Illuminant changes under different surface collections: examining some principles of color appearance

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I report the results of a set of experiments designed to study whether the visual system's adjustments to illuminant changes vary with the surface collection in a scene. Simulations of flat matte surfaces rendered under diffuse illumination were presented on a CRT monitor. Under several surface collections subjects set asymmetric color matches between a standard surface and a test surface that were rendered under illuminants with different spectral power distributions. The three subjects' data span 28 different illuminant × surface collection conditions. Five different standard surfaces were used. Two results stand out. First, a change in surface collection did not induce a substantial change in the effect of illuminant changes on the subjects' settings. In this sense the results are consistent with the hypothesis that the visual system's adjustments to illuminant changes do not depend on the surface collection. Second, the illuminant-induced changes in the subjects' settings for a given surface collection were well approximated by a von Kries model, in which the change in the von Kries coefficients is a linear function of the illuminant change. In addition, I tested the hypothesis that the gain of the signal from each cone class is regulated by the photopigment absorptions originating entirely within that cone class. I found some clear deviations from this hypothesis, which indicates interactions among the cone classes. A first-order quantification of these interactions is provided.

1. INTRODUCTION

Illuminant changes greatly affect the light that is reflected from an illuminated surface, without, however, having a comparable effect on a surface's color appearance. Indeed, the color appearance of surfaces remains relatively stable across different illuminants. This stability of surface color appearance reflects an adjustment of our visual system to changes in illumination, usually called color constancy.

Asymmetric color matching has been widely used as an experimental method to investigate theoretical properties of this adjustment.[1] In this method a subject sets a test surface under a test illuminant to match the appearance of a standard surface under a standard illuminant. Changes in the subject's settings as a function of changes in illumination then reflect the visual system's adjustment to this change in the visual context. In fact, these measurements provide the basic data for a theory of how surface color appearance depends on the illuminant.

Recently Brainard and Wandell[2] and Bäuml[3] reported data that suggest three first-order principles to describe asymmetric color matches across different visual contexts. In both studies the stimuli were CRT simulations of flat surfaces rendered under diffuse illumination. As a first principle, Brainard and Wandell found good support for a von Kries hypothesis.[4] That is, when the standard and the test surfaces were represented by their cone coordinates, for any illuminant change the mapping between matching standard and test surfaces was well described by a diagonal linear transformation. As a second principle, Brainard and Wandell found that these diagonal linear transformations depend linearly on the illuminant changes, a property that they called illuminant linearity. As a third principle, Bäuml found the effect of illuminant changes to be roughly independent of the surface collection in a scene, indicating that the visual system's adjustments to illuminant changes do not vary with the surface collection. This principle is compatible with a possible effect of the surface collection on the color appearance of a test surface, for instance, through color induction, a well-established phenomenon of color appearance.[5,6] It expresses the idea that such an effect of surface collection does not interact with the illuminant's effect on the appearance of a test surface, thus imposing considerable restrictions on our system's adjustments to illuminant changes. In what follows, this hypothesis will be referred to as collection invariance. To the extent that the three principles hold true, they have strong implications for a theory of color appearance.[7]

The three principles have been tested empirically, but each to different degrees. The von Kries principle was found to hold well in studies that used simulations of illuminated surfaces[2,8] and simple center–surround situations.[9,10] Nevertheless, one may handle certain experimental situations more satisfactorily by using a more general theory.[11,12] Illuminant linearity was examined in two studies[2,3] and was found to be well supported by this data. Finally, collection invariance was examined in the recent study by Bäuml.[3] Although the principle was found to hold in a reasonable way, these experiments provided only the first step toward examining the principle thoroughly. In fact, the tests were conducted with use of a paradigm in which approximately isoluminant surfaces were used and subjects' achromatic loci were measured on an isoluminant plane in color space. Since these features of the paradigm limit the generality of the principle, further experimental tests of the principle are necessary. These tests must investigate surface collections that produce surfaces of varying luminance and must measure

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the effect of illuminant changes on both achromatic and chromatic test surfaces of varying luminance.

This study reports the results from a set of experiments designed to examine the collection-invariance principle in further detail. The experiments were designed to compare the degree of validity of the principle with that of illuminant linearity and of the von Kries principle and to include tests of these two principles. As in previous studies by Brainard and Wandell[2] and by Bäuml,[3] simulations of illuminated surfaces were presented on a CRT monitor. The effect of illuminant changes on test surfaces was measured under different surface collections with the method of asymmetric color matching. Subjects set several different test surfaces, both achromatic and chromatic ones.

Two results stand out. First, a change in surface collection did not induce a substantial change in the effect of the illuminant changes on the subjects' settings. In this sense the results are consistent with the hypothesis that the visual system's adjustments to illuminant changes do not depend on the surface collection. Second, the changes in the subjects' setting for a given surface collection were well approximated by a von Kries model, in which the change in the von Kries coefficients is a linear function of the illuminant change. I integrated the three principles into a summary model of color appearance. This model provided a good first-order account of the data. In addition, I examined the hypothesis that the gain of the signal from each cone class is regulated by the photopigment absorptions originating entirely within that cone class.[4,13,14] I found some clear deviations from this hypothesis, which indicates interactions among the cone classes. A first-order quantification of these interactions is provided.

2. METHOD

The methods used in this study were similar to those used by Brainard and Wandell[2] and by Bäuml.[3] The visual stimuli were presented on a CRT monitor. The stimulus was a simulation of an array of flat matte surfaces rendered under spatially uniform illumination, and a test surface. This array of illuminated surfaces represented one combination of simulated illuminant and simulated surface collection. The stimulus was presented against a large dark background that consisted of two different surface reflectances rendered under the same illuminant as was the surface collection. The subjects pressed buttons to set the appearance of the test surface. While both the simulated illuminant and the simulated surface collection were fixed during a subject's settings, the local position of a quarter of the stimuli, including the test surface, was changed every second. This randomization was intended mainly to isolate the effect of illuminant changes from the effects of other variables. For instance, it should have minimized local effects such as local adaptation and should have prevented subjects from using the appearance of a fixed surface as a reference to identify changes in the simulated illuminant.

A. Visual Display

Figure 1 shows the visual display. It consisted of 25 small foreground regions against a large partitioned background region. The foreground regions consisted of one oval region (test surface) and 24 rectangular regions (simulation of illuminated surfaces). These rectangular regions subtended 2.6 vertical by 2.1 horizontal deg of visual angle and were separated by 0.3 deg vertically and 0.2 deg horizontally. The whole background region subtended 15.2 vertical by 19.8 horizontal deg of visual angle. It consisted of three large rectangular regions, the left and right regions subtending 15.2 vertical by 2.2 horizontal deg of visual angle and the middle region subtending 15.2 vertical by 15.4 horizontal degrees.

The stimuli were displayed on a computer-controlled color monitor (BARCO Calibrator). The display was generated at 60 Hz noninterlaced. The three primaries of the monitor were controlled by an 8-bit digital-to-analog converter. The signals of the primaries could be varied in 256 steps from zero to maximal intensity for each pixel. The luminance of each primary was measured with a high-precision photometer (Fa. Lichtmesstechnik, Model L 1003). The CIE xy coordinates of the phosphors were provided by the manufacturer.

A given surface under a given illuminant was simulated by multiplication of the surface-reflectance function and the illuminant spectral power function. This product is the spectral power distribution of the reflected light. The CIE XYZ tristimulus coordinates of this reflected light were computed and the values in the monitor frame buffer appropriately set.

B. Illuminants and Surface Collections

Seven experimental illuminants were used that were selected from the CIE daylight locus.[1] They were typical for natural daylight. All the experimental illuminants were constructed from the three-dimensional linear model of natural daylights proposed by Judd *et al.*[15] The experimental illuminants varied with respect to both their chromaticity and their luminance. The spectral properties and the color coordinates of the illuminants are provided in Appendix B.

Four experimental collections of surface reflectances were constructed, each consisting of 24 surface reflec-

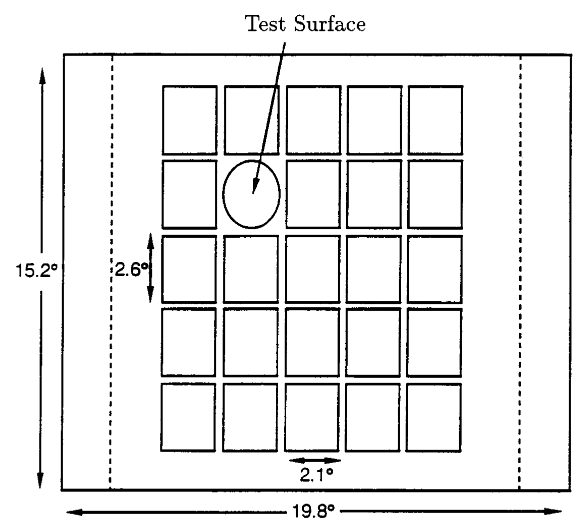

Fig. 1. Visual display. Subjects saw CRT simulations of a collection of 24 flat matte surfaces rendered under a spatially uniform illuminant (rectangular regions) and a test surface (oval region). A detailed description of the stimulus is given in Section 2.

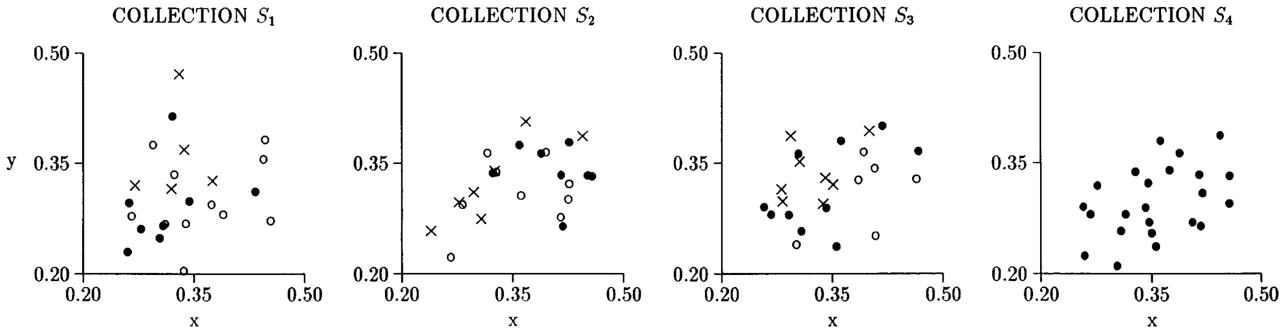

Fig. 2. Experimental surface collections. Each plot shows for one of the four experimental surface collections the CIE xy coordinates of the collection's single surface reflectances when the surfaces are rendered under the standard illuminant D_0 (see Table 2 in Appendix B). To include some rough information in this figure about the luminance variation within the collections, I categorized the luminance of the single surfaces into three classes: open circles, surfaces with a relatively low luminance; filled circles, surfaces with a moderate luminance; crosses, surfaces with a relatively high luminance. In surface collections S_1, S_2, and S_3 the luminance ratio of the surface with the highest luminance to the surface with the lowest luminance was approximately 13/1. In surface collection S_4 the surfaces were nearly isoluminant.

tances. All surface reflectances were approximations of Munsell chips. They were drawn from the large set of surface reflectance functions used in the study of Brainard and Wandell.[2,16] The spectra of the Munsell chips were approximated by appropriate linear combination of six basis surface-reflectance functions.[17,18] Figure 2 shows the chromaticity gamut of all surfaces from all four surface collections when the surfaces were rendered under experimental illuminant D_0 (see Table 2 in Appendix B). Surface collections S_1, S_2, and S_3 showed considerable differences with respect to their luminance. In all three collections the luminance ratio of the surface with the highest luminance to the surface with the lowest luminance was approximately 13/1. In surface collection S_4 the surfaces were nearly isoluminant. The background surfaces were identical to those used in my recent study.[3] Their luminance was approximately half that of the (foreground) surface with the lowest luminance.

C. Subjects

Three subjects with normal color vision took part in the study. Two of them (MW and BM) were not informed about the goals of the experiment. The third one (KHB) was the author.

A subject made settings for one (MW) or two (BM and KHB) test surfaces under each combination of two surface collections and the seven experimental illuminants. Each of the five different test surfaces was specified through a certain color appearance, i.e., a specific hue, saturation, and brightness. The three subjects made settings for one achromatic test surface each; in a second and later part of the experiment subjects BM and KHB in addition made settings for one chromatic test surface each. Subject MW made settings for surface collections S_1 and S_2, subject BM for surface collections S_1 and S_3, and subject KHB for surface collections S_1 and S_4.

D. Procedure

In each experimental session three combinations of surface collection and illuminant were presented to a subject. For each combination a subject made four settings during a session. Each combination of surface collection and illuminant was presented to a subject in two (BM) or three (MW and KHB) different sessions. This resulted in eight or twelve settings for each of the combinations.

The subject began an experimental session with 5 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 4 min of adaptation to these illuminated surfaces, the test surface appeared and the subjects made four settings for this condition, readapting between settings for 30 s. After these four settings, the next combination of surface collection and illuminant was presented. Exactly the same procedure was used as in the first combination.

Each subject made settings by pressing the buttons of a mouse. For the achromatic settings the subjects were instructed to set a test surface that appeared to them to be neither reddish nor greenish, neither yellowish nor bluish, and neither blackish nor whitish. The subjects had no problems with this task. For the chromatic settings the subjects were instructed to set a chromatic test surface that they believed they could most easily memorize and set in later sessions.[19] In fact, after some practice sessions the subjects' settings for the chromatic surface were quite comparable in precision with those for the achromatic surface. Taken together the three subjects' data included 728 individual matches.

E. Data Analysis

The representation of the subjects' settings and the experimental illuminants was based on the use of the Smith–Pokorny[20] cone fundamentals. I used a version that is normalized to a peak value of 1.0.

I report tests of several models of the illuminant's effect on color appearance. All the models include one or more transformations, which map certain illuminant changes (illuminant linearity) or standard test surfaces (von Kries principle) into differences between subjects' settings under two different illuminants. For each model transformation an error measure was required for choice of a best-fitting transformation. The size of the difference between the observed and the predicted settings was evaluated relative to an estimate of the surfaces' covariances.

For each surface set under one of the illuminants there were eight or twelve repeated measurements by each subject. On the basis of these repeated measurements for each surface i its covariance matrix $\mathbf{\Delta}_i$ was estimated. The differences between the observed and the predicted settings were minimized by minimization of the error measure

$$\sum_i \sum_j \mathbf{e}_{ij}{}^t \mathbf{\Delta}_i{}^{-1} \mathbf{e}_{ij} \, ,$$

where $\mathbf{e}_{ij}$ denotes the difference between the observed and the predicted settings for surface i under replication j. This error measure is equivalent to transforming the model deviations into a coordinate frame in which the errors form a spherical cloud with the Euclidean distance in that frame.[21] I used the iterative search procedure PRAXIS[22] to perform the error minimizations.[23]

3. RESULTS

A. Effect of Illuminant Changes

Figure 3 shows the effect of illuminant changes on the five test surfaces. The upper row shows the illuminant effects for collection S_1, and the lower row shows the illuminant effects for the collections S_2, S_3, and S_4. The effects are shown with CIE xy chromaticity coordinates.

The seven diamonds in each of the six plots represent the xy coordinates of the seven experimental illuminants. Each plot also shows the mean xy coordinates of a subject's one (two) test surface(s) set under each of the seven illuminants. Circles refer to achromatic test surfaces, crosses to chromatic ones. In general the data show a regular pattern in that, loosely speaking, the coordinates of the test surfaces adjusted by the subjects shift from more bluish locations in the diagram to more yellowish locations as the illuminant changes from bluish to yellowish locations. This pattern holds for all test surfaces. It demonstrates the well-known tendency of our visual system to color-constant performance for the present experimental paradigm. As the figure shows, varying the illuminant alters the subjects' settings by approximately 50% relative to the color coordinates of the illuminant. This degree of color constancy is quite comparable with that found by other researchers, who have used the same experimental paradigm in previous studies.[2,3,8]

B. Preliminaries

I held one of the illuminants (D_0) fixed. I will refer to it as the standard illuminant in what follows. Illuminants were represented by the degree to which their cone coordinates differed from those of the standard illuminant. These differences are called illuminant changes. For each test surface in each surface collection I fixed the surface's cone coordinates, which each subject set under the standard illuminant. In what follows, I will refer to the cone coordinates of these surfaces as the standard test surfaces. The color coordinates of these standard test surfaces are provided in Appendix B. The surfaces' coordinates, which each subject set under each of the experimental illuminants, were represented by the degree to which they differed from those of the respective standard test surface. These differences are called changes in the test surfaces.

I represent the illuminant D_i ($i = 0, \ldots, 6$) by the three-dimensional vector $\mathbf{d}_i$ and represent a test surface's cone coordinates set under illuminant D_i and surface

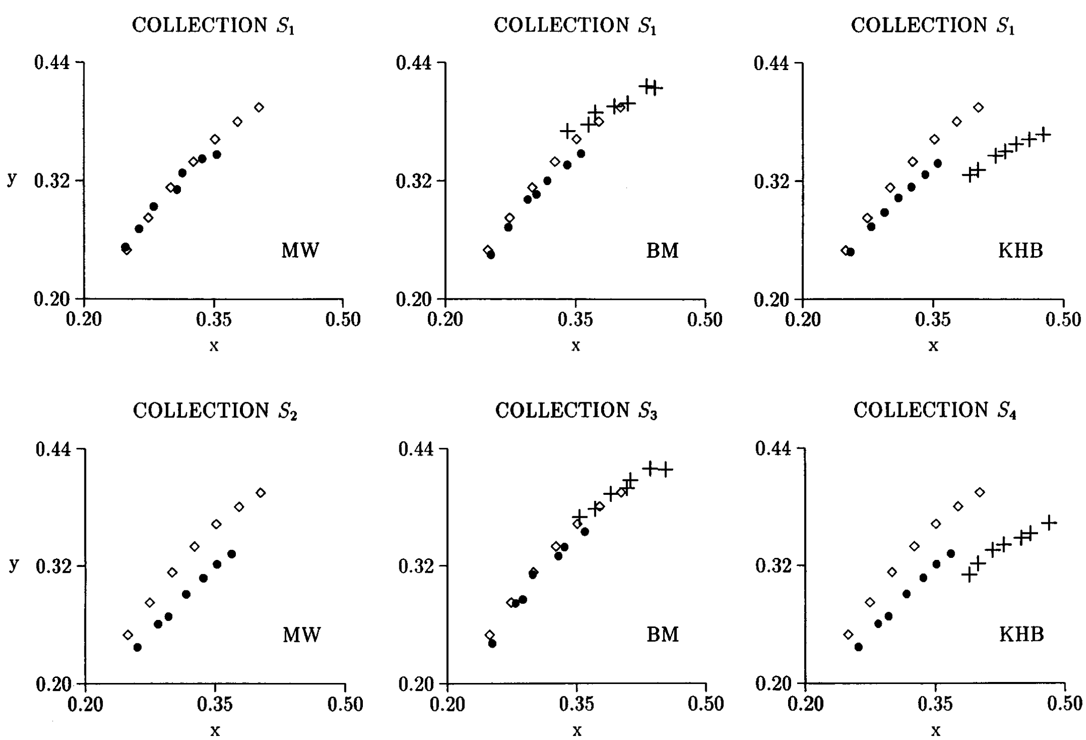

Fig. 3. Test surfaces set by the three subjects. The upper row shows the illuminant effects for collection S_1 separately for the three subjects. The lower row shows the illuminant effects for collections S_2, S_3, and S_4. The effects are shown with CIE xy chromaticity coordinates. The seven diamonds in each of the six plots represent the xy coordinates of the seven experimental illuminants. Each plot also shows the mean xy coordinates of a subject's (two) test surface(s) set under each of the seven illuminants. Circles, achromatic test surfaces; crosses, chromatic surfaces.

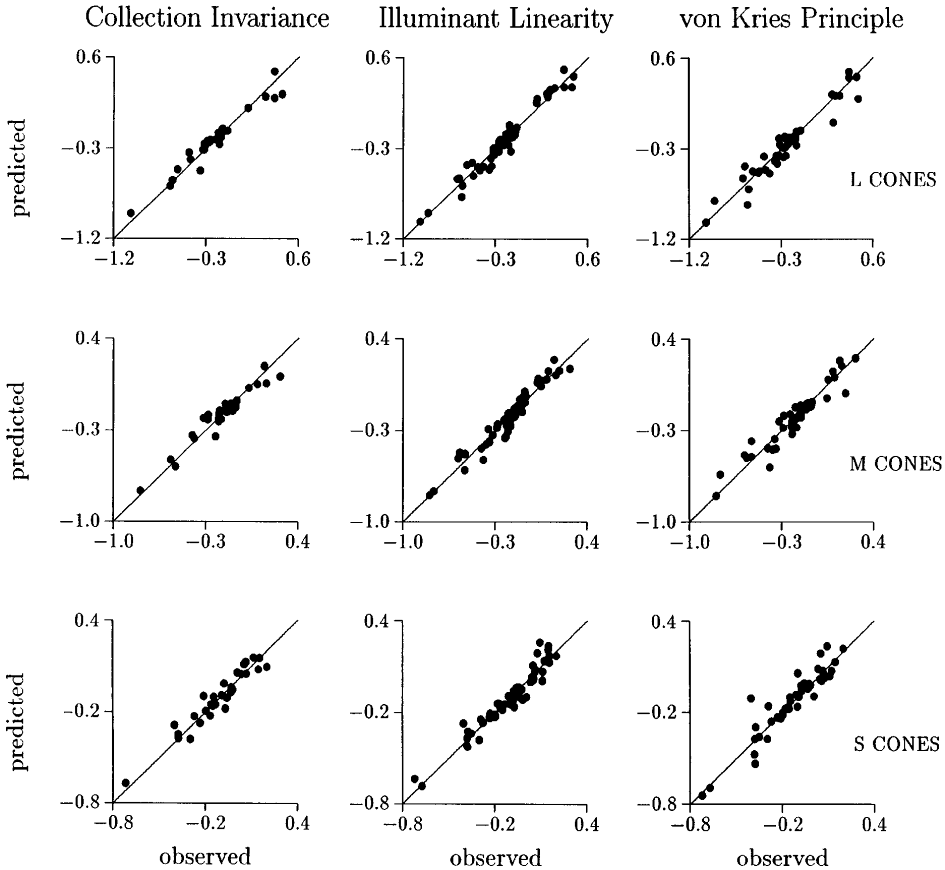

Fig. 4. Collection invariance, illuminant linearity, and the von Kries principle. Scatterplots compare observed mean changes in the test surfaces with the predictions of these changes. The quality of fit of the three principles is shown separately for the three cone classes. The data are merged over subjects and test surfaces. If a principle held perfectly, all data points would fall on the diagonal line. L, long-wavelength-sensitive; M, middle-wavelength-sensitive; S, short-wavelength-sensitive.

collection S_j by the three-dimensional vector $\mathbf{t}_{ij}$. Correspondingly, illuminant changes are represented by vectors $\boldsymbol{\Delta}\mathbf{d}_i$ ($= \mathbf{d}_i - \mathbf{d}_0$), and illuminant-induced changes in the cone coordinates of the test surfaces are represented by vectors $\boldsymbol{\Delta}\mathbf{t}_{ij}$ ($= \mathbf{t}_{ij} - \mathbf{t}_{0j}$), where j refers to a fixed surface collection S_j.

C. Collection Invariance

Given a certain surface collection S_j, the hypothesis of collection invariance states that the illuminant-induced change in a test surface's cone coordinates, $\boldsymbol{\Delta}\mathbf{t}_{ij}$, does not depend on S_j. That is, given another surface collection S_k, it must hold true for all test surfaces t and all illuminant changes $\boldsymbol{\Delta}\mathbf{d}_i$ that

$$\boldsymbol{\Delta}\mathbf{t}_{ij} = \boldsymbol{\Delta}\mathbf{t}_{ik}\,.$$

To examine the degree of validity of this principle in the data, I compared for each subject the illuminant-induced changes in the test surfaces' coordinates under collection S_1 (observed) with the illuminant-induced changes in these surfaces' coordinates under collection S_2, S_3, or S_4 (predicted). The leftmost column of Fig. 4 depicts the result of this comparison. To the extent that the data fall on the diagonal line, the illuminant changes induced the same effects on the test surfaces for the two surface collections. For all three cone classes the data are fairly close to the diagonal.

D. Illuminant Linearity

The hypothesis of illuminant linearity states that for each surface collection S_j the illuminant-induced changes in a test surface's cone coordinates, $\boldsymbol{\Delta}\mathbf{t}_{ij}$, depend linearly on illuminant changes $\boldsymbol{\Delta}\mathbf{d}_i$. In more detail, illuminant linearity assumes the existence of a 3×3 matrix $\mathbf{M}_{tj}$ for each surface collection S_j and each test surface t that transforms illuminant changes, $\boldsymbol{\Delta}\mathbf{d}_i$, into test surface changes, $\boldsymbol{\Delta}\mathbf{t}_{ij}$:

$$\boldsymbol{\Delta}\mathbf{t}_{ij} = \mathbf{M}_{tj}\boldsymbol{\Delta}\mathbf{d}_i\,.$$

This model was fitted to each subject's data set. The model's quality of fit is illustrated in the middle column of Fig. 4. This figure compares the observed changes in the cone coordinates with the changes predicted when this linear model is fitted to the data. If the model were perfect, all data would fall on the diagonal. For all three cone classes the data are fairly close to the diagonal.

E. von Kries Principle

The von Kries hypothesis states that the effect of any illuminant change $\boldsymbol{\Delta}\mathbf{d}_i$ on arbitrary test surfaces t can be described by a diagonal linear transformation. In more detail, the von Kries principle assumes that there exists a

3×3 diagonal matrix $\mathbf{K}_{ij}$ for each illuminant change $\Delta\mathbf{d}_i$ and each surface collection S_j that linearly transforms the standard test surfaces $\mathbf{t}_{0j}$ into the illuminant-induced changes in test surfaces $\Delta\mathbf{t}_{ij}$:

$$\Delta\mathbf{t}_{ij} = \mathbf{K}_{ij}\mathbf{t}_{0j}\,.$$

Subject MW made settings for only one test surface; in this case the hypothesis is trivially true. Subjects BM and KHB made settings for more than one test surface, and the hypothesis can thus be tested for their data sets. The model was fitted to the data set of each of the two subjects. The quality of fit of the principle is visualized in the rightmost column of Fig. 4. This figure compares the observed changes in the cone coordinates with the changes predicted when this linear model is fitted to the data. For all three cone classes the data are fairly close to the diagonal.

F. Evaluation of the Three Principles

I compared the fit of each of the three principles to data with the subjects' precision and with a no-model prediction, which represents the effect to be explained. I evaluated the fits of the three principles by using the differences between the observed and the predicted settings as error measures.[24] To evaluate the subjects' precision, I used as error measures the variation of the repeated settings. Finally, to evaluate the size of the effect, I used as error measures the differences of the single settings from the respective standard surfaces. In all these cases the surfaces' covariance matrices were used for the analyses (see Section 2).

Figure 5 shows the results. The difference between the first and the fifth bars of the figure reveals the size of the effect of illuminant changes in the present experiment. Changing the illuminant had a considerable effect on the test surfaces' cone coordinates. The second, third, and fourth bars show the quality of fit of the three principles—collection invariance, illuminant linearity, and von Kries—to the data. Two results stand out. First, the errors resulting from the three principles are similar in size. In this sense the results provide no reason to reject one of the three principles without also rejecting the other two. Second, the errors resulting from the three principles are close to the subjects' precision, reflecting a reasonable fit of all three principles to the data.

G. Combining the Three Principles: A Summary Model

The three principles were integrated into one summary model. I started out with illuminant linearity, imposed collection invariance as a first restriction, and imposed the von Kries principle as a second restriction.

As described above, for any test surface t and any surface collection S_j, illuminant linearity states that there exists a 3×3 matrix $\mathbf{M}_{tj}$ that transforms illuminant changes $\Delta\mathbf{d}_i$ into changes in the test surface's cone coordinates $\Delta\mathbf{t}_{ij}$. Thus matrix $\mathbf{M}_{tj}$ is free to depend both on the surface collection and on the test surface. Collection invariance reduces this freedom by imposing the restriction that the matrices $\mathbf{M}_{tj}$ do not vary with the surface collection; i.e., $\mathbf{M}_{tj} = \mathbf{M}_{tk}$ for any two surface collections S_j, S_k. The von Kries principle further restricts the transformations. As shown in Appendix A, including this principle results in

$$\Delta\mathbf{t}_{ij} = \mathbf{P}_t\mathbf{M}\Delta\mathbf{d}_i\,.$$

$\mathbf{P}_t$ is a 3×3 diagonal matrix whose diagonal elements are the cone coordinates of the standard test surface t under one fixed surface collection. $\mathbf{M} = \mathbf{P}_t^{-1}\mathbf{M}_t$ is a 3×3

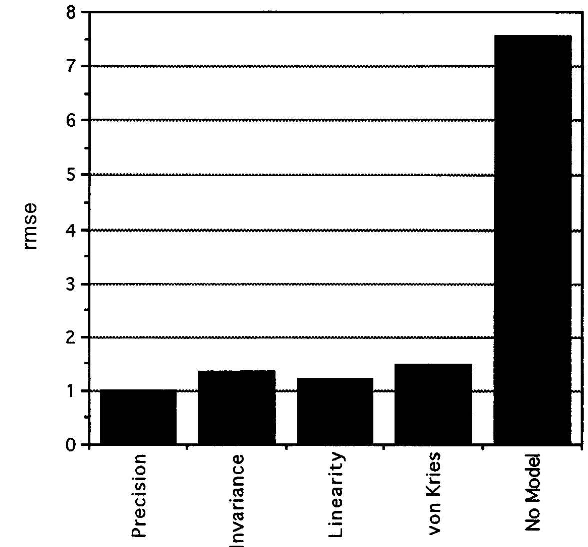

Fig. 5. Quality of fit of collection invariance, illuminant linearity, and the von Kries principle. The quality of fit of the three principles is compared with the subjects' precision and the size of the effect (no model). The error measurements are root-mean-square errors (rmse's).

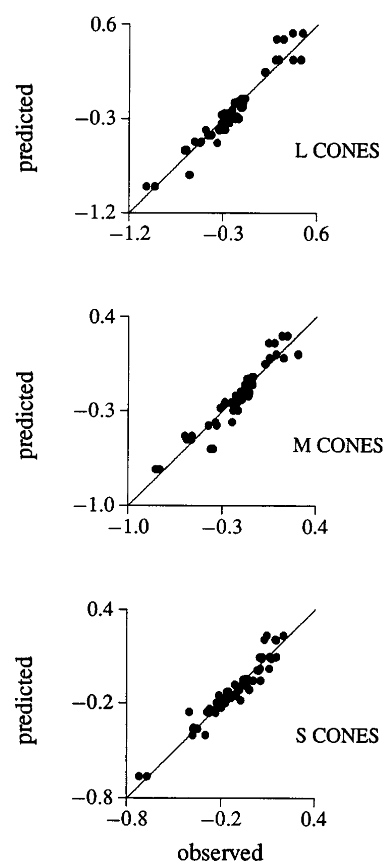

Fig. 6. Summary model. Scatterplot comparing the observed mean changes in the test surfaces with the model's predictions of these changes (see Fig. 4).

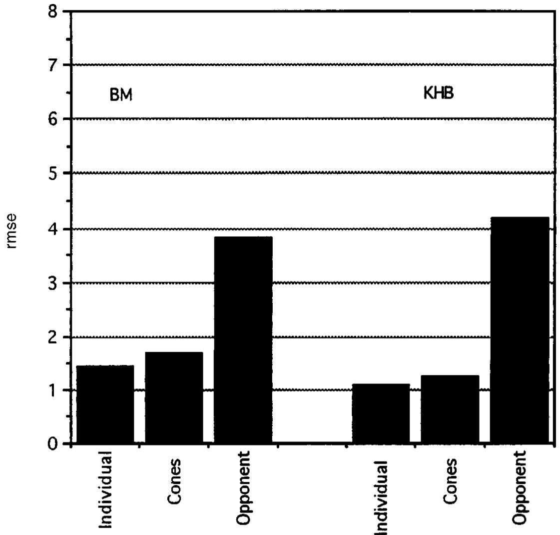

Fig. 7. Site of adaptation. Comparison of quality of fit of the hypotheses that (1) adaptation is sited at the cones, (2) adaptation is sited at an opponent stage, and (3) adaptation is sited at a putative stage that linearly combines the outputs from the three cone classes. This putative stage was estimated individually from a subject's data set. The error measurements are rmse's.

matrix that does not depend on the test surface and whose nine elements represent the parameters of the model. Indeed, this equation combines the three principles.

The quality of fit of this summary model to the data is depicted in Fig. 6. This figure compares the observed changes in the cone coordinates with the changes predicted when this model is fitted to each subject's data. The data are fairly close to the diagonal. This holds true for all three cone classes. The rmse measured for this summary model is 1.538.

H. Site of Adaptation

In the version used above, the von Kries principle includes two assumptions. First, for any illuminant change the mapping between matching standard and test surfaces can be described by a diagonal linear transformation. Second, the site of adaptation is at the cones. We come up with a more general von Kries principle by proposing the existence of three putative von Kries mechanisms that linearly combine the outputs of the three cone classes and mediate the effect of illuminant changes through changes in their gains. Thus

$$\mathbf{\Delta t}_{ij} = \mathbf{C}^{-1}\mathbf{K}_{ij}\mathbf{C}\mathbf{t}_{0j}\,,$$

where $\mathbf{C}$ is the color matrix that transforms the outputs from the three cone classes into the responses of the three putative von Kries mechanisms. Of course, restricting $\mathbf{C}$ to be the identity matrix restates the original von Kries principle.

I examined to what extent this more general von Kries principle improves the description of the data compared with the principle's original version. In addition, I examined an opponent version of the principle. In this case I specified the color matrix $\mathbf{C}$ through a Jameson–Hurvich[25] matrix that transforms the cone outputs into the responses of two chromatic opponent mechanisms and one achromatic mechanism.

Figure 7 compares the rmse's separately for the three different versions of the principle for the data of subjects BM and KHB. The general version and the cone-based version of the principle provide a good description of the data and compare well in their quality of fit. The opponent version provides a poor fit to the data, thus negating the idea that adaptation is sited at an opponent stage.[26] The conclusion that adaptation is sited at the cones in the present experiment is also indicated by the color-sensitivity-function estimates of the three putative von Kries mechanisms that are specified through the estimate of color matrix $\mathbf{C}$. Figure 8 shows the three sensitivity functions that I found for the experiment's whole data set.[27] The functions are close to the Smith–Pokorny cone fundamentals.[28]

I. Regulation of the Cones

If we accept the von Kries principle, illuminant linearity leaves open the question of how exactly the gain of the three cone classes is regulated. I examined whether the data are consistent with the hypothesis that the gain of each cone class is regulated independently of the signals of the other two cone classes. This hypothesis implies

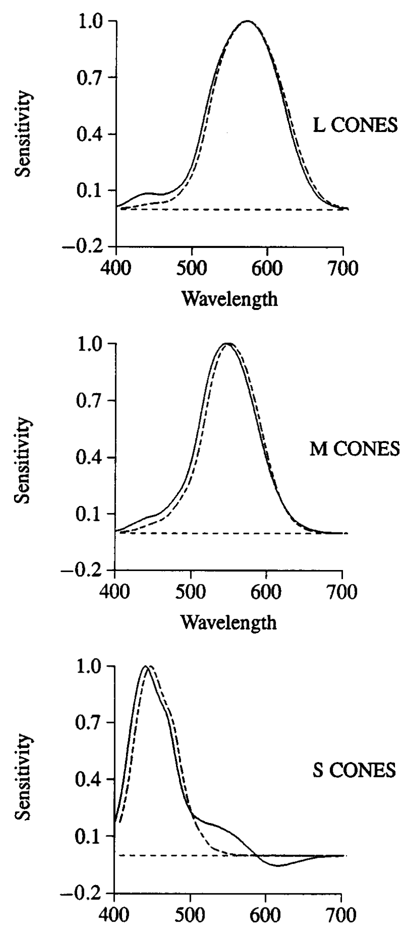

Fig. 8. Color-sensitivity-function estimates of the three putative von Kries mechanisms (solid curves). The estimates are based on fitting a version of the summary model to the experiment's whole data set that includes a general von Kries principle, illuminant linearity, and collection invariance (see text). The estimates are compared with the Smith–Pokorny cone fundamentals (dashed curves).

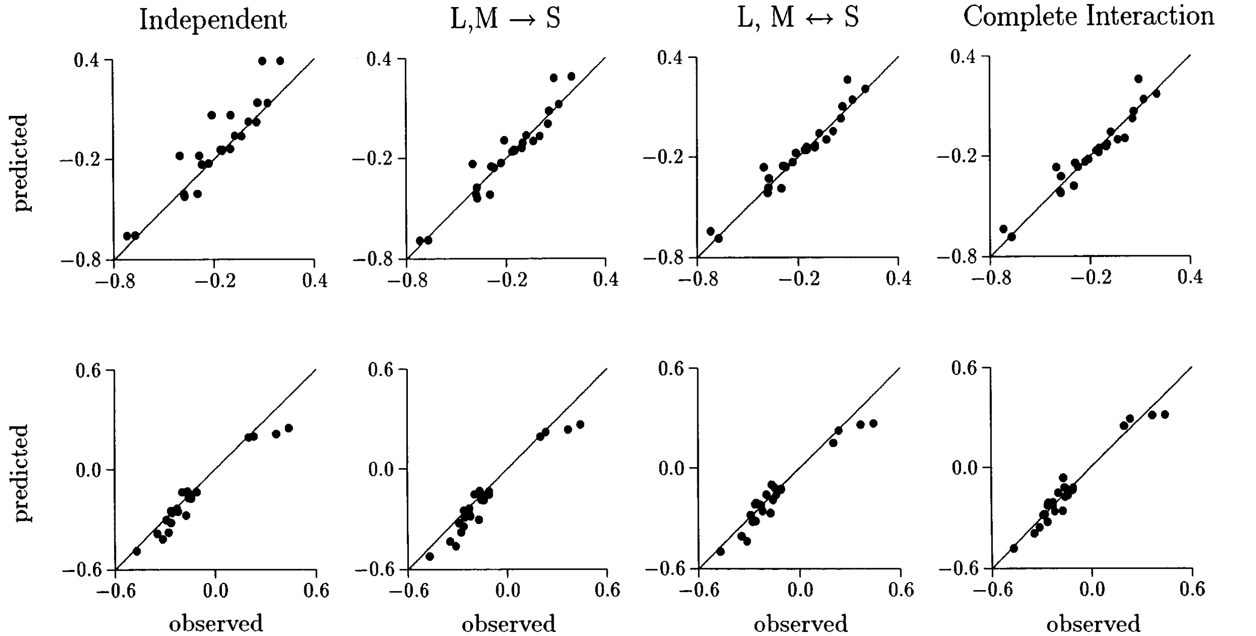

Fig. 9. Regulation of the three cone classes. Visual comparison of four nested hypotheses about the regulation of the gain of the three cones classes. Scatterplots compare observed versus predicted S-cone coordinates for subject BM (upper row) and observed versus predicted L-cone coordinates for subject KHB (lower row). Assumptions are, in the first column, that the gain of each cone class does not depend on the signal from the other two classes; in the second column, that the L and the M cones have an effect on the gain of the S cones; and in the third column, that the S cones have an additional effect on the gain of the L and M cones. In the fourth column a complete interaction among the cone classes is assumed.

that matrices $\mathbf{M}_{tj}$, which map illuminant changes $\mathbf{\Delta d}_i$ into changes in test surfaces $\mathbf{\Delta t}_{ij}$, are diagonal.

There were some clear deviations from this hypothesis in the data. Figure 9 shows scatterplots comparing observed versus predicted S-cone coordinates for subject BM (upper row) and observed versus predicted L-cone coordinates for subject KHB (lower row). The first column (Independent) shows the predictions when diagonal matrices $\mathbf{M}_{tj}$ are fitted to the subjects' data, and the fourth column (Complete Interaction) shows the predictions when the nonrestricted matrices $\mathbf{M}_{tj}$ are fitted to the subjects' data. The complete-interaction variant accounts well for the data, whereas the independent variant leads to some systematic deviations from the data.

I examined two hypotheses, which are less restrictive than the hypothesis of the independence of the cone classes. One assumes a regulation of the gain of the S cones by the L and the M cones (second column), and the other assumes an additional regulation of the gain of the L and the M cones by the S cones (third column). The latter hypothesis differs from the hypothesis of a complete interaction only by excluding interactions between the L and the M cones. The four hypotheses are nested. They restrict an increasing number of elements of $\mathbf{M}_{tj}$ to be zero when the elements are moving from complete interaction to independence.

The plots of Fig. 9 suggest a considerable effect of the L and the M cones on the gain of the S cones and smaller effects of the L and the M cones on the gain of the S cones and between the L and the M cones. This pattern of results is also reflected in the rmse's of the four hypotheses found for the experiment's whole data set. The errors that I measured are 1.514 (independent), 1.329 (L, M → S), 1.259 (L, M ↔ S), and 1.186 (complete interaction).

Table 1 shows parameter estimates of matrix **M** of the summary model when this model is fitted to the experiment's whole data set. As shown in Appendix A, the parameters of this matrix directly determine the coefficients of the von Kries matrices. In this sense this matrix provides information on how the gain of each cone class depends on the other two cone classes' responses to illuminant changes. Interactions among the cone classes are indicated to the extent that the nondiagonal elements of this matrix deviate from zero.

The parameter estimates suggest that there are interactions among the cone classes. The size of these interactions, however, varies considerably across cone classes. This is reflected in the ratios of the three parameters found to affect the gain of a single cone class. First, the data indicate a relatively large effect of the L and the M cones on the gain of the S cones, where the gain of the S cones is negatively affected by the L cones and positively affected by the M cones. Second, the data indicate a moderate effect of the M and the S cones on the gain of the L cones, with the gain of the L cones being posi-

Table 1. Regulation of the Gain of the Three Cone Classes[a]

Gain	L Illuminant	M Illuminant	S Illuminant
L	7.1×10^{-2}	2.1×10^{-2}	-1.2×10^{-2}
M	0.7×10^{-2}	9.2×10^{-2}	-0.3×10^{-2}
S	-4.3×10^{-2}	7.4×10^{-2}	11.7×10^{-2}

[a]The nine numbers show how the gain of the three cone classes was modulated by a change in the L-, M-, and S-cone coordinates of the illuminant in the present experiment. These numbers represent the coefficients of matrix **M** of the summary model that were found to fit the experiment's whole data set best.

tively affected by the M cones and negatively affected by the S cones. Finally, the data indicate only a small effect of the L and the S cones on the gain of the M cones, where the gain of the M cones is positively affected by the L cones and negatively affected by the S cones.

4. DISCUSSION

A. Three Principles of Color Appearance

I measured and analyzed asymmetric color matches under several combinations of simulated illuminant and surface collection. I found the von Kries principle and illuminant linearity to hold well in a given surface collection. Indeed, the illuminant-induced changes in the subjects' settings were consistent with the hypothesis that illuminant changes affect the relative sensitivities of the three cone classes and that the change in sensitivity is a linear function of the illuminant change. I also found the collection-invariance principle to hold well. In fact, the effect of illuminant changes on the subjects' settings did not vary substantially with the surface collection, indicating that the visual system's adjustments to illuminant changes do not depend on the surface collection.

On the basis of this result, the three principles were integrated into one summary model. This model predicts changes in color appearance as a function of changes in the illuminant, where the predictions are not assumed to depend on the surface collection. The model is linear. It has the desirable feature that a relatively small number of measurements determines the parameters of the model. In fact, since daylight illuminants can be well approximated by a three-dimensional linear model,[15,29] three asymmetric matches are already sufficient to fix the model's parameters. For the modest range of contrasts that I could obtain with the CRT monitor, the model provided a good first-order approximation of the data.

B. Site and Source of Adaptation

The present study supports the hypothesis that illuminant changes affect the gain of the three cone classes. This result agrees with results from several previous studies that examined this issue under a variety of experimental situations.[2,8–10] The support from the present study, however, is based not only on the result that the von Kries principle is found to hold well when the test surfaces are represented by their cone coordinates but also on the result that no other linear combination of the three cone classes' responses was found that led to a substantially better description of the data in terms of the von Kries principle. As a corollary of this result, the data also clearly rejected the idea that adaptation is sited at an opponent stage.

Accepting the hypothesis that the site of adaptation is at the cones, we might ask, How is the sensitivity of each cone class regulated? An old hypothesis states that the gain of the signal from each cone class is regulated by the photopigment absorptions originating entirely within that cone class.[13,14] This hypothesis was challenged during the past two decades through the results of a number of sensitivity and appearance studies. One line of studies demonstrated that S-cone sensitivity depends on the response of the L and the M cones to the background,[10,30] and another line of study demonstrated that the L- and the M-cone sensitivity depends on the response of the S cones to the background.[31] Interactions among the L and the M cones were even found.[32]

Using the method of asymmetric color matching, the present study also found interactions among the different cone classes. Above all, the data indicated a considerable dependence of the gain of the S cones on the L (−) and the M (+) cones. However, there was also a moderate dependence of the gain of the L cones on the M (+) and the S (−) cones, whereas the gain on the M cones was found to depend only to a small degree on the L (+) and the S (−) cones. These results are in good qualitative agreement with those from the previous studies.[33] The parameters estimated for these interactions (see Table 1) may also provide a first-order quantification of the regulation of the cone sensitivities, although future studies including a wider range of test surfaces and illuminants can be expected to come up with more exact estimates.

C. Separation of the Illuminant Effect from the Surface Collection

In my recent study[3] I examined the role of surface collection in the visual system's adjustment to illuminant changes, using collections that differed greatly with respect to the range of hue and saturation spanned by their surfaces. I did not find the visual system's adjustment to depend in a major way on the surface collection. In the present study I examined the role of the luminance factor in more detail. In particular, I compared the illuminant effect for two surface collections, of which one collection (S_1) spanned a considerable range of different luminances whereas the other collection (S_4) was isoluminant. There was no evidence that the illuminant effect was different for the two surface collections. These results indicate that neither changes in hue and saturation of a collection's surfaces nor changes in the surfaces' luminance affect the visual system's adjustments to changes in illumination in a major way. The data for the other two surface collections included in this study confirmed this view.

D. Related Paradigm: Simultaneous Color Constancy

The present experimental paradigm emphasizes the role of adaptation mechanisms in color constancy.[2] Other paradigms, such as the paradigm of simultaneous color constancy, emphasize the role of simultaneous mechanisms in color constancy; these paradigms try to reduce a subject's possibility of adaptation. In general, these different paradigms induce quite different degrees of color constancy. For instance, Arend and Reeves[34] and Arend *et al.*[35] found that asymmetric color matches approach only approximately 20% relative to the illuminant within the paradigm of simultaneous constancy, compared with approximately 50% within the present experimental paradigm.[2,3,8] On the other hand, the degree of color constancy can be as high as 85% within the simultaneous-constancy paradigm if subjects are instructed to set paper matches instead of the traditional hue, saturation, and brightness matches.[34,35]

Despite these differences in the degree of color constancy across the two paradigms, there is evidence for a separation of the illuminant effect from the surface collection in both experimental situations. The evidence

Table 2. Experimental Illuminants[a]

	d_0	d_1	d_2	x	y	L
D_0	8.077×10^{-2}	-4.9863×10^{-2}	-3.500×10^{-2}	0.326	0.339	57.84
D_1	3.846×10^{-2}	1.113×10^{-1}	6.303×10^{-2}	0.249	0.249	29.76
D_2	6.538×10^{-2}	7.838×10^{-2}	-1.415×10^{-2}	0.274	0.282	48.48
D_3	5.385×10^{-2}	5.995×10^{-3}	-4.107×10^{-2}	0.300	0.313	38.99
D_4	6.538×10^{-2}	-7.263×10^{-2}	3.824×10^{-2}	0.351	0.362	46.73
D_5	5.385×10^{-2}	-7.730×10^{-2}	1.199×10^{-1}	0.377	0.380	38.71
D_6	9.615×10^{-2}	-1.565×10^{-1}	4.328×10^{-1}	0.402	0.394	70.00

[a]All seven illuminants stem from the CIE daylight locus. They were constructed from a three-dimensional linear model of natural daylight (see Section 2). This table gives the illuminants' weights for the three basis functions, the corresponding CIE xy coordinates, and luminance. D_i, daylight number i; d_k, weight for basis function k; x, x chromaticity; y, y chromaticity; L, luminance.

for the simultaneous-constancy paradigm comes from a recent study by Arend and Spehar.[36] These researchers investigated simultaneous mechanisms in lightness constancy. They presented subjects CRT simulations of achromatic Mondrian patterns in order to study how the lightness of a test surface adjusted by a subject varied as a function of illuminant changes and the reflectances that surround this surface. Although Arend and Spehar found that the surrounding reflectances had an effect on the lightness of the test surface, this effect did not vary with the illuminant. This result is consistent with the collection-invariance principle.

Often color constancy mechanisms are divided into two classes: adaptation mechanisms and simultaneous mechanisms.[5,34] Adaptation mechanisms are considered to develop slowly and to depend primarily on temporal interactions whereby the sensitivities of the visual system's color channels change over time in response to the changed illuminant. Simultaneous mechanisms are considered to be virtually instantaneous and are assumed to depend primarily on spatial interactions among responses of color channels to light at various locations in the retinal image. The present results together with those from the study of Arend and Spehar suggest that there is a separation of the effects of illuminant and surface collection for both kinds of mechanism.

APPENDIX A: COMBINING ILLUMINANT LINEARITY AND THE VON KRIES PRINCIPLE

Given two standard test surfaces t, u with a certain color appearance and cone coordinates $\mathbf{t}_0$, $\mathbf{u}_0$ adjusted by a subject under standard illuminant D_0, changes in illumination $\mathbf{\Delta d}_i$ $(= \mathbf{d}_i - \mathbf{d}_0)$ induce changes in the subject's settings $\mathbf{\Delta t}_i$ $(= \mathbf{t}_i - \mathbf{t}_0)$, $\mathbf{\Delta u}_i$ $(= \mathbf{u}_i - \mathbf{u}_0)$, where $\mathbf{t}_i$, $\mathbf{u}_i$ are the cone coordinates of the test surfaces adjusted by the subject under illuminant D_i.

Illuminant linearity states that the changes in the subject's settings and the changes in illumination are related by 3×3 matrices $\mathbf{M}_t$, $\mathbf{M}_u$ such that $\mathbf{\Delta t}_i = \mathbf{M}_t \mathbf{\Delta d}_i$ and $\mathbf{\Delta u}_i = \mathbf{M}_u \mathbf{\Delta d}_i$. The von Kries principle states that for any illuminant change $\mathbf{\Delta d}_i$ there exists a 3×3 diagonal matrix $\mathbf{K}_i$ such that $\mathbf{\Delta t}_i = \mathbf{K}_i \mathbf{t}_0$ and $\mathbf{\Delta u}_i = \mathbf{K}_i \mathbf{u}_0$. These equations can be rewritten as $\mathbf{k}_i = \mathbf{P}_t^{-1} \mathbf{\Delta t}_i = \mathbf{P}_u^{-1} \mathbf{\Delta u}_i$, where the three-dimensional vector $\mathbf{k}_i$ consists of the three diagonal elements of matrix $\mathbf{K}_i$, and $\mathbf{P}_t$, $\mathbf{P}_u$ are 3×3 diagonal matrices whose diagonal elements are the cone coordinates of the surfaces $\mathbf{t}_0$, $\mathbf{u}_0$.[37]

Table 3. Subjects' Standard Test Surfaces under the Two Surface Collections[a]

		1. Collection			2. Collection		
Subject	Surface	x	y	L	x	y	L
MW	A	0.307	0.311	6.753	0.309	0.322	6.984
BM	B	0.304	0.306	14.213	0.299	0.311	14.050
KHB	C	0.309	0.302	8.778	0.317	0.291	7.265
BM	D	0.395	0.396	12.151	0.409	0.399	12.739
KHB	E	0.432	0.350	8.039	0.430	0.341	7.103

[a]See Section 3. For all three subjects the 1. Collection is S_1. The 2. Collection is S_2 for MW, S_3 for BM, and S_4 for KHB (compare Fig. 2). The surfaces are shown with use of CIE xy coordinates and luminance. x, x chromaticity; y, y chromaticity; L, luminance.

We combine illuminant linearity and the von Kries principle. Since $\mathbf{P}_t^{-1} \mathbf{\Delta t}_i = \mathbf{P}_u^{-1} \mathbf{\Delta u}_i$ it holds that $\mathbf{P}_t^{-1} \mathbf{M}_t \mathbf{\Delta d}_i = \mathbf{P}_u^{-1} \mathbf{M}_u \mathbf{\Delta d}_i$, and thus $\mathbf{P}_t^{-1} \mathbf{M}_t = \mathbf{P}_u^{-1} \mathbf{M}_u \equiv \mathbf{M}$, where $\mathbf{M}$ is a 3×3 matrix that does not depend on the standard test surface. As a result, $\mathbf{\Delta t}_i = \mathbf{P}_t \mathbf{M} \mathbf{\Delta d}_i$ and $\mathbf{\Delta u}_i = \mathbf{P}_u \mathbf{M} \mathbf{\Delta d}_i$. Notice that these equations are equivalent to the single equation $\mathbf{k}_i = \mathbf{M} \mathbf{\Delta d}_i$ that directly reflects the linear relationship between the von Kries coefficient $\mathbf{k}_i$ and the illuminant changes $\mathbf{\Delta d}_i$, showing how the coefficients of the von Kries matrices $\mathbf{K}_i$ can be computed from the changes in illumination. This relationship is the reason that the coefficients of $\mathbf{M}$ can be interpreted as containing information on how the gain of the single cone classes is regulated.

Within the summary model proposed above, the von Kries coefficients $\mathbf{k}_i$ vary with the surface collection. This is due to the fact that matrix $\mathbf{M}$ varies with the surface collection. To see this, notice that, given two surface collections S_j and S_l, $\mathbf{k}_{ij} = \mathbf{P}_{tj}^{-1} \mathbf{M}_t \mathbf{\Delta d}_i = \mathbf{M}_j \mathbf{\Delta d}_i$ and $\mathbf{k}_{il} = \mathbf{P}_{tl}^{-1} \mathbf{M}_t \mathbf{\Delta d}_i = \mathbf{M}_l \mathbf{\Delta d}_i$, and, as a result, $\mathbf{M}_l = \mathbf{P}_{t_l}^{-1} \mathbf{P}_{t_j} \mathbf{M}_j$. The two matrices $\mathbf{M}_j$, $\mathbf{M}_l$ for the two surface collections S_j, S_l are therefore related by a diagonal matrix, i.e., by three independent scalars. These three scale factors set the overall sensitivity of each of the three von Kries mechanisms when one is moving from one surface collection to another.

APPENDIX B: EXPERIMENTAL ILLUMINANTS AND STANDARD TEST SURFACES

This appendix consists of two tables. Table 2 specifies each of the seven experimental illuminants. Table 3 specifies each of the five standard test surfaces.

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23. The models were also evaluated with other error measures. For instance, I minimized the differences between the observed and the predicted settings by using one single global covariance matrix estimated for all surfaces simultaneously or by using the CIE LUV metric space.[1] The conclusions drawn about the quality of the models did not depend on the choice of error measure.
24. For illuminant linearity and the von Kries principle the linearly transformed illuminant changes, or standard surfaces, were used for the prediction. For collection invariance the mean of the illuminant-induced change in the test surfaces under the two surface collections was used for the prediction of the individual changes observed under the two surface collections.
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27. A version of the summary model was fitted to the data that includes the more general von Kries principle, illuminant linearity, and collection invariance. The same 18 parameters were used to describe each subject's data set. With the restriction of using the same parameters for the different subjects, the rmse of the model is 1.836, compared with 1.446 when the model is fitted individually to each subject's data.
28. The rmse's of the general version of the summary model (including the free color matrix **C**) and the cone-based version of the summary model (with **C** being the identity matrix) are practically identical. The rmse of the general version is 1.836, and that of the cone-based version is 1.840.
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