five foreground collections (C_1–C_5) and the two background surfaces (B_1, B_2) are shown. (A) Settings of subject AS made under the neutral (●) and the blue (○) illuminants. (B) Settings of subject GR made under the neutral (●) and the yellow (▷) illuminants. The dashed curves represent the settings the two subjects would have set if they had adjusted the settings perfectly to the change from neutral to bluish or yellowish illumination.

Also as expected, the settings vary not only with the illuminant but also with the image surfaces. This can be seen from Fig. 3 when we compare the LMS coordinates that subject AS and subject GR set for the ten surface collections, when the illuminant was constant. These settings vary both as a function of the foreground surfaces and as a function of the background surface. These results are consistent with those from previous CRT studies by showing adjustments of the visual system to both illuminant changes and changes in the image surfaces.

Figure 4 replots the data of Fig. 3 in terms of CIE xy chromaticity coordinates and additionally shows subject AS's data for the yellowish illuminant and subject GR's data for the bluish illuminant. Figures 4(a) and 4(b) show the chromaticity coordinates of subject AS's settings and subject GR's settings, respectively, shown separately for the two background surfaces. As can be seen, there is a clear dependence of the settings on the illumination in the image. When the illuminant changes from neutral to blue, the settings shift into the bluish part of the diagram; when the illuminant changes from neutral to yellow, the settings shift into the yellowish part. This feature of the diagram reflects the high degree of illuminant adjustment that is present in the data. Interestingly, the settings show only moderate dependence on the image surfaces. This result indicates that the settings' variation with image surfaces found in the cone coordinates is to a considerable degree due to an effect on the settings' luminance values and less to an effect on the settings' chromaticity coordinates. This is particularly obvious when we compare the settings for the two background surfaces. Whereas the change in background surface hardly induces a change in the settings' chromaticity coordinates, there are clear effects of background surface in all three cone coordinates (see Table 1 in Appendix A for further details).

B. Surface-Independent von Kries Model

According to the von Kries principle, the effect of an illuminant change on a subject's settings can be described by a 3×3 diagonal matrix $K_{\epsilon c}$, which represents the scaling of the incoming cone signals for a change from some standard to a test illuminant ϵ and a given collection of image surfaces C. In the present case this principle says that the achromatic setting n_c, done under the neutral illuminant and a collection of image surfaces C, and the achromatic setting m_c, done under the blue or yellow illuminant and the same collection of image surfaces, are related by the equation

$$m_c = K_{\epsilon c} n_c \,.$$

Since for each subject only one prototype color appearance of the test surface was used—an achromatic light of a certain brightness level—this version of the von Kries principle is trivially true in the present experiment. However, since achromatic settings were done under a number of different collections of image surfaces, the present data permit a test of the question of to what extent the von Kries matrix $K_{\epsilon c}$ depends on the image surfaces. If the von Kries scalings varied only with illumination and were the same for different collections of image surfaces, then the principle would reduce to the more restrictive equation

$$m_c = K_{\epsilon} n_c \,.$$

If this restrictive version of the von Kries principle held true, then the foreground and background surfaces in the present experiment should not have an effect on the visual system's adjustment to an illuminant change and the matrix $K_{\epsilon c}$ should be identical for the ten surface collections used in this experiment. In this case the ratios of the cone coordinates that the subject set under the bluish or yellowish illuminant, m_c, and those that she set under the neutral illuminant, n_c, should be the same across the ten surface conditions. Indeed, for each surface collection these ratios define the von Kries scaling for an illuminant change in the present context.

Figure 5 replots the data from Fig. 3 in terms of such cone ratios. Thus ratios of cone coordinates are shown for the change from neutral to bluish illumination (AS) and for the change from neutral to yellowish illumination

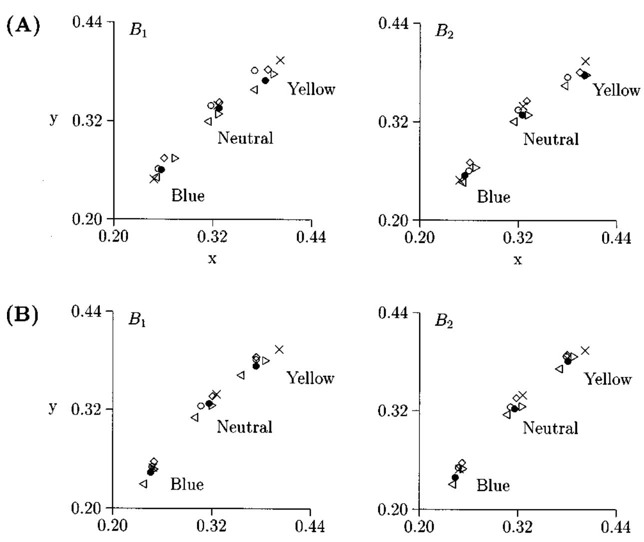

Fig. 4. Mean achromatic settings as a function of illumination and image surfaces. For each of the two background surfaces (B_1, B_2) and each of the three experimental illuminants (neutral, blue, yellow) the CIE xy chromaticity coordinates of the two subjects' achromatic settings are shown [(C_1(●), C_2(○), C_3(◁), C_4(▷), C_5(◇)]. The chromaticity coordinates of the three experimental illuminants are also shown (×). (A) Settings of subject AS. (B) Settings of subject GR.

(GR). In addition, for each illuminant change the graphs show the best-fitting theoretical cone ratio. This theoretical ratio was estimated from the subjects' data by minimizing the error that results when it is assumed that the illuminant adjustment is independent of the image surfaces (see Subsection 3.C for details). Although the cone ratios are not perfectly constant across surface conditions, the deviations from independence appear quite small. A similar pattern of results arose for the two subjects' settings for the other illuminant change.

C. Evaluation of the Model

To evaluate the degree to which the illuminant adjustment varies with image surfaces in the present experiment, I compared with the precision in the task the error that resulted when the von Kries matrix $K_{\epsilon c}$ was assumed to be independent of the image surfaces. To determine precision, I computed the mean setting for each combination of illumination and surface collection and used this mean for the prediction of the repeated settings. To determine the degree of independence, I fitted a single diagonal matrix for each illuminant change, restricted to be constant across the ten surface collections, and used the resulting matrix K_{ϵ} to predict the subject's settings for the illuminant change. In each case the resulting errors were computed relative to the covariance of repeated settings.[2,30,31] All the settings from each subject were included in the analysis.

Assuming independence results in an error of 2.05 units for subject AS and 2.20 units for subject GR, compared with precision values of 1.51 units (AS) and 1.57 units (GR). Independence, therefore, describes the role of surface collection within a tolerance of roughly 1.5 times the precision of repeated settings. This result parallels the typical finding for such well-established principles as the von Kries principle or illuminant linearity[1–5] and indicates that, at least in the present experiment, independence is indeed comparable in its quality of fit with the other principles. Figure 6 shows scatterplots comparing the predictions, which are based on the proposal that the von Kries scalings do not vary with image surfaces, with the settings the two subjects made under the different combinations of foreground and background surfaces. As expected from the error measures above, there is good agreement between predictions and settings.

4. DISCUSSION

A. Role of Image Surfaces in Illuminant Adjustment

The results from the present study show clear effects of changes in illumination and changes in the image surfaces on the appearance of an achromatic test surface, thus replicating findings from several previous studies.[1,9,18] Of primary interest in the present study is the question of to what extent these effects of illumination and image surfaces interact. To address this issue theoretically, a model that is based on two assumptions was investigated. The first assumption is the von Kries principle, according to which the illuminant adjustment of our visual system occurs in terms of the three cone signals. The second assumption is a restriction on this principle, which assumes that the von Kries scalings that result in

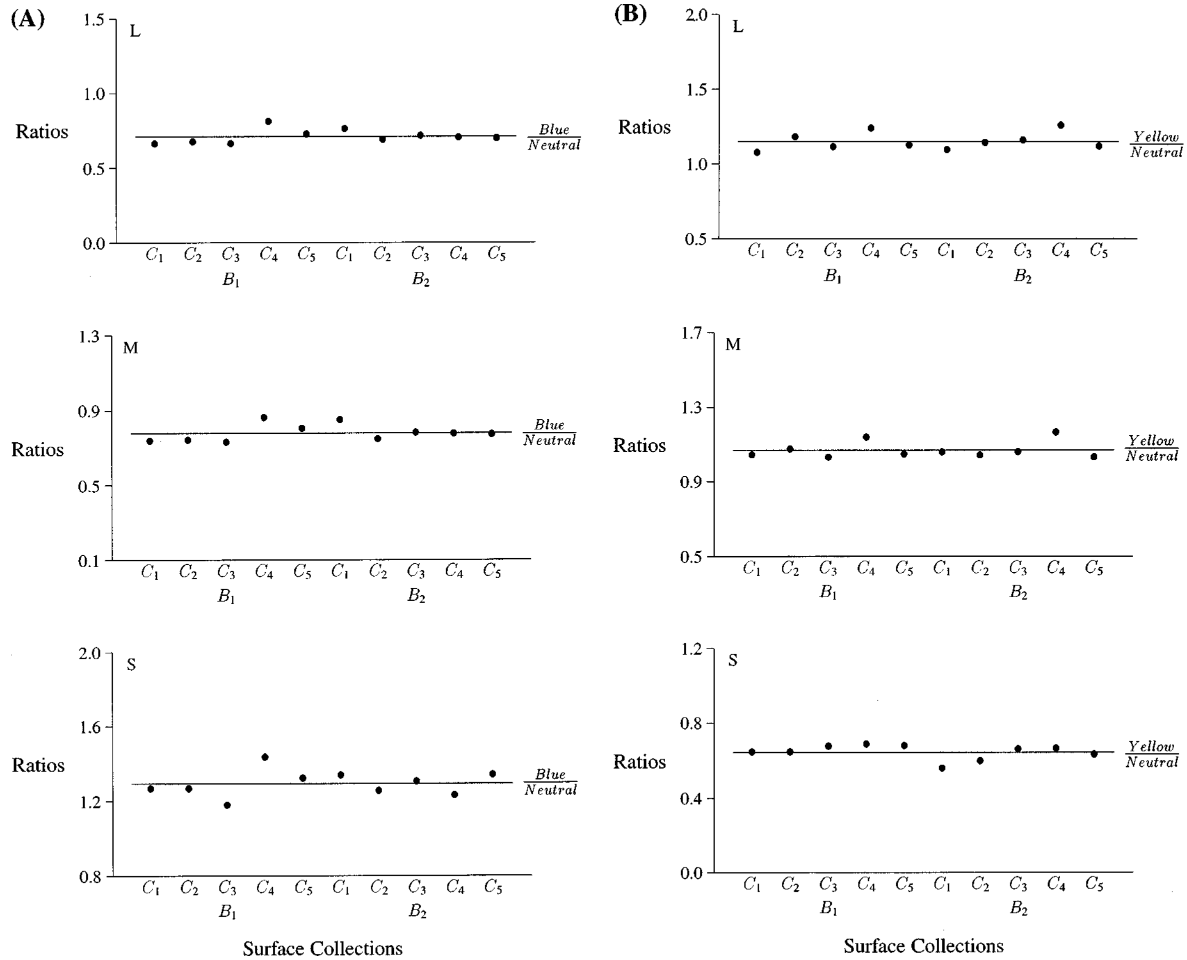

Fig. 5. Cone ratios as a function of image surfaces. The same data as in Fig. 3 are plotted. This time, however, for each cone type and each surface condition the ratios of coordinates (A) $L_{\text{blue}}/L_{\text{neutral}}$, $M_{\text{blue}}/M_{\text{neutral}}$, $S_{\text{blue}}/S_{\text{neutral}}$, and (B) $L_{\text{yellow}}/L_{\text{neutral}}$, $M_{\text{yellow}}/M_{\text{neutral}}$, $S_{\text{yellow}}/S_{\text{neutral}}$ are plotted together with a theoretical, constant cone ratio. If the illuminant adjustment of the two subjects were completely independent of the image surfaces, all ratios would fall on the theoretical line.

response to an illuminant change do not depend on image surfaces. As it turned out, this restrictive von Kries principle provides a good, although not perfect, description of the subjects' settings.

The finding of a rough independence of the effects of illumination and image surfaces suggests that our visual system is able to distinguish between the effects that are caused by illuminant changes and those that are caused by changes in the image surfaces. In this sense the system might build up roughly separate representations of illumination and surfaces and adjust to each of them independently. Although possible, adopting this view might be premature. Indeed, *a priori* it is far from clear whether the pattern of results found in the present study is inconsistent with the view that the illuminant adjustment is based on some simple image statistics. Although recent studies have provided clear evidence that the adjustment is not based on one simple image statistic, such as the arithmetic mean or the maximum excitation in one of the three cone types,[9,14–17] it might still be the case that our visual system uses a number of such statistics acting in concert[32] to exhibit a behavior that, to first approximation, is in agreement with a surface-independent illuminant adjustment.

The finding that the von Kries scalings are roughly independent of the image surfaces is not trivial, however. In two previous studies[1,9] I investigated another type of independence that is based on the assumption that the *difference* in a subject's settings across a change in illumination is the same for different surface collections, which deviates from the present proposal that the *von Kries scaling* is the same for different surface collections. Whereas the data from these previous studies are indeed consistent with both types of independence hypotheses (see Subsection 4.B), the present findings are consistent only with the von Kries–based independence hypothesis. In fact, the difference-based independence hypothesis leads to substantially larger errors in describing the subjects' settings than does the von Kries–based independence hypothesis.[33] The present data, therefore, can distinguish between the two types of independence.

B. Relation to Previous Studies

The result from the present study that image surfaces play only a minor role in illuminant adjustment is consistent with the data from two other recent studies, one also using CRT simulations of illuminated surfaces and one using more natural viewing conditions. In a previous

CRT study of mine,[9] two subjects made achromatic settings under all combinations of seven illuminants and twelve collections of image surfaces. The visual display was similar to the one used in the present study. The main differences were that the stimuli were presented against a relatively dark background region and that the foreground regions were larger and the background region was smaller than in the present study. In addition, the background region was tripartite and consisted of three nonneutral surfaces that changed their local positions randomly. This was done to prevent subjects from using the appearance of the background surface as a reference to identify changes in the simulated illuminant.

Just as in the present study, both illumination and image surfaces affected the achromatic settings considerably. I reanalyzed the data from this experiment to examine to what extent the putative von Kries scalings for an illuminant change varied with the image surfaces. Consistent with the present results, I found the scalings to be largely independent of the image surfaces. Assuming independence induced an error of 2.21 units for one subject (AH) and 2.01 units for the other (MP), compared with precision values of 1.52 units (AH) and 1.48 units (MP). This pattern of results parallels the one found in the present experiment. Figure 7 shows scatterplots comparing the L, M, and S coordinates of the two subjects' mean settings for each change in viewing context with the predictions of these settings, which are based on the assumption that the von Kries scalings do not depend on image surfaces. As can be seen, there is good agreement between settings and predictions.

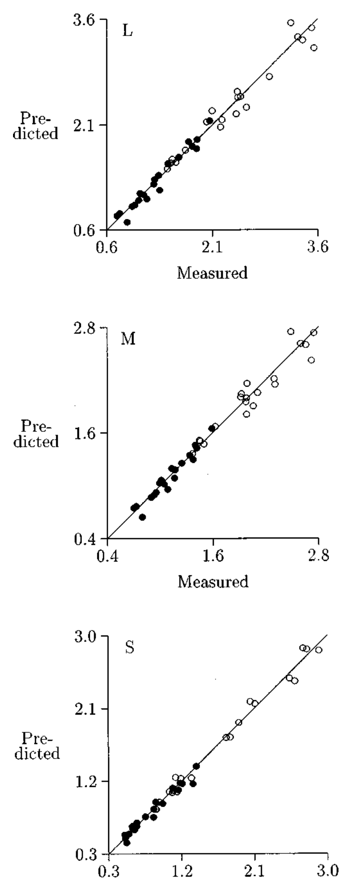

Fig. 6. Scatterplots of independence fit. The three graphs compare the LMS coordinates of subject AS's (●) and subject GR's (○) mean achromatic settings with the predictions of a model, which assumes that the von Kries scalings for an illuminant change do not depend on the image surfaces. To the extent that the data fall on the diagonal line, they indicate that the illuminant adjustment is independent of the image surfaces.

In another recent study, Brainard[18] investigated the effect of illuminant changes and changes in image surfaces on the achromatic loci under more natural viewing conditions. Subjects viewed colored surfaces in an experimental room where the illumination was under computer control. Brainard found considerable shifts of the achromatic loci when the illuminant was changed but found only modest shifts when the image surfaces were changed. Most interestingly in the present context, the two types of shifts showed only a small amount of interaction. These results indicate that, also under more natural viewing conditions, the visual system's adjustment to an illuminant change is largely the same under different surface conditions. Because the effect of image surfaces *per se* was quite small in Brainard's experiment,[34] his data provide a relatively weak test of the independence proposal. Larger effects of image surfaces, as have been found in the present study, lead to a stronger test of the proposal. The conclusion is the same in the two cases, however.

C. Possible Roles of Image Surfaces and Stimulus Configuration

There are at least two reasons why the conclusion that image surfaces play only a minor role in the illuminant adjustment of our visual system must remain preliminary. First, there are a huge number of possible variations in surface collections, and the present study and previous ones investigated just a few. Furthermore, since typically the same image surfaces are shown under several illuminants within an experiment, the range of surfaces that can be presented on the monitor is quite reduced. Second, the amount of dependence of the illuminant adjustment on the image surfaces may vary with the stimulus configuration employed. In the present study, for instance, there was a large neutral background field with a constant local position. This background field might have allowed the visual system to use it as a reference to identify changes in the simulated illuminant. Fortunately, the present pattern of results does not change when the background field is relatively dark and consists of several nonneutral surfaces that change their local positions randomly (see Subsection 4.B). In this sense the finding that the illuminant adjustment is roughly independent of the image surfaces is not limited to the present stimulus configuration. Discovering whether it generalizes to completely different stimulus configurations as well, such as configurations in which there is no well-defined background surface, is a high priority for future research.

D. Degree of Color Constancy

It is a question of considerable interest for color-constancy research whether the color-constancy performance of our visual system differs fundamentally between CRT situa-

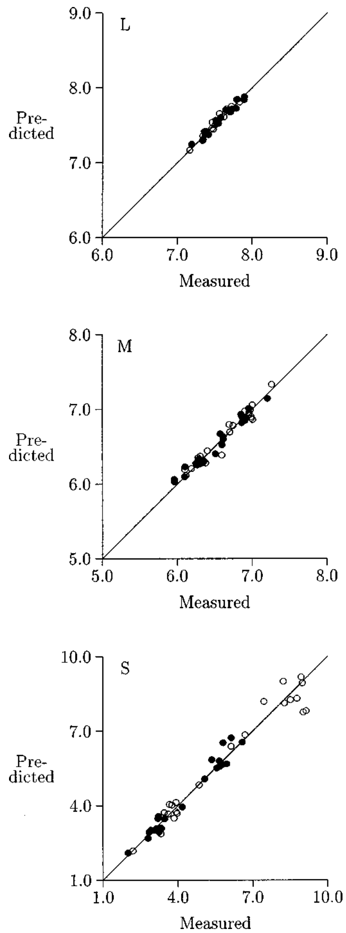

Fig. 7. Scatterplot of independence fit. These graphs show a reanalysis of data from a previous study of mine.[9] They compare the mean LMS coordinates of the two subjects' achromatic settings (AH, ●; MP, ○) with the predictions of a model that assumes that the von Kries scalings for an illuminant change do not depend on the image surfaces. To the extent that the data fall on the diagonal line, they indicate that the illuminant adjustment is independent of the image surfaces.

tions and more natural viewing conditions. A number of recent results indicate that there is no fundamental difference. In both types of situations, for instance, there is evidence that asymmetric appearance matches can be well described by the von Kries principle,[2–4] and in both types of situations there is evidence that the illuminant adjustment is largely independent of the image surfaces (for additional evidence on this point, see Schirillo *et al.*[35]). However, there also seem to be differences between CRT studies and those with more natural viewing conditions.

Indeed, one of the puzzles that has arisen from recent color-constancy studies is why the studies differed so much in the amount of illuminant adjustment that they reported. While some studies found only moderate amounts of illuminant adjustment in their subjects' settings (50–60%),[1,3,9,36] others found fairly high amounts of adjustment (80–90%).[18,37] This difference in amount of illuminant adjustment might well reflect the difference in the degree of naturalness in the experimental images employed. While in the studies that found moderate levels of adjustment subjects were presented CRT simulations of illuminated surfaces, in the studies that found high levels of adjustment more natural stimulus conditions were used, so that subjects viewed real surfaces rendered under real illuminants.

In the present study subjects were also presented CRT simulations of illuminated surfaces. The degree of illuminant adjustment the subjects showed (82%), however, was quite comparable with the degree of adjustment that has typically been found in the studies that used more natural viewing conditions. Why there is such a high degree of illuminant adjustment in the present study must remain unclear at this point. However, it might have to do with the fact that the test surfaces employed in this experiment were clearly decremental relative to the local background field (compare Subsection 2.B and Table 1 in Appendix A), whereas in previous CRT studies the test surfaces were usually incremental relative to the local background field.[1,3,9] Accordingly, the moderate degree of adjustment found in previous CRT studies and the high degree of adjustment found in the present study might reflect nothing other than a demonstration of the so-called increment–decrement asymmetry of our visual system.[38–40]

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, I asked one new female subject to make achromatic settings for several different viewing contexts. In contrast to the present experiment, the large background field was dark (<0.01 cd/m^2), a feature that made the test surface incremental relative to the local background. Just as in the present experiment the achromatic settings showed clear effects of illumination. The degree of illuminant adjustment, however, was substantially lower than in the present study (56% versus 82%) and was quite comparable with the degree of adjustment found in previous CRT studies. These results indicate that possibly the increment–decrement asymmetry that has typically been demonstrated with simple center–surround situations generalizes to more complex situations as well. The studies in which more natural stimulus conditions were employed thus might have used decremental rather than incremental test surfaces. While this is a possible explanation for the different degrees of color constancy found in previous studies, of course, other possibilities remain as well.[4,18]

E. Color Appearance versus Surface Color

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*.[28,41–43] Indeed, under certain circumstances, we may be able to perceive stimuli of different color appearance—i.e., stimuli that differ in terms of their hue, saturation, and brightness—as being the same surfaces that are only differently illuminated, i.e., as sharing the same surface color. An interesting question that arises from this observation is whether the illuminant adjustment that underlies color appearance and the illuminant adjustment that underlies surface color differ quantitatively or qualitatively.

Recent experimental results have shown that not only color appearance but also surface color perception is roughly consistent with the von Kries principle,[2] thus providing an initial indication of a quantitative difference between the two. In the same study, evidence was found that the illuminant adjustment that underlies surface color perception is largely independent of the image surfaces. In fact, the von Kries scalings for a given illuminant change varied only mildly with image surfaces. The present results come to an analogous conclusion with respect to color appearance. They thus provide a second indication for the hypothesis that color appearance and surface color differ quantitatively and not qualitatively.

APPENDIX A: SUBJECTS' SETTINGS

This appendix consists of Table 1, which provides the CIE xyY coordinates of the two subjects' settings in the present experiment. The settings are shown as a function of the illumination in the image and as a function of the image surfaces.

Table 1. Mean Achromatic Settings[a]

Illumination	Foreground	Background	Subject AS			Subject GR		
			x	y	Y	x	y	Y
Neutral	C_1	B_1	0.328	0.335	7.74	0.317	0.327	15.00
Neutral	C_2	B_1	0.318	0.338	10.52	0.307	0.324	16.33
Neutral	C_3	B_1	0.314	0.319	7.45	0.299	0.310	14.63
Neutral	C_4	B_1	0.328	0.328	6.52	0.321	0.325	13.64
Neutral	C_5	B_1	0.328	0.342	8.69	0.321	0.336	14.60
Neutral	C_1	B_2	0.325	0.328	10.02	0.316	0.322	20.58
Neutral	C_2	B_2	0.320	0.334	12.15	0.311	0.324	20.27
Neutral	C_3	B_2	0.314	0.320	9.21	0.306	0.315	19.25
Neutral	C_4	B_2	0.333	0.328	9.78	0.326	0.325	18.38
Neutral	C_5	B_2	0.330	0.345	10.60	0.318	0.335	19.48
Blue	C_1	B_1	0.258	0.260	5.30	0.246	0.243	10.40
Blue	C_2	B_1	0.254	0.261	7.30	0.248	0.250	11.68
Blue	C_3	B_1	0.251	0.251	5.07	0.237	0.229	10.35
Blue	C_4	B_1	0.275	0.274	5.95	0.251	0.247	9.90
Blue	C_5	B_1	0.261	0.274	6.52	0.250	0.256	10.77
Blue	C_1	B_2	0.255	0.254	7.89	0.244	0.238	14.26
Blue	C_2	B_2	0.260	0.260	8.56	0.248	0.250	16.58
Blue	C_3	B_2	0.252	0.246	6.75	0.240	0.230	13.74
Blue	C_4	B_2	0.269	0.264	7.07	0.254	0.249	14.98
Blue	C_5	B_2	0.261	0.270	7.62	0.252	0.256	15.20
Yellow	C_1	B_1	0.384	0.369	8.50	0.374	0.373	15.73
Yellow	C_2	B_1	0.371	0.381	11.36	0.374	0.381	18.72
Yellow	C_3	B_1	0.370	0.358	8.19	0.355	0.362	15.93
Yellow	C_4	B_1	0.395	0.377	9.82	0.386	0.380	16.47
Yellow	C_5	B_1	0.387	0.382	9.37	0.374	0.384	16.08
Yellow	C_1	B_2	0.401	0.376	11.42	0.381	0.380	20.56
Yellow	C_2	B_2	0.380	0.374	13.17	0.379	0.386	22.53
Yellow	C_3	B_2	0.376	0.364	10.33	0.370	0.371	21.71
Yellow	C_4	B_2	0.404	0.377	11.80	0.389	0.386	22.59
Yellow	C_5	B_2	0.395	0.380	11.94	0.380	0.388	21.27

[a] The CIE xyY coordinates of the two subjects' mean settings as a function of illumination (neutral, blue, yellow) and image surfaces (foreground collections C_1–C_5, background surfaces B_1, B_2) are shown.

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34. The effect of image surfaces on subjects' achromatic settings is smaller in Brainard's study than in the present one. This difference might have to do with the fact that in the present study subjects adjusted the test surface to appear achromatic and to have a certain brightness level, whereas in Brainard's study subjects did achromatic settings with a fixed luminance level. Indeed, the effect of image surfaces on the settings' chromaticity coordinates was also fairly small in the present experiment (see Subsection 3.A).
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