Color constancy in the nearly natural image. 2. Achromatic loci

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Received April 28, 1997; revised manuscript received August 28, 1997; accepted September 5, 1997

Most empirical work on color constancy is based on simple laboratory models of natural viewing conditions. These typically consist of spots seen against uniform backgrounds or computer simulations of flat surfaces seen under spatially uniform illumination. In this study measurements were made under more natural viewing conditions. Observers used a projection colorimeter to adjust the appearance of a test patch until it appeared achromatic. Observers made such achromatic settings under a variety of illuminants and when the test surface was viewed against a number of different backgrounds. An analysis of the achromatic settings reveals that observers show good color constancy when the illumination is varied. Changing the background surface against which the test patch is seen, on the other hand, has a relatively small effect on the achromatic loci. The results thus indicate that constancy is not achieved by a simple comparison between the test surface and its local surround. [S0740-3232(98)00102-1]

1. INTRODUCTION

In the companion paper[1] we introduce the problem of color constancy and discuss the distinction between simultaneous and successive constancy. The term *simultaneous constancy* refers to the case in which the illumination varies within a single scene, for example when the spectrum of the illumination changes across a shadow boundary. The term *successive constancy* refers to the case in which the illumination varies from one time to another, for example because the spectrum of the illumination differs between dawn and noon. The companion paper presents experiments designed to study simultaneous constancy under nearly natural viewing conditions. This paper presents experiments that measure successive constancy under similarly natural conditions.

Asymmetric matching provides a convenient and natural experimental method for studying simultaneous color constancy.[1–3] Although asymmetric matching may also be employed to study successive constancy,[4–6] matching across time involves a memory component and can be challenging for observers. A simpler experimental task is to have subjects adjust a test patch until it appears achromatic.[7–12] This task is easy even for the most naïve of observers. In this paper we study how the achromatic locus depends on viewing context.

Most studies of color constancy investigate the stability of object color appearance when the illumination is varied.[1–4,6,10,11,13–18] Although this is a natural question, it neglects an important aspect of constancy, namely, whether object color appearance is stable when the other objects in the scene are varied.[19–23] Computational studies indicate that it is difficult to design a visual system that adjusts to changes of illumination without introducing a dependence of color appearance on the stimulus at multiple scene locations.[22–25] For example, a visual system that codes color as a function of local contrast will show approximate color constancy when the illuminant is changed. At the same time, object color for such a visual system will depend markedly on the collection of objects in the scene.[19,26] The assumption that color constancy is achieved through the influence of the local surround is implicit in studies of constancy that employ the classic stimulus configuration of an isolated test presented on a uniform background (see for example Burnham *et al.*[15]).

In this paper we measure how the achromatic locus depends on two contextual variables. First, we study how it depends on the illumination. Second, we study how it depends on changes in the objects in the scene—in particular, changes in the immediate vicinity of the test location.

2. GENERAL METHODS

A. Overview

The apparatus consisted of an entire experimental room, shown schematically in Fig. 1. The spectral power distribution of the ambient illumination in the room was produced by theater stage lamps and was under computer control. The observer judged the appearance of a test patch, located on the far wall of the room. The light reflected from the test patch to the observer consisted of two components. The first was from the ambient illumination. The second was generated by a computer-controlled projection colorimeter. This second component was spatially coincident with the test patch. The use of the colorimeter made it possible to vary the chromaticity of the light reaching the observer from the test patch while holding its luminance approximately constant. The observer's task was to adjust the chromaticity of the test patch so that it appeared achromatic. A more detailed description follows.

B. Experimental Room

The experimental room was 8 ft. 9 in. $\times$ 11 ft. 4 in. Its walls and ceiling were painted a matte gray of roughly 50% reflectance; its floor was covered with a gray carpet.

The test patch consisted of a 8.5 in. × 11 in. Munsell matte *N* 3/ paper and was mounted near the right-hand edge of a 48 in. × 72 in. sheet of particle board painted the same gray as the room. From the observer's vantage point (111 in. away), the test patch subtended 4.4° × 5.7° of visual angle. In most experimental conditions, the test patch was surrounded by a thin 1/4-in. border of black felt. The test patch was mounted on a 1/4-in.-thick board, so that there was depth relief between it and the background surface.

It was possible to vary the immediate context in which the test patch was viewed. The most complex configuration that we used is illustrated in the right panel of Fig. 1. In this configuration, the test patch was seen amidst an array of 14 matte 8.5 in. × 11 in. (4.4° × 5.7°) Munsell papers and against a background surface that consisted of a large piece of matte poster board. Each Munsell paper was mounted on a 1/4-in.-thick board and was surrounded by a thin (1/4 in.) black felt border. The poster board was 32 in. × 40 in. (16° × 20°). It was partially occluded by the Munsell papers, as illustrated in the figure. We had several different pieces of poster board, each with a different surface reflectance, and we could thus vary the identity of the background surface from session to session.

In all experiments, additional objects in the room were visible to the observer. These included a white table, a brown metal bookcase, and the walls, floor, and ceiling of the room. In early experiments, a light trap provided a black area at the right front of the room.

The ambient illumination of the room was controlled by four sets of theater stage lamps (SLD Lighting, 6-in. Fresnel #3053, BTL 500-W bulb), as shown in the figure by the triads of circles. In early experiments, each set consisted of two lamps. One lamp from each set had a broadband blue gelatin filter (Roscolux #65), and the other had a broadband yellow filter (Roscolux #08). We refer to this as the BY illuminant setup. In later experiments, each set consisted of three lamps. One lamp from each set had a dichroic red filter (Rosco 6100 "Flame Red"), one a dichroic green filter (Rosco 4959 "Light Green"), and one a dichroic blue filter (Rosco 4600 "Blue"). In this case, the light from each triad was passed through a gelatin diffuser to minimize colored shadows. We refer to this as the RGB illuminant setup. For both illumination arrangements, the lamp intensities were controlled from software by varying the rms voltage across the bulbs (NSI 5600 Dimmer Packs, NSI OPT-232 interface card, 100 voltage quantization levels). We yoked the voltages of all lights with the same color filter together. By varying the intensities of the differently filtered lamps, we varied the spectral power distribution of the ambient illumination. Control software (described in detail elsewhere[1,27]) corrected for spectral shifts introduced when the voltage to individual bulbs was varied.

The chromaticity and luminance of the test patch were controlled by the projection colorimeter. In early experiments, the colorimeter consisted of three slide projectors (Kodak 4400) stacked vertically. The light from each projector passed through a red, green, or blue dichroic filter so that we had three independent primaries. The beam from each projector was masked so that its projection was spatially coincident with the test patch. In later experiments, the colorimeter was a custom device. In

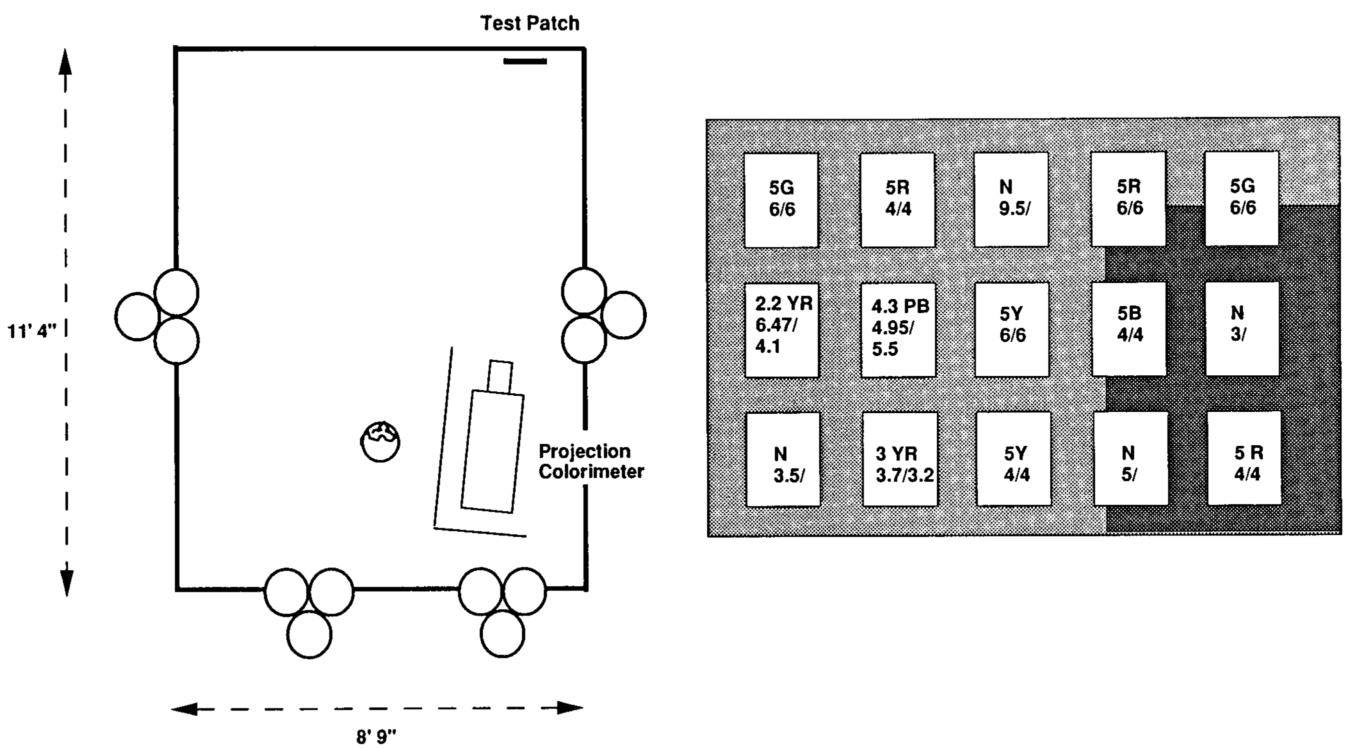

Fig. 1. Experimental room. Left panel, top view; right panel, schematic of the observers' view of the far wall of the room in its most complex configuration. Other objects in the room were visible to the observers, including a brown metal bookcase and an off-white table. Not drawn proportionally; locations are approximate.

this device, the light source for each primary was a slide projector bulb (Type FHS, 300 W, 82V). Light from each bulb passed through a heat-absorbing filter and a red, green, or blue dichroic filter (OCLI). The light from the three bulbs was then combined with dichroic beam splitters (OCLI) and passed through a slide projector condenser (Kodak 4400), an adjustable mask, and a slide projector lens (WIKO, 100 mm, *f*2.8). The beam from the custom colorimeter was masked so that its projection was spatially coincident with the test patch. The custom colorimeter provided better spatial uniformity than its three-projector predecessor. For both versions of the colorimeter, the intensity of each primary was controlled by adjusting the voltage supplied to the corresponding projector lamp (NSI 5600 Dimmer Packs, NSI OPT-232 interface card, factory modified to provide 255 voltage quantization levels). Control software (described in detail elsewhere[1,27]) compensated for the ambient illumination reflected to the observer from the test patch and corrected for spectral shifts introduced when the voltage to the bulbs was varied. For the experiments reported here, we used the projection colorimeter to hold the luminance of the test patch constant while we varied its chromaticity. Although the test patch was spot illuminated, this illumination was not perceptually apparent; the test patch appeared to be a reflective surface over most of the luminance range we used.[27]

C. Experimental Procedure

The observers' task was to adjust the appearance of the test patch until it appeared achromatic.[7–12] During an adjustment, control software held the luminance of the test patch approximately constant. The observer used buttons (early experiments) or knobs (later experiments) to control the CIELAB a^* and b^* coordinates of the test patch. Varying the a^* coordinate of the test patch varies the appearance of the test patch along a roughly red–green perceptual axis; varying the b^* coordinate varies the appearance of the test patch along a roughly blue–yellow perceptual axis.

At the beginning of each experimental session, the ambient lighting was set and the observer adapted for 20 s. The observer then made a block of achromatic settings at a number of different test patch luminances. In some experiments, there was only a single illuminant per experimental session. In these experiments, observers made two blocks of settings per session. These blocks were separated by a rest period of 20 s. In other experiments, observers made settings under two different illuminants within a single session. In these experiments, the illuminant was changed gradually between blocks (10 s) and the observer then adapted for an additional 10 s. In sessions with two illuminants, the illuminants were presented in random order and observers made two blocks of settings under each illuminant.

Immediately following each session, the observer's achromatic settings were replayed and the proximal stimulus reaching the observer for each setting was measured directly (Photo Research PR-650). This procedure compensates for any calibration error introduced by voltage drift over time, by voltage drift with temperature, or from interactions between channels within the dimmer control packs. We also measured the ambient illumination incident on the test patch (excluding the colorimeter component) and the light reflected to the observer from the background surface behind the test patch. (In early experiments we did not measure the background directly. In these cases, we subsequently computed the light reflected to the observer from the measurement of the ambient illumination and a measurement of the background surface reflectance function.)

D. Adjustment Starting Points

In pilot experiments we observed that for our conditions, the chromaticity at which an achromatic adjustment starts influences the final achromatic setting. In general, the final achromatic setting is pulled toward the point at which the adjustment started. This fact implies that how the starting point for the adjustments is chosen must be handled with some care.

To study color constancy, a natural way to start the adjustments is to choose a random surface reflectance, render it under the ambient illumination, and use the result as the starting point. This procedure accurately models what would be seen by an observer viewing a random collection of surfaces under an unknown illuminant. Since the illumination differs across conditions, this starting rule will not equate the adjustment starting points in terms of the proximal stimulus reaching the eye.

For the bulk of our experiments, we adopted an adjustment starting rule that is roughly equivalent to the procedure described above. We refer to this rule as the basic starting rule. Each adjustment began at CIELAB a^*b^* coordinates chosen randomly within the rectangle $[-25, 25] \times [-25, 25]$. Note that the transformation between CIE XYZ tristimulus coordinates and CIELAB $L^*a^*b^*$ coordinates depends on the specification of a white point.[28] For the basic starting rule, we took the white-point tristimulus coordinates to be those of the illuminant. Thus the actual CIE xy chromaticities of the adjustment starting points differed across illuminants. Indeed, given this method of specifying the white point, the CIE xy chromaticity of CIELAB a^*b^* coordinates (0,0) match those of the illuminant. This means that for the basic starting rule, the starting point for the adjustment was chosen from a gamut centered on the illuminant chromaticity. This is essentially the same as would be achieved by choosing a random surface and rendering it.

E. Observers

Ten observers participated in the experiments reported here. Observer DHB (male, mid-30's, color normal as tested by anomaloscope) is the author. Observer JMK (male, mid-30's, color normal as tested by anomaloscope) was a postdoctoral volunteer. Observer WAB (female, mid-20's, color normal by self-report) was a graduate student volunteer. Observer MDR (female, mid-20's, color normal as tested by psuedoisochromatic plates) was a graduate student volunteer. Observer Kl (male, mid-20's, color normal as tested by psuedoisochromatic plates, Menicon EX contact lenses) was a graduate student volunteer. Observer PW (male, mid-20's, color normal as tested by psuedoisochromatic plates) was a paid undergraduate. Observers RLJ, JPH, and AMO (male, mid-

20's, color normal by self-report) were paid undergraduates. Observer JAD (female, mid-20's, color normal by self-report) was a paid undergraduate.

3. RESULTS

This paper reports a large data set collected by use of the basic methods described above. For convenience of exposition, we have divided the results into seven separate experiments. Experiments 1 and 2 measure the effect of the illuminant change for a variety of illuminants and background surfaces. Experiment 3 compares directly the effect of the changing the illuminant and changing the background surface. Experiments 4 and 5 investigate the effect of adding a large piece of red cloth in the vicinity of the test patch. Experiments 6 and 7 study the effect of the adjustment starting rule. Specific methods are provided in the exposition for each experiment.

A. Experiment 1: Effect of the Illuminant

Experiment 1 makes baseline measurements of the effect of the illuminant on color appearance. Experiment 1 was conducted with the BY illuminant setup. Observers viewed the test patch among an array of 14 Munsell papers, as shown at the right of Fig. 1. Two illuminants were used in each experimental session, we refer to these as the Blue and Yellow illuminants, respectively. We used a number of different background surfaces. We refer to these as the Gray, Red, Yellow, Dark Blue, Brown, and White background surfaces. Table 1 provides the CIE xy chromaticities and luminances of the illuminants and background surfaces.

Observers made achromatic settings at four CIELAB L^* values (50, 70, 90, 110). For each illuminant, CIELAB values were computed with respect to a white point defined by its CIE XYZ tristimulus coordinates. Since the computation of CIELAB coordinates depends on the white point, the actual photopic luminances at which settings were made differed across the two illuminants. In each block, settings at the four different L^* values were made in random order. We used the basic starting rule for this experiment.

1. *Achromatic Loci*

Figure 2 shows individual achromatic settings obtained in a single session. Each panel of the figure shows a two-

Table 1. Chromaticities and Luminances of Illuminants and Backgrounds[a]

Experiment 1	Blue Illuminant			Yellow Illuminant		
	CIE x	CIE y	Lum. (cd/m^2)	CIE x	CIE y	Lum. (cd/m^2)
Illuminant (gray background)	0.353	0.373	13.6	0.509	0.418	15.2
Illuminant (all backgrounds)	0.346	0.371	13.6	0.509	0.419	16.3
Gray background	0.463	0.463	0.5	0.555	0.555	0.6
Red background	0.622	0.622	0.6	0.368	0.368	0.4
Yellow background	0.515	0.515	0.5	0.553	0.553	0.6
Dark Blue background	0.236	0.298	1.6	0.416	0.412	1.5
Brown background	0.468	0.394	2.2	0.581	0.394	3.4
Black background	0.349	0.369	0.6	0.515	0.415	0.7
White background	0.355	0.379	11.6	0.515	0.420	14.5

Experiment 2	CIE x	CIE y	Lum. (cd/m^2)
Illuminant 0	0.412	0.403	18.3
Illuminant 1	0.305	0.396	18.0
Illuminant 2	0.403	0.300	19.9
Illuminant 3	0.403	0.498	17.4
Illuminant 4	0.486	0.407	17.3
Illuminant 5	0.293	0.309	19.5
Illuminant 6	0.491	0.314	20.4
Illuminant 7	0.312	0.490	18.1
Illuminant 8	0.474	0.482	18.4

[a] The top half of the table gives values for Experiment 1. There is some session-to-session variability in the measured values. The top line specifies the Blue and Yellow illuminants averaged over all sessions where the Gray background was used. The second line specifies the same illuminants averaged over all sessions in Experiment 1. The chromaticities and luminances of the light reflected to the observer from the background surfaces are specified for the two experimental illuminants. The specified values were obtained by averaging over all sessions in which the particular background surface was used. The bottom half of the table provides the chromaticities and luminances of the nine experimental illuminants used in Experiment 2, obtained by averaging across sessions.

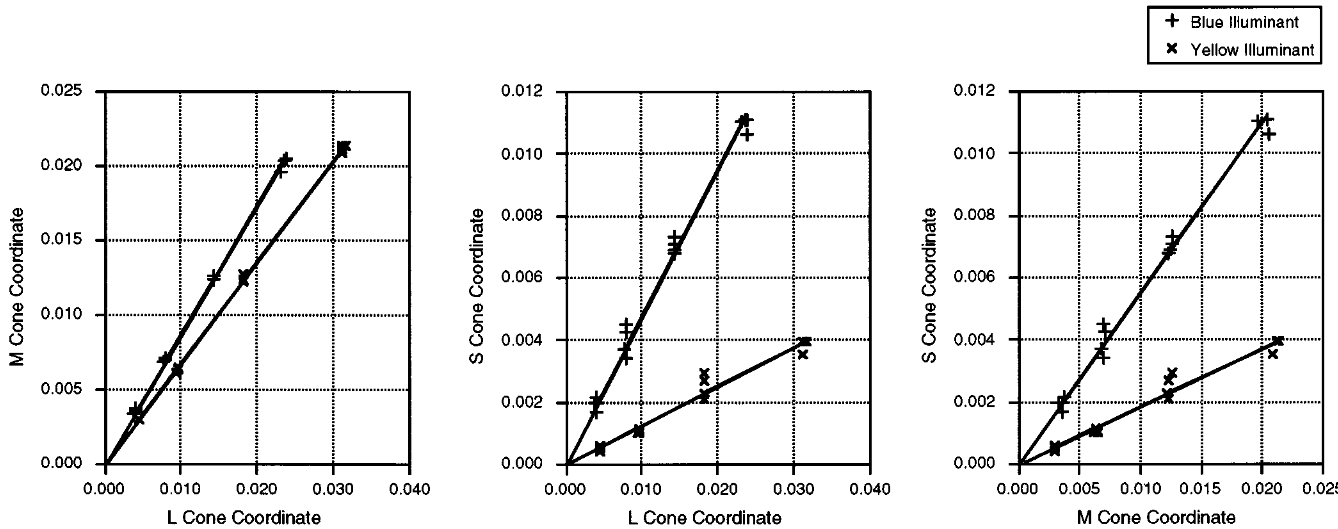

Fig. 2. Linearity of achromatic loci. Each panel shows a scatterplot of the cone coordinates of the individual achromatic settings from a single session, for observer PW and Gray background. Each panel shows a two-dimensional view of the three-dimensional cone space. Each pair of lines is a two-dimensional projection of a single line fitted to the data in the three-dimensional cone space. The lines are constrained to pass through the origin. The cone coordinates were computed from our full spectral measurements with respect to the Smith–Pokorny fundamentals.[60,61] The peak of each cone fundamental was normalized to 1.0.

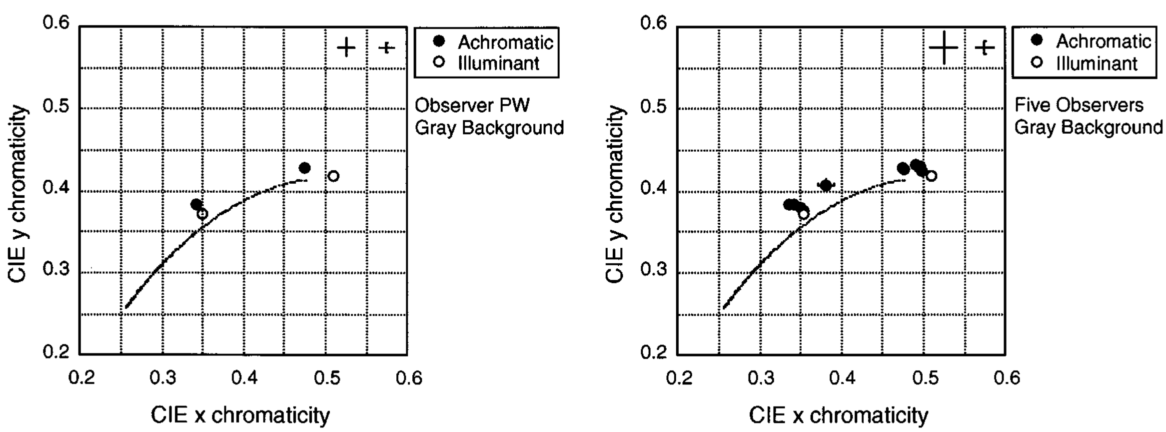

Fig. 3. Basic results from Experiment 1 for the Gray background for observer PW (left panel) and for five observers (right panel). Both plots: solid circles, CIE xy chromaticity of achromatic loci determined under two illuminants (Blue and Yellow); open circles, illuminant chromaticities. Note the large effect of the illuminant on the achromatic locus. The data for all observers are quite similar, with the exception of the achromatic setting under the Blue illuminant for observer JPH. Where visible, the error bars for the achromatic loci represent ± 1 standard error of the mean, computed between sessions. For each observer, we computed the average of the within-session standard deviations of the individual achromatic settings. The crossed bars in the upper right of the left plot show these for observer PW. The corresponding bars in the right plot show the maxima of these mean standard deviations, computed across observers. In both plots, the left cross was computed from the settings under the Blue illuminant and the right cross was computed from the settings under the Yellow illuminant. The solid curves in both panels plot the blackbody locus from 2500 °K to 20000 °K.

dimensional view of the three-dimensional cone space. Each cluster of points represents repeated settings at a single nominal CIELAB L^* value. The data in the figure lie along a single straight line through the origin. The best-fitting line is shown in the figure. In each panel, the plotted line is a two-dimensional projection of the same line in the full three-dimensional cone space.

The fact that the data lie along a line imply that the chromaticity of the achromatic point is independent of test stimulus luminance. This allows us to summarize the achromatic locus simply by its chromaticity.[29]

To find the chromaticity of the achromatic locus, we proceeded as follows. For each separate session, we found the line through the origin that best fitted the observers' achromatic settings at all four luminances. Each line may be specified by its CIE xy chromaticity. We averaged the chromaticities of the lines from each separate session to obtain the plotted achromatic points. The left panel of Fig. 3 shows such a summary for a single condition and observer. The open circles show the chromaticities of the two experimental illuminants. The corresponding solid circles show the chromaticities of the two achromatic loci. The gray background was used for the condition shown. The data show that changing the illuminant has a large effect on the achromatic locus. As shown in the right panel, this is true for all five observers (PW, DHB, WAB, RLJ, and JPH) who observed in this condition.

To assess the precision of the obtained achromatic loci, we computed the between-session standard error of measurement (SEM) for the mean x and y chromaticities. Except as otherwise noted, at least two sessions were run for each condition presented in this paper, and error bars corresponding to ± 1 SEM are plotted with each achromatic point. Typically, however, the SEM's are smaller than the plotted points and are not visible.

Although the data shown in Fig. 2 indicate that a single chromaticity summarizes the achromatic locus, we can also use a summary measure to examine this issue. For each session we computed the within-session standard deviation of the chromaticities of the individual achromatic settings. For each condition we then averaged these within-session standard deviations. The two crosses in the upper right of the left panel of Fig. 3 show the result for one condition and observer. The left cross represents ± 1 mean session standard deviation for the Blue illuminant settings, and the right cross represents ± 1 mean session standard deviation for the Yellow illuminant settings. The sizes of these crosses provide a visual sense of the scatter in the chromaticities of the individual achromatic settings. The right panel of Fig. 3 shows the Blue and Yellow illuminant achromatic loci for five observers. Here the crosses at the upper left of the figure indicate the maxima, taken across observers, of the mean session standard deviations.

2. *Effect of the Illuminant*

The data in Fig. 3 indicate that changing the illuminant affects the achromatic locus. This is to be expected for a color-constant visual system. Consider a nonselective surface that reflects light equally at all wavelengths. The light reflected from it to an observer has the same chromaticity as the illuminant. Suppose that the nonselective surface appears achromatic under a typical daylight. Then for this illuminant, the achromatic locus will have the same chromaticity as the illuminant. For a color-constant visual system, the color appearance of the nonselective surface should remain unchanged as the illuminant varies. Thus for such a system, the achromatic locus should track any changes in the illuminant chromaticity. This is roughly what is seen in Fig. 3.

3. *Degree of Constancy*

Although the achromatic loci do not superimpose exactly on the illuminant chromaticities, this does not necessarily indicate a failure of constancy. Constancy *per se* does not specify the appearance of nonselective surfaces; it requires only the invariance of whatever appearance such surfaces have. Thus a visual system may be color constant even though the chromaticities of the achromatic loci differ from those of the illuminants. The differences could indicate simply that the percept of achromaticity is associated with a selective surface (i.e., one that does not reflect light equally at all wavelengths). To interpret the achromatic data in terms of constancy, we need to take this possibility into account. Because of surface metamerism, there is no unique method for doing so. I have, however, implemented what I feel is a reasonable calculation.

We assume that the effect of the illuminant may be described by a von Kries transformation.[30] That is, we assume that changing the illuminant has the effect of changing the gain on the three types of cone. That such a *diagonal model* provides a good description of the effect of the illuminant is supported by a number of previous studies.[1,4] In this case we can use the achromatic loci measured under two illuminants to derive a transformation that maps the chromaticity of a stimulus seen under the first illuminant to the chromaticity of a perceptually matching stimulus seen under the second illuminant. The appendix provides the details of this calculation. We can then use the calculation to compute the chromaticity of a stimulus, seen under the second illuminant, that would be a perceptual match to a stimulus with the chro-

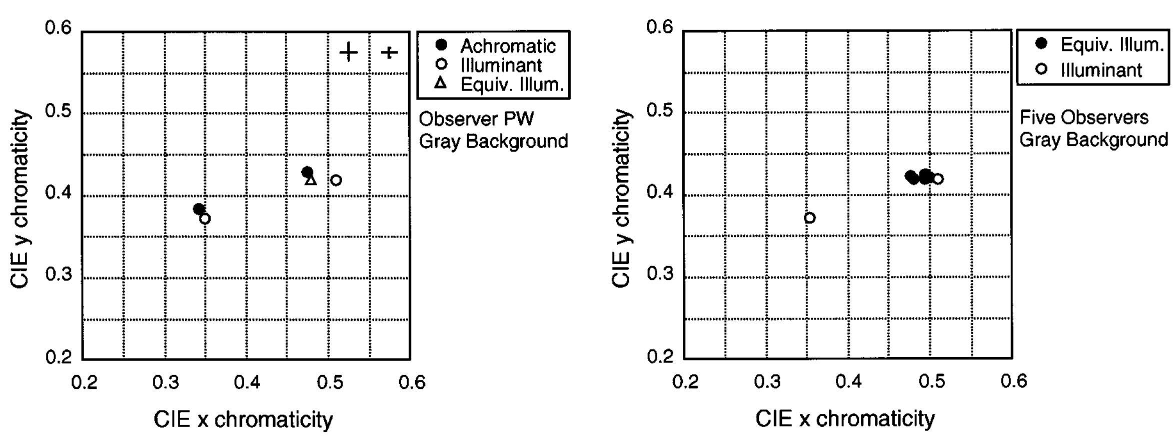

Fig. 4. Equivalent illuminants. Data from Experiment 1 for the Gray background surface. The left panel illustrates the equivalent illuminant calculation for observer PW. Open circles, chromaticities of the Blue and Yellow illuminants; solid circles, chromaticities of the measured achromatic loci under the two illuminants. The data are the same as those shown in the left panel of Fig. 3. Open triangle, equivalent illuminant computed from these data. Here, the equivalent illuminant represents the effect of the illuminant change relative to Blue illuminant chromaticity. In the right panel, closed circles represent the equivalent illuminants for five observers in the Gray background condition, computed from the data shown in the right panel of Fig. 3. Open circles represent the illuminant chromaticities. The equivalent illuminant representation separates the effect of the illuminant change from the scatter of the achromatic points within a single illuminant condition. The effect of the illuminant change is very similar across the five observers. Thus the differences between observers seen in Fig. 3 are primarily shifts in the achromatic loci within a single illuminant condition.

maticity of the first illuminant, seen under the first illuminant. We call the result of this calculation the chromaticity of the *equivalent illuminant*. (See Brainard *et al.*[1] for a more general discussion of the notion of an equivalent illuminant.)

The left panel of Fig. 4 illustrates the equivalent illuminant calculation. The data are the same as in the left panel of Fig. 3. The open triangle plots the chromaticity of the equivalent illuminant. The relation between this and the actual illuminant chromaticities summarizes how the visual system adjusts to the illuminant, irrespective of what surface is seen as achromatic. The summary depends on the adequacy of the diagonal model. This is not tested by the current data set. The right panel of the figure shows as closed circles the equivalent illuminants for five observers measured on the Gray background surface.

We can use the equivalent illuminant to compute a color-constancy index[1,2,10] as follows. Let the CIE 1976 uv chromaticity coordinates of the first illuminant be $\mathbf{c}_1 = (u_1, v_1)$, the uv chromaticity coordinates of the second illuminant be $\mathbf{c}_2 = (u_2, v_2)$, and the uv chromaticity coordinates of the equivalent illuminant be $\mathbf{c}_d = (u_d, v_d)$. We define the constancy index CI by

$$\mathrm{CI} = 1 - \frac{\|\mathbf{c}_2 - \mathbf{c}_d\|}{\|\mathbf{c}_2 - \mathbf{c}_1\|}. \tag{1}$$

This index is 1 if $\mathbf{c}_d = \mathbf{c}_2$ (perfect constancy) and 0 if $\mathbf{c}_d = \mathbf{c}_1$ (no effect of the illuminant). It behaves reasonably if $\mathbf{c}_d$ lies near the line connecting $\mathbf{c}_1$ and $\mathbf{c}_2$. We use the uv chromaticity diagram because it is more perceptually uniform than the xy chromaticity diagram.[31]

Table 2 provides the constancy indices for the five observers of Experiment 1 for each background surface. For the data collected on the Gray background surface, the mean index is 0.84.

Table 2. Constancy and Background Indices[a]

Experiment 1

Observer	Background	CI	BI (Blue)	BI (Yellow)
PW	Gray	0.80		
RLJ	Gray	0.88		
WAB	Gray	0.92		
DHB	Gray	0.86		
JPH	Gray	0.75		
PW	Red	0.81	0.08	0.13
RLJ	Red	0.94	0.00	0.04
WAB	Red	0.87	0.10	0.10
DHB	Red	0.86	−0.13	−0.02
PW	Yellow	0.86	0.21	0.35
RLJ	Yellow	0.93	0.01	−0.03
WAB	Yellow	0.90	0.14	0.04
PW	Dark Blue	0.82	0.20	0.08
PW	Brown	0.75	−0.02	0.00
PW	Black	0.73		
PW	White	0.95		

Experiment 2

Illuminant	CI, JAD	CI, DHB
1	0.93	0.86
2	0.81	0.80
3	0.87	0.82
4	0.81	0.83
5	0.94	0.86
6	0.87	0.91
7	0.93	0.82
8	0.78	0.78

[a] The top half of the table gives the indices computed for each observer/background pair in Experiment 1. The average constancy index for the Gray background is 0.84. The average constancy index for all observer/background pairs for the five observers is 0.85. The background indices were computed with respect to the Gray background surface for both the Blue and the Yellow illuminants. The average background index for the Blue illuminant is 0.07 and for the Yellow illuminant is 0.08. The bottom half of the table gives the constancy indices for Experiment 2 for illuminants 1–8, computed with respect to illuminant 0. The average index is 0.87 for observer JAD and 0.84 for observer DHB.

B. Experiment 2: More Illuminants

Experiment 1 examined the effect of the illuminant for two illuminants with chromaticities near the daylight locus. One might expect better adjustment to these illuminants than to others. The purpose of Experiment 2 was to explore this notion.

Experiment 2 was identical to Experiment 1 with four exceptions. First, we used the RGB illuminant setup rather than the BY illuminant setup. Second, because the achromatic loci measured in Experiment 1 were well described by lines through the origin, observers in Experiment 2 made achromatic settings at only two CIELAB L^* values (50 and 70). Third, settings were made for one illuminant per session. Finally, we did not use a background surface, so that the immediate surround was the gray sheet of particle board rather than a matte posterboard. We used the basic starting rule for this experiment.

Across sessions, we used nine different illuminants, which we call illuminants 0–8. The illuminant chromaticities and luminances are tabulated in Table 1. Two observers (DHB and JAD) participated in the experiment. Observer JAD made settings in two sessions per illuminant. Observer DHB made settings in only one session per illuminant.

Figure 5 shows the results for both observers, plotted as equivalent illuminants. The equivalent illuminants were computed with respect to illuminant 0, which is at the center of the quasi-grid. There is no obvious pattern in the degree of compensation to the different illuminants. In particular, there is no indication that the visual system compensates more fully for illuminant changes along the blackbody locus. The constancy indices for both observers for the individual illuminants are given in Table 2. The mean index for JAD is 0.87 and for DHB is 0.84. These indices are very similar to the ones obtained for the Gray background in Experiment 1.

C. Intermediate Discussion

1. Effect of the Background Surface

The data from Experiments 1 and 2 indicate that observers in our experiment adjust quite well to changes in illumination. One possible mechanism for the effects we observe is simultaneous contrast. The data we have presented so far were collected when the background in the vicinity of the test was either the Gray background surface (Experiment 1) or gray particle board (Experiment 2). The chromaticity of the light reflected from these backgrounds was very close to that of the illuminant. As the illuminant was changed, so too was the local surround of the test. Experiments on chromatic induction (simultaneous contrast) generally show that changing the chromaticity of a uniform surround will shift the achromatic locus in that direction, at least for test stimuli at or below the luminance of the background.[8,9,12]

A color-constant system must adjust to changes of the illuminant. At the same time, color appearance should remain constant when other objects in the scene are varied. If the adjustment to the illuminant seen above were simply the result of simultaneous contrast from the surround, it would hardly be proper to describe the visual system as color constant.[19,22,26]

To see how large the effects of simultaneous color contrast are for our viewing conditions, we can examine the data from Experiment 1 collected with non-Gray background surfaces. If simultaneous contrast is the explanation for the observed constancy, then we would expect changing the background surface to have a substantial effect on the achromatic loci.

Figure 6 shows the results for observer PW. The left panel shows the chromaticities of the background surfaces under the two illuminants. These vary quite widely. The right panel shows the corresponding achro-

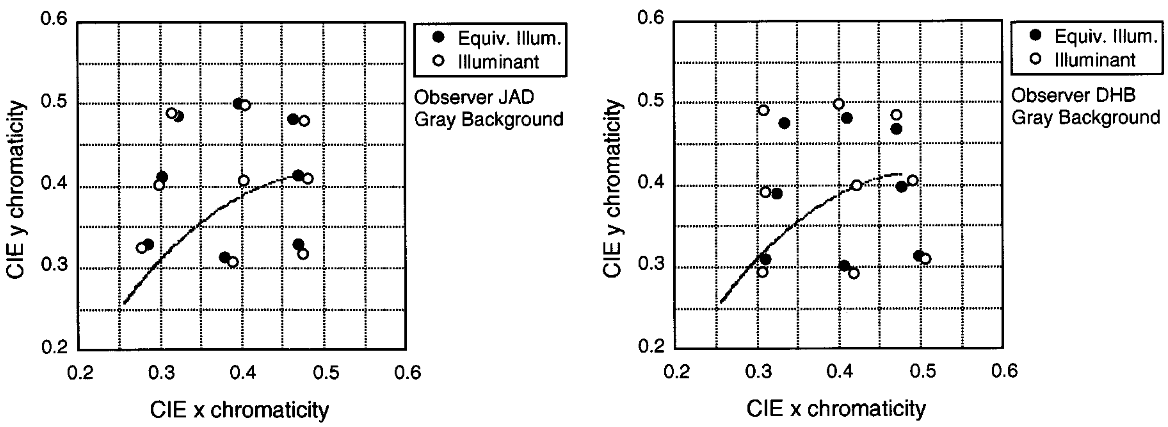

Fig. 5. Equivalent illuminants. Data from Experiment 2 for the Gray background surface for observers JAD (left) and DHB (right). Open circles, chromaticities of nine experimental illuminants; solid circles, eight equivalent illuminants, computed with respect to illuminant 0. (Illuminant 0 is at the center of the grid of nine illuminants.) The variation in the illuminant chromaticities between the two observers represents variability in actual illuminant measurements in the sessions for the two observers. The solid curves in both panels plot the blackbody locus from 2500 °K to 20000 °K.

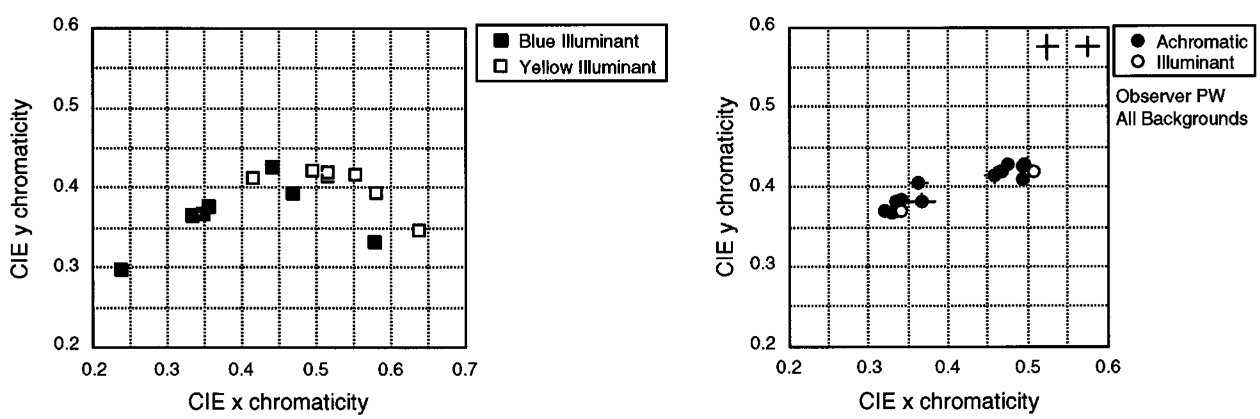

Fig. 6. Effect of background surface. The left panel shows the chromaticities of the Gray, Red, Yellow, Dark Blue, Brown, White, and Black background surfaces under the Blue and Yellow illuminants. Solid squares, chromaticities of the light reflected from the background surfaces under the Blue illuminant; open squares, corresponding chromaticities under the Yellow illuminant. The right panel shows the achromatic loci for observer PW measured for the seven background surfaces. Solid circles, achromatic loci; open circles, chromaticities of the Blue and Yellow illuminants. The error bars on the solid circles represent ± 1 between-session standard error. Note that the achromatic loci cluster near the illuminant even though the chromaticities of the background surfaces scatter widely. For each condition, we computed the average of the within-session standard deviations of the individual achromatic settings. The crossed bars in the upper right represent the maxima of these, computed across the conditions shown. The left cross was computed from the settings under the Blue illuminant and the right cross from the settings made under the Yellow illuminant.

matic settings under the two illuminants. There is only a modest effect of the background surface on the achromatic loci.

We can quantify the effect of the background surface with an index akin to the color-constancy index. Let $\mathbf{c}_g$ be the chromaticity of the Gray background and let $\mathbf{c}_b$ be the chromaticity of a second background surface. Both $\mathbf{c}_g$ and $\mathbf{c}_b$ are defined with respect to a single illuminant. Given the achromatic loci measured under the two background surfaces, we can ask how far the loci shift when the background is changed relative to the change in background itself. To answer this question, we proceed as we did for our constancy index and use the achromatic loci to compute a diagonal mapping. We then apply this mapping to $\mathbf{c}_g$ to obtain $\mathbf{c}_{db}$. We define our background index as

$$\mathrm{BI} = 1 - \frac{\|\mathbf{c}_b - \mathbf{c}_{db}\|}{\|\mathbf{c}_b - \mathbf{c}_g\|}. \tag{2}$$

This index is 1 if the locus shifts by an amount equal to the shift in background and 0 if the locus does not shift at all when the background is changed. In terms of constancy, the interpretation of background index values is reversed: 0 represents good constancy with respect to changes in the background surface, whereas 1 indicates a severe failure of constancy.

Table 2 gives the background indices for the Red, Yellow, Dark Blue, and Brown background surfaces for the subset of observers who observed in these conditions.[32] Sometimes the computed background index is negative. This indicates that the effect of the background was not to move the achromatic locus in the direction of the background change. Because of this, the background index should be taken only as a broad summary of the data. Nonetheless, the average background index for the Blue and the Yellow illuminants was 0.07 and 0.08, respectively. This quantifies the characteristic of the data seen in Fig. 6 and confirms that the effect of simultaneous contrast is quite modest compared with the effect of the illuminant change or, equivalently, that the visual system exhibits good constancy with respect to changing the background surface.

2. *Effect of the Illuminant with Colored Background Surfaces*

Does the good constancy with respect to illuminant changes that we observed above depend on the presence of an achromatic (Gray) background surface? We can also use the data from Experiment 1 to answer this question. For each background, we computed the equivalent illuminant for the Blue to Yellow illuminant change. Figure 7 plots the equivalent illuminants from all of our Experiment 1 conditions. This representation separates the effect of the illuminant change from the effect of the background surface. Just as in Fig. 4, the equivalent illuminants cluster in the vicinity of the Yellow illuminant. The average constancy index across the conditions that used a non-Gray background surface was 0.86, very close to the value 0.84 obtained for the Gray background surface. The visual system's adjustment to an illuminant change is not perturbed when the test is seen on a colored background.

3. *Effect of the Panels*

Experiments 1 and 2 were conducted when the test surface was seen among an array of Munsell papers (as shown in Fig. 1). A number of computational models of constancy suggest that better information about the illuminant is available in the image when there are many distinct surfaces in the image.[23–25] To determine whether the presence of the panels mediated the good constancy seen, we had two observers repeat a number of the conditions in Experiment 1 with the panels taken down.

In general the results were very similar to those obtained with the panels. Here we report only summary measures. Observer PW made settings for the Gray and Red background surfaces. His constancy index averaged across these two conditions was 0.81, the same as it was for these two conditions when these panels were in place. His background index (averaged over the Blue and Yellow illuminants) for the change between Red and Gray background was 0.09, compared with 0.10 when the panels were in place. Observer JPH made settings for the Gray, Red, Yellow, and Blue background surfaces. His average constancy index was 0.88, and average background index was 0.08. This constancy index is higher than we measured for him with the Gray background surface and the panels in place (0.77) but well within the range we see across subjects in the condition with panels. His background index (averaged over background surfaces and illuminants) was 0.08, very similar to our average of 0.07 from Experiment 1.[33] The data for Observer JPH are shown in Fig. 12 below.

Our conclusion is that the panels per se have little effect on either the effect of the illuminant or the effect of the background. This is consistent with the results we obtained for asymmetric matching in the companion paper.[1] It should be emphasized that even with the panels down, the visual field seen by the observer was quite complex and contained objects of several different colors. Thus this result should not be interpreted as falsifying extant computational models or to mean that the contextual information provided by light outside of the background surface is irrelevant. Indeed, the results of Experiment 3

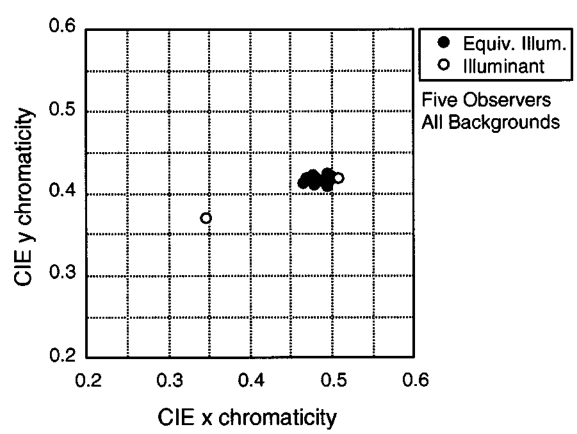

Fig. 7. Equivalent illuminants. Data from Experiment 1 for all observer–background pairs measured. Solid circles, equivalent illuminants; open circles, illuminant chromaticities. The effect of the illuminant change is very similar across all of the background surfaces.

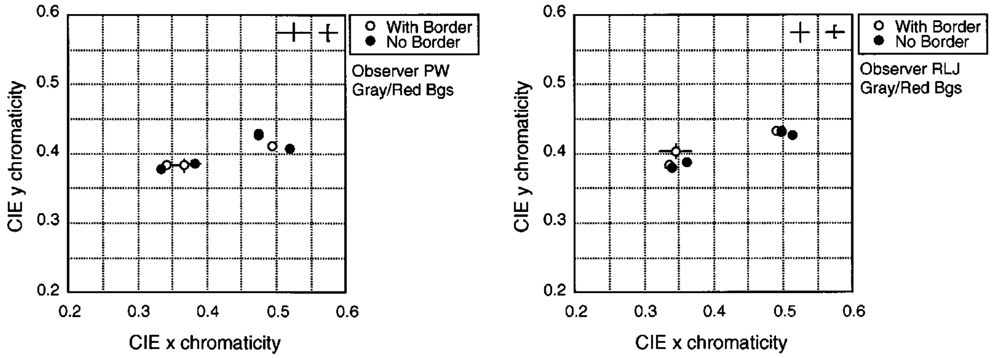

Fig. 8. Comparison of achromatic settings made with and without the thin black border surrounding the test patch for two observers. Open circles, achromatic loci with the border present for the Gray and Red background surfaces; solid circles, settings for the same background surfaces without the border. The error bars on each point represent ±1 between-session standard error. There is little effect of the border. For each condition, we computed the average of the within-session standard deviations of the individual achromatic settings. The crossed bars in the upper right of each plot represent the maxima of these, computed across the conditions shown. The left cross was computed from the settings under the Blue illuminant and the right cross from the settings made under the Yellow illuminant.

below demonstrate that such light plays an important role in determining color appearance. What these results do suggest (within the limited range explored) is that performance is robust with respect to the details of the contextual stimulus.

4. Effect of the Black Border

A number of factors might account for the relatively small effect of the background surface in our experiments. One is the thin (1/4 in.) black felt border that was interposed between the test surface and the background surface. Under some conditions, a thin border around a test can affect its appearance.[34–36] In our experiments, the presence of this border made it easier to align the projection colorimeter, since alignment error within the border was not visible to the observer. We conducted a control experiment to rule out the possibility that the presence of the border substantially affected the effect of the background surface. For this control, we constructed a second test surface that did not have the felt border and carefully aligned the colorimeter with it. We then had observers make achromatic adjustments in this no-border condition. We used the BY illuminant setup and both the Gray and the Red background surfaces. The surrounding grid of Munsell panels was present, and each of these was still surrounded by a 1/4 in. black border. We used the basic starting rule. Figure 8 shows the results for two observers. The effect of the background surface is still very small. The average background index for the Red background in the no-border condition (computed with respect to the Gray background in the same condition) is 0.13, while for these two observers the corresponding index was 0.06 with the border. In a similar experiment that used the Yellow background and a single illuminant (the Gray illuminant from Experiment 3 below), observer DHB had a background index of 0.34 without the border and 0.24 with it.[37] Removing the border also has only a minimal effect for observer DHB in Experiment 4 below. Although the presence of the border may slightly reduce the effect of simultaneous contrast, this effect is not large even with the border. The presence of the border in our experiments cannot be the explanation for why we observe small contrast effects.

D. Experiment 3: Matched Backgrounds

It remains possible that the background surfaces used in Experiment 1 had particular chromaticities and luminances that do not produce large contrast effects. To control for this possibility, observer DHB ran in Experiment 3. In this experiment, we matched background chromaticities and luminances across illuminant and background surface changes.

In Experiment 3, we used the RGB illuminant setup and no surrounding grid of Munsell panels. The observer made achromatic settings under an illuminant that was approximately metameric to D65, which we refer to as the Gray illuminant. We used seven different background surfaces: Gray, Red, Yellow, Dark Blue, Light Blue, Light Green, and Pale Yellow. For each background surface other than Gray, we then found a corresponding illuminant such that the tristimulus coordinates of the light reflected to the observer from the Gray background surface under this light were the same as the light reflected from the background surface of interest under the Gray illuminant. We refer to the illuminants so determined as the Red, Yellow, Dark Blue, Light Blue, Light Green, and Pale Yellow illuminants. The observer made achromatic settings for each of these illuminants with the Gray background surface in place. As in Experiment 2, achromatic settings were made at CIELAB L^* levels of 50 and 70. Settings were made in only one session per condition. We used the basic starting rule. Table 3 provides the chromaticities and luminances of the seven experimental luminances and of the light reaching the observer from the background for each illuminant/background surface combination studied.

The design of Experiment 3 can be thought of as consisting of two sets of conditions. In one set, the light reaching the observer from the background surface was manipulated by changing the background surface while holding the illuminant constant. In the other, the light reaching the observer was manipulated by changing the illuminant while holding the background surface con-

Table 3. Stimuli for Experiments 3 and 6[a]

Illuminant	CIE x	CIE y	Lum. (cd/m^2)
Gray	0.317	0.327	20.1
Red	0.574	0.321	21.4
Yellow	0.448	0.391	38.1
Dark Blue	0.247	0.280	10.6
Light Blue	0.275	0.292	29.1
Light Green	0.291	0.339	23.8
Pale Yellow	0.410	0.373	32.0
Gray Background			
Illuminant			
Gray	0.303	0.325	6.1
Red	0.563	0.322	6.0
Yellow	0.434	0.394	11.3
Dark Blue	0.236	0.275	3.2
Light Blue	0.264	0.288	8.7
Light Green	0.282	0.337	7.1
Pale Yellow	0.396	0.374	9.5
Gray Illuminant			
Background			
Gray	0.303	0.325	6.1
Red	0.564	0.314	5.7
Yellow	0.425	0.392	11.4
Dark Blue	0.219	0.266	2.8
Light Blue	0.259	0.309	9.4
Light Green	0.276	0.347	7.7
Pale Yellow	0.385	0.374	9.8

[a] The top section of the table provides the chromaticities and luminances of the seven experimental illuminants used in Experiments 3 and 6. The design of Experiments 3 and 6 was identical except for the adjustment starting rule used. The table provides the average of the stimulus measurements made for the two experiments. The middle section provides the chromaticities and luminances of the light reflected to the observer from the Gray background surface under the seven illuminants. The bottom section gives the chromaticities and luminances of the light reflected to the observer from the seven background surfaces under the Gray illuminant. For symmetry, the data for the Gray background surface under the Gray illuminant is provided in both the middle and bottom sections.

stant. Across the two sets there were matched pairs of conditions, in that the light reaching the observer from the background surface was approximately the same for both members of the matched pair.

Figure 9 shows the results. It is clear that there is a large difference between the two conditions. When the background surface is changed with a constant illuminant, there is only a modest effect on the achromatic loci. When the illuminant is changed, on the other hand, the achromatic loci shift substantially, as one would expect for a color-constant system. The illuminant, and not the local background, is the best predictor of the achromatic locus.

We can quantify the observations from Experiment 3. When the illuminant was changed, the mean constancy index was 0.80. This is similar to the constancy indices obtained Experiments 1 and 2. For the same conditions, we can also compute the background index. Since the light reflected from the Gray background surface has a chromaticity very close to that of the illuminant, the background indices should be very similar to the corresponding constancy indices, and indeed they are: the mean is 0.82. We can also compute background indices for the case where the background surface is changed and the illuminant is held fixed. Here we obtain a value of only 0.15. This value is much lower than the corresponding indices obtained when the illuminant is changed. The difference between the two conditions rules out the possibility that simultaneous contrast from the background surface is the explanation for the color constancy observed. The visual system also takes into account changes that occur outside the 16° × 20° area subtended by the background surface, and the effect of such changes can be quite substantial. This result confirms conclusions drawn by Shevell and colleagues on the basis of experiments that employed relatively simple stimulus configurations.[38,39] Table 4 provides the constancy and

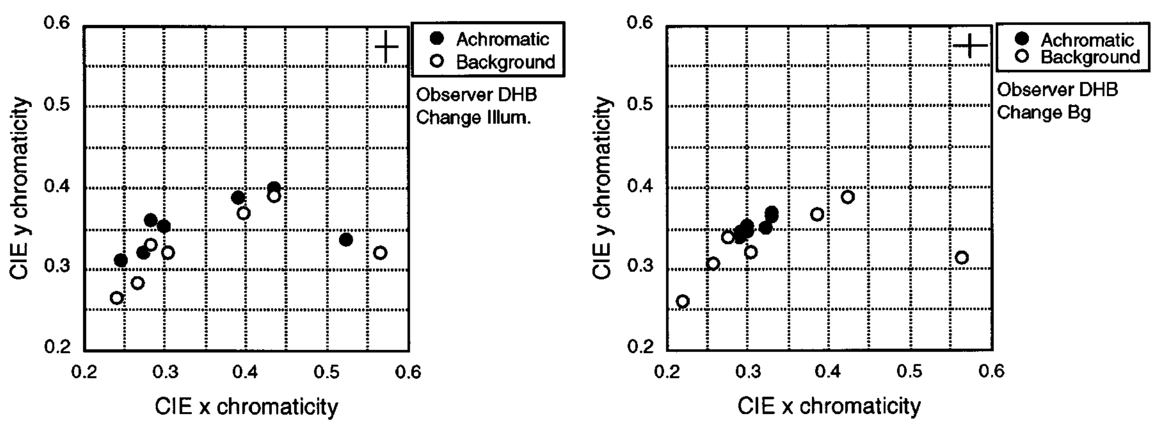

Fig. 9. Comparison of the effect of illuminant change and of background surface for Experiment 3, which directly compares the effect of two manipulations. The left panel shows the effect of changing the illuminant. Open circles, chromaticities of the Gray background surface under seven experimental illuminants. These chromaticities are very similar to those of the illuminants themselves. Solid circles, chromaticities of the achromatic loci. Settings were made in only one session per condition, so there are no error bars. Changing the illuminant has a large effect on both the chromaticity of the background surface and the achromatic loci. The right panel shows the effect of changing the background surface while holding the illuminant constant. Open circles, chromaticities of the seven background surfaces; solid circles, chromaticities of the corresponding achromatic loci. The spread of the achromatic loci is much smaller in this condition. Rather than tracking the background chromaticities, the achromatic loci cluster near the illuminant. For each condition, we computed the average of the within session standard deviations of the individual achromatic settings. The crossed bar shown in the upper right of each plot shows the maximum of these, computed across the conditions shown.

Table 4. Constancy and Background Indices for Experiment 3, Observer DHB[a]

Illuminant/ Background	Change Illuminant: CI	Change Illuminant: BI	Change Background: BI
Red	0.80	0.80	0.07
Yellow	0.91	0.89	0.24
Dark Blue	0.80	0.80	0.13
Light Blue	0.76	0.78	0.18
Light Green	0.64	0.71	−0.10
Pale Yellow	0.91	0.91	0.37

[a] CI, constancy index; BI, background index. The first column provides the constancy indices for the conditions measured with the Gray background surface, computed for each illuminant with respect to the Gray illuminant. The mean of these indices is 0.80. The second column provides the background indices for the same observer computed for the same conditions. Since the chromaticity of the light reflected from the Gray background surface is close to that of the illuminant, these background indices are very close to the constancy indices. The mean of these indices is 0.82. The third column provides the background indices computed when the illuminant (Gray) was held fixed and the background surface was changed, computed with respect to the data obtained with the Gray background surface. The mean of these indices is 0.15. If the effect of the illuminant were governed entirely by simultaneous contrast from the background surface, the two sets of background indices should be identical. In fact, they differ considerably.

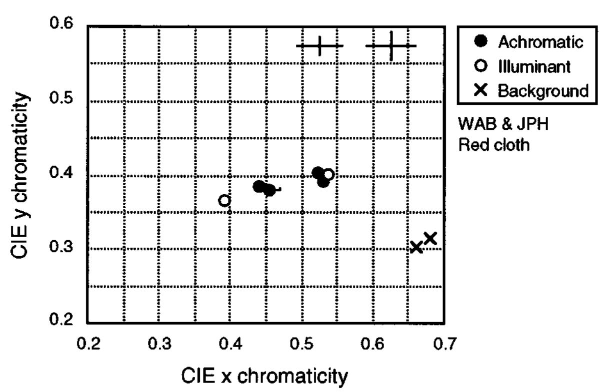

Fig. 10. Settings made with the red cloth. Solid circles, achromatic settings measured for Observers WAB and JPH, with the error bars representing ±1 between-session standard error. Open circles, chromaticities of the Blue and Yellow illuminants. Notice that these are shifted from their location in other experiments because of interreflection from the red cloth. For each condition, we computed the average of the within-session standard deviations of the individual achromatic settings. The crossed bars in the upper right represent the maxima of these, computed across the conditions shown. The left cross was computed from the settings under the Blue illuminant and the right cross from the settings under the Yellow illuminant. Note that the scatter in the x-chromaticity settings indicated by these crosses is quite large. This scatter is systematic with luminance and indicates that a single point does not completely characterize the measured achromatic locus.

background indices for each illuminant/background surface combination studied in Experiment 3.

E. Experiments 4 and 5: Size of the Background Surface

Perhaps the small contrast effect observed in Experiments 1 and 3 is due to the small size of the background surface compared with the entire experimental room. A number of experimental results in the literature suggest that 16° × 20° is large enough to produce an asymptotic contrast effect.[9,40–42] On the other hand, these results were generally obtained with smaller test stimuli than our 4.4° × 5.7° test. In Experiment 4, we greatly increased the size of the background surface by draping the far wall of the experimental room in red cloth. The cloth extended around both the right and left corners of the room and completely covered the white table that was located below the test panels. It also covered a normally gray partition that was placed immediately to the observer's left. In the vicinity of the test, the red cloth extended 37° vertically, with the test roughly centered in this extent. When the observer fixated the test, the cloth extended 67° to the left and extended through the full horizontal visual field to the right. The gray floor and ceiling remained visible to the observer, as did gray areas above and below the extent of the cloth.

Figure 10 shows the results of Experiment 4 for observers WAB and JPH. Except for the removal of the panels and background surface and the addition of the red cloth, the methods for these subjects were identical to Experiment 1. For both observers, the red cloth introduces a modest contrast shift under the Blue illuminant and little contrast shift under the Yellow illuminant.

In principle, one could compute a background index for the shift under the two illuminants relative to a baseline condition in which the red cloth was not present. A comparison of the illuminant chromaticities in this figure and those plotted in (e.g.) Fig. 3, however, shows that the addition of the red cloth not only changes the background surface but also shifts the illuminant measured at the test panel location. Presumably, this shift occurs because of interreflection off of the large amount of red cloth in the room. Because of the illuminant shift, computation of a background index is not appropriate for these data. Nonetheless, it is clear from the data that the shift caused by the red cloth is not as large as the effect of the illuminant measured in the experiments measured without the red cloth. The constancy index for both observers was 0.60, smaller than that generally measured for conditions without the red cloth. This smaller constancy index might be attributed to the fact that the contrast effect of the red cloth is larger for the Blue illuminant settings than for the Yellow illuminant settings, perhaps because there is very little shift in the chromaticity of the red cloth with the change of illuminant.

One feature worth noting in Fig. 10 is that the x-chromaticity standard deviations (shown by the crosses at the top of the plot) are quite large compared with other data reported in this paper. A more detailed examination of the data indicates that these large standard deviations result from a systematic shift in achromatic chromaticity with luminance, so a full understanding of the red cloth condition will eventually require a model of how achromaticity varies with luminance and how this variation interacts with the viewing conditions.

To control for the possibility that the red cloth had a chromaticity and luminance that simply did not induce large effects, we conducted an analog of Experiment 3 above for observer DHB. We compared achromatic settings in two conditions. In one, we used the Gray illuminant of Experiment 3 and arranged the red cloth as described above. In the other, we used a red illuminant whose chromaticity made the chromaticity of the Gray background surface approximately that of the red cloth seen under the Gray illuminant. This experiment used the RGB illuminant setup, the basic starting rule, and L^* values of 50 and 70; observations were made in one session per condition. For the red-cloth condition, settings were made both for a test panel with the normal 1/4-in. border and for a test panel with no border. Figure 11 shows the results. These show the same pattern in Experiment 3. Changing the illuminant has a large effect on the achromatic point, whereas adding the red cloth has only a small effect. The small effect of the red cloth is seen both with and without the border.

The small effect of the red cloth in the above experiments speaks to theories of color constancy that suppose that constancy is achieved not through simultaneous contrast but rather through adaptation to the space average of the light reaching the eye from the entire image.[22,24,43,44] Theories based on this idea are often referred to as depending on the "gray world assumption" since they predict good constancy if the average surface reflectance in an image is nearly constant across images.[45] The red cloth occupied enough of the visual field to bias the space average of the light reaching the observer. Nonetheless, it had only a small effect on the achromatic loci. In this sense our results are consistent with those of McCann, who also showed a dissociation between the effect of the illuminant and the effect of the

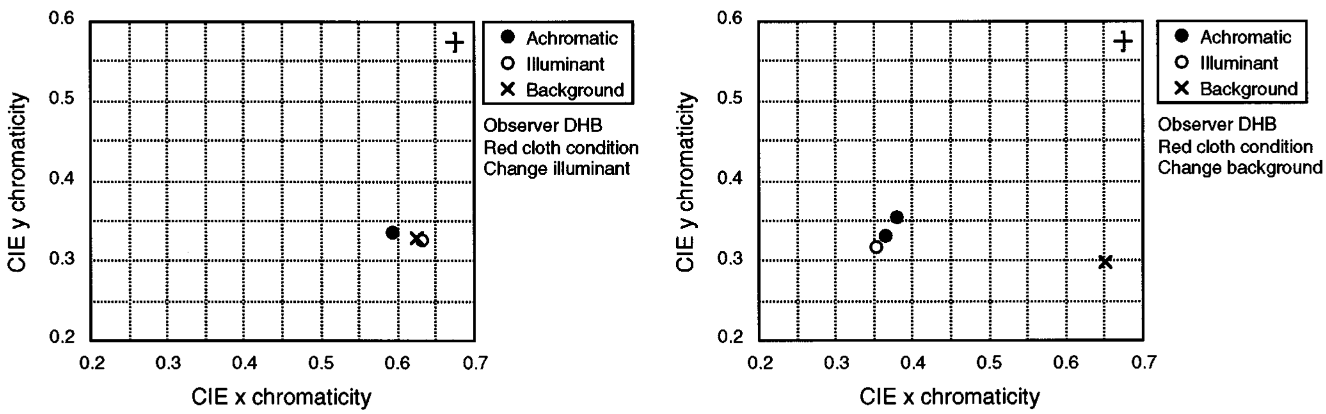

Fig. 11. Settings made with the red cloth compared with settings made under a red illuminant for observer DHB. The left panel shows the achromatic locus measured under the red-cloth illuminant. Solid circle, chromaticity of the achromatic locus; open circle, chromaticity of the illuminant; cross, chromaticity of the Gray background surface under this illuminant. Settings were made in only one session per condition, so there are no error bars. The right panel shows settings made under the Gray illuminant with the red cloth. Solid circles, achromatic loci. One solid circle represents measurements made with the normal 1/4-in. black felt border around the test; the other solid circle represents measurements made with no border. Open circle, measured chromaticity of the Gray illuminant in the red-cloth condition; cross, chromaticity of the light reflected from the red cloth.

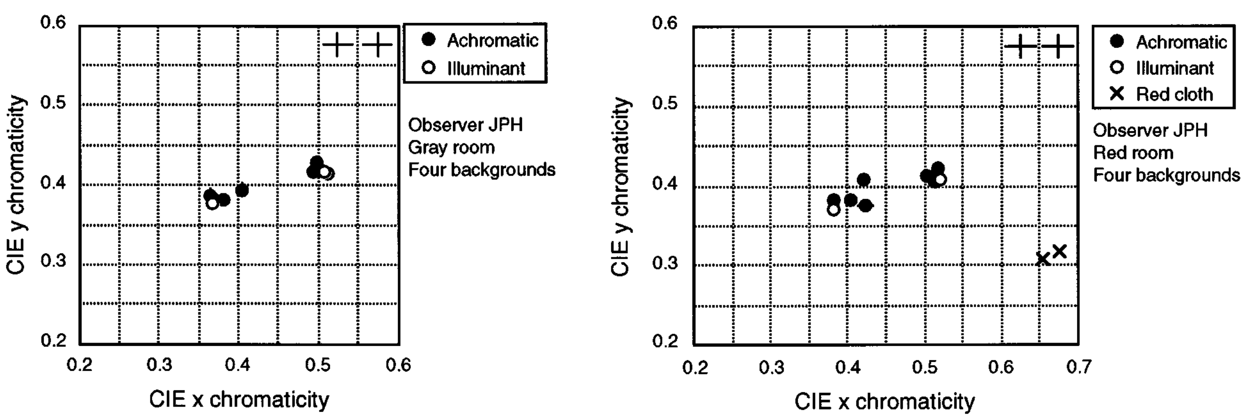

Fig. 12. Settings made with red cloth and different background surfaces for observer JPH. The left panel shows data for four background surfaces and no red cloth. This condition is like Experiment 1 except that here the Munsell panels were removed. Solid circles, achromatic loci measured under the Blue and Yellow illuminants; open circles, illuminant chromaticities. The error bars on the closed circles represent ± 1 between-session standard error. The right panel shows data for the same observer with the same background surfaces but with the red cloth in place. The legend is the same as in the left panel with the addition of the crosses, which plot the chromaticity of the light reflected from the red cloth under the two illuminant conditions. The data collected with and without the red cloth are very similar, which suggests that the change in space average chromaticity of the light reaching the observer induced by the red cloth has very little effect on the achromatic locus. For each condition, we computed the average of the within-session standard deviations of the individual achromatic settings. The crossed bars in the upper right represent the maxima of these, computed across the conditions shown. The left cross was computed from the settings under the Blue illuminant and the right cross from the settings made under the Yellow illuminant.

Table 5. Constancy and Background Indices for Experiment 5, Observer JPH[a]

Background Surface	CI		BI				RCI	
			No Cloth		Red Cloth			
	No Cloth	Red Cloth	Blue Illum.	Yellow Illum.	Blue Illum.	Yellow Illum.	Blue Illum.	Yellow Illum.
Gray	0.93	0.84					0.10	0.10
Red	0.86	0.68	0.12	0.10	0.08	0.01	0.07	0.03
Yellow	0.87	0.72	0.17	0.14	0.13	−0.10	0.05	0.04
Dark Blue	0.86	0.84	−0.05	0.01	0.20	0.18	0.03	0.04
Mean	0.88	0.77	0.08	0.08	0.13	0.03	0.06	0.05
Mean (Blue/Yellow)			0.08		0.08		0.06	

[a] CI, constancy index; BI, background index. The first column provides the constancy indices measured for the change from Blue to Yellow illuminant in the condition where the red cloth was not present. The second column gives the same indices when the red cloth was present. The third through sixth columns give the background indices (computed with respect to the Gray background surface) for each background surface under each illuminant both with and without the red cloth. The final two columns give the red cloth indices under the Blue and Yellow illuminants. The second to last row of the table provides the means of each column, while the last row consolidates these means (where applicable) across the Blue and Yellow illuminants.

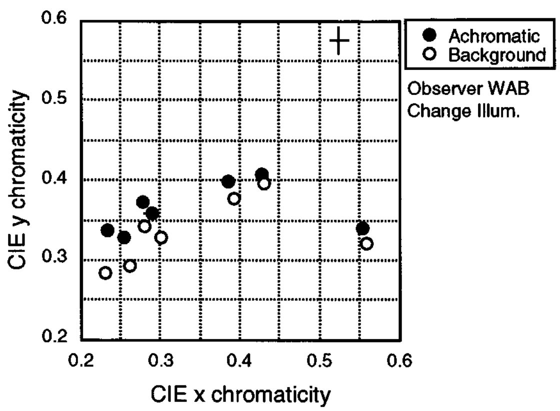

Fig. 13. Comparison of the effect of illuminant change and background surface, adaptive starting rule. Data from Experiment 6, observer WAB. Except for the change in starting rule, the experiment is identical to Experiment 3 and the data may be compared with those in Fig. 9. The left panel shows the effect of changing the illuminant. Open circles, chromaticities of the Gray background surface under seven experimental illuminants. These chromaticities are very similar to those of the illuminants themselves. Solid circles, chromaticities of the achromatic loci. The error bars on the closed circles represent ± 1 between-session standard error. Changing the illuminant has a large effect on both the chromaticity of the background surface and the achromatic loci. The right panel shows the effect of changing the background surface while holding the illuminant constant. Open circles, chromaticities of the seven background surfaces; solid circles, chromaticities of the corresponding achromatic loci. The spread of the achromatic loci is much smaller in this condition. Rather than tracking the background chromaticities, the achromatic loci cluster near the illuminant. For each condition, we computed the average of the within-session standard deviations of the individual achromatic settings. The crossed bar in the upper right of each plot shows the maxima of these, computed across the conditions shown.

mean stimulus.[46] Still, some caution is warranted in drawing firm conclusions about the role of the spatial average, as we do not know exactly how large a bias in spatial average was produced by the red cloth (see Section 4).

The small effect of the red cloth can be seen even more clearly in the data from Experiment 5, which were collected by Observer JPH. These data are shown in Fig. 12. The left panel of this figure shows a replication of Experiment 1 with the exception that the Munsell panels were removed. These data were discussed above. The right panel of the figure shows a replication of the experiment with the red cloth placed behind the panels. The light trap was present to the left of the test in both cases. This reduces the shift of the illuminant at the test patch that is due to interreflection from the red cloth. By comparing the left and right panels, we can examine the effect of changing the space average of the light reaching the observer while holding the local surround of the test (determined by the background surface in the 16° × 20° region adjacent to it) constant. When we hold the local surround constant, there is not much difference between the achromatic loci with and without the red cloth.

We can quantify the effect of the red cloth for Observer JPH by computing an index that measures the effect of adding the red cloth. This index is computed analogously with our background index, with the exception that we use the chromaticity of the red cloth and of the gray paint rather than of the immediate background surface to compute it. The average index (across four background surfaces) is 0.05 under the Blue illuminant and 0.06 under the Yellow illuminant. This compares with an average (over illuminants and background surfaces) background index of 0.08 both in the red cloth and no red cloth conditions and average constancy indices of 0.77 and 0.88 in the red cloth and no red cloth conditions. Table 5 gives a more detailed breakdown.

F. Experiments 6 and 7: Effect of the Starting Rule

All of the experiments described above used the basic starting rule, which seems most natural for studies of constancy. We also conducted experiments that used an adaptive starting rule that equated the initial adjustment starting points in terms of the proximal stimulus reaching the observer. Although less valid as a model of natural scenes viewed under different illuminants, this rule is not subject to the objection that it biases the experimental results in favor of good constancy. We refer to this rule as the adaptive starting rule.

The adaptive starting rule works as follows. The starting CIELAB a^*b^* chromaticity of the first adjustment in a block was chosen randomly within the rectangle $[-25,25] \times [-25,25]$, computed not with respect to the actual illuminant but rather with respect to a reference illuminant that was fixed within a group of experiments. On each additional adjustment in the block, the starting chromaticity of the adjustment was chosen randomly within the rectangle $[-25,25] \times [-25,25]$ defined with respect to a white point whose luminance matched that of the reference illuminant and whose chromaticity was defined by the average achromatic chromaticity of the adjustments set thus far in the block. Thus in this procedure, the starting chromaticity for the adjustments is independent of the actual illuminant used (since it is tied to a fixed reference illuminant) and over trials tracks the observer's subjective achromatic point.

We repeated Experiment 3 for Observer WAB, using the adaptive starting rule. The reference illuminant was chosen as the Gray illuminant. We refer to this as Experiment 6. Otherwise the methods were the same as for Experiment 3 except that two sessions per condition were run rather than just one. The results are shown in Figure 13 and are on the whole similar to those obtained with the basic starting rule for Observer DHB (see Fig. 9). The main difference is that the effect of the background surfaces is larger in Fig. 13. This is confirmed by examining the constancy and background indices, which are given in the top portion of Table 6. When the illuminant was changed, the mean constancy index was 0.82 for WAB, similar to the value of 0.80 obtained for DHB in Experiment 3 above. But the mean background index for WAB was 0.39, considerably higher than the value of 0.15 obtained for DHB and also higher than the values obtained in Experiments 1 and 5.

To confirm that the larger background index obtained for observer WAB when the background surface was changed was not idiosyncratic to this observer, we can examine data from an experiment conducted by Rutherford, Kraft, and myself as part of an ongoing project to compare constancy measured with real scenes and with computer simulations.[47] This experiment, which we refer to as Experiment 7, was essentially a replication of Experiment 6 with only the Yellow background surface/illuminant paired condition. There were three minor differences between Experiments 6 and 7. First, the illuminants used in Experiment 7 were a little more luminous than those in Experiment 6 (see Tables 3 and 7). Second, a partial grid of Munsell panels was used in Experiment 7, while in Experiment 6 no panels were present. The partial grid consisted of the left three columns of the grid shown in Fig. 1, with the N9.5/paper replaced by a 5P 4/6 paper. The two right columns of panels were not used, so that the back-

Table 6. Constancy and Background Indices for Experiments 6 and 7[a]

Experiment 6, Observer WAB

Illuminant/Background	Change Illuminant CI	Change Illuminant BI	Change Background BI
Red	0.95	0.96	0.32
Yellow	0.91	0.87	0.76
Dark Blue	0.70	0.68	−0.03
Light Blue	0.86	0.86	0.20
Light Green	0.53	0.61	0.41
Pale Yellow	0.94	0.91	0.71

Experiment 7

Illuminant/Background	Change Illuminant CI MDR	CI DHB	CI JMK	Change Illuminant BI MDR	BI DHB	BI JMK	Change Background BI MDR	BI DHB	BI JMK
Yellow	0.86	0.92	0.77	0.86	0.93	0.78	0.34	0.41	0.13

[a] CI, constancy index; BI, background index. The top part of the table is in the same format as in Table 4. The first column provides the constancy indices for the conditions measured with the Gray background surface, computed for each illuminant with respect to the Gray illuminant. The mean of these indices is 0.82. The second column provides the background indices for the same observer computed for the same conditions. Since the chromaticity of the light reflected from the Gray background surface is close to that of the illuminant, these background indices are very close to the constancy indices. The mean of these indices is 0.82. The third column provides the background indices computed when the illuminant was held fixed (it was the Gray illuminant) and the background surface was changed, computed with respect to the data obtained with the Gray background surface. The mean of these indices is 0.39. The bottom part provides the same information for Experiment 7, for three observers. Each group of three columns in the bottom part of the figure corresponds to one column in the top part.

Table 7. Experiment 7 Stimuli[a]

Illuminant	CIE x	CIE y	Lum. (cd/m^2)
Gray	0.320	0.320	24.9
Yellow	0.448	0.385	50.5
Gray Background Illuminant			
Gray	0.307	0.317	8.1
Yellow	0.434	0.388	16.2
Gray Illuminant Background			
Gray	0.307	0.317	8.1
Yellow	0.429	0.384	15.2

[a] This experiment is analogous to Experiment 3, but only one illuminant/background surface pair was investigated. The top section provides the chromaticities and luminances of the two experimental illuminants. The middle section provides the chromaticities and luminances of the light reflected to the observer from the Gray background surface under these two illuminants. The bottom section gives the chromaticities and luminances of the light reflected to the observer from the two background surfaces under the Gray illuminant. For symmetry, the data for the Gray background under the Gray illuminant is provided in both the middle and bottom sections.

ground surface was unobstructed by panels. Third, two pieces of white copier paper with grids of black lines drawn on them were mounted on the far wall of the room, but were well removed from the test. Observers MDR, DHB, and JMK participated in Experiment 7. The adaptive starting rule was used.

The results of Experiment 7 confirm the basic conclusions drawn from Experiment 6. The constancy and background indices for Experiment 7 are given in Table 6. The average constancy index for the three observers was 0.85, and the average background index when the illuminant was changed was 0.86. In contrast, the average background index when the background surface was changed from Gray to Yellow was 0.29.

The results of Experiments 6 and 7 also suggest that the effect of using the adaptive rule is to increase the measured effect of the background surface, presumably because the adaptive rule does not pull the settings toward the illuminant as strongly as does the basic starting rule. For observer DHB, we can compare directly the size of the constancy and background indices for the Yellow background surface/illuminant pair in Experiments 3 and 7. We see that this constancy index is essentially the same in the two experiments but that his background index increases from 0.24 to 0.41. This increase is presumably due to the change in starting rule, since the other experimental variations between Experiments 3 and 7 are minor.

We have compared the effect of varying the starting rule on the constancy index for two other observers in two different conditions. Observer JAD observed in a replication of Experiment 1 conducted with the RGB illuminant setup and without any background surface. She observed in conditions with both the basic and the adaptive starting rule. Her constancy index dropped from 0.93 to 0.81 when the starting rule was changed from basic to adaptive. As part of a project to study the effect of the illuminant on colors displayed on color monitors, Ishigami and I also conducted an experiment similar to Experiment 1 but using the adaptive starting rule. This is described elsewhere.[42] Observer KI replicated the experiment using the basic starting method. His constancy index changed from 0.52 to 0.48 when the starting rule was changed from basic to adaptive. It is not clear why KI's data showed so little constancy in this experiment. The second observer in the published experiment (AMO) also showed unusually low constancy (index 0.56, adaptive starting rule). Observer DHB replicated the experiment with the adaptive rule and obtained a constancy index of 0.80, so it seems unlikely that any of the differences in experimental detail between this and Experiment 1 were crucial.

4. DISCUSSION

A. Degree of Color Constancy

For our natural viewing conditions, successive color constancy with respect to illuminant changes is very good. For the ecologically valid basic starting rule, the average constancy index in experiments not involving red cloth and with the normal 1/4-in. border around the test was 0.82.[48] Even for the adaptive starting rule, the average constancy index was 0.76. The good constancy shown by our observers is consistent with the high degree of adjustment to the illuminant reported by Berns and Gorzynski[40] and Gorzynski[41] for experiments that, like ours, employed real illuminants and papers.

The high constancy indices in our experiments may be contrasted with those that have been reported for successive constancy measured by using stimuli displayed on color monitors. These are typically in the range 0.50–0.60.[5,9] With a haploscopic technique and stimuli displayed on monitors, which might be taken to measure successive constancy, Lucassen and Walraven found constancy indices in the range 0.38–0.76, again lower than ours.[17] These comparisons suggest that there are important differences between the rather natural stimuli we used and simulations rendered on color monitors. Whether these differences can be explained by simple considerations (e.g., differences in the size of the visual field, size of the test stimuli, overall luminance level) remains to be determined.[49] It does suggest that some caution is warranted when one is generalizing results from monitor-based experiments.

One particularly intriguing feature of the good constancy we observed is that it did not seem to depend on the chromaticity of the illuminant change, at least for the modest changes we employed. This is seen most clearly in Experiment 2, which studied the effect of eight different illumination changes. This result is interesting since it contradicts the idea, suggested by a number of theorists, that the visual system could take advantage of the fact that most natural illuminant variation is along the daylight locus.[25,52]

Our experiments measured successive constancy with the technique of achromatic adjustment. It is possible that different results would obtain if we measured constancy for chromatic colors. In an experiment that studied simultaneous constancy with use of several different methods, however, Speigle and Brainard[53] found good agreement between results obtained with achromatic adjustment and with asymmetric matching. This result has not yet been extended to successive constancy, but it does suggest that the achromatic locus is not special.

B. Role of Local Contrast

The high constancy indices observed in our experiments were not obtained at the cost of inordinately high sensitivity to the local background. The average background index for the basic starting rule experiments was 0.07, while for the adaptive starting rule it was 0.32. Both of these indices are much lower than the corresponding constancy indices (0.82 and 0.76, respectively). If color appearance were governed entirely by local contrast, the constancy and background indices should have been the same. Our result means that color appearance cannot be predicted solely on the basis of local contrast. The only caveat is the possibility that the thin black area that surrounded our test patch has a major effect on color appearance. For certain stimulus conditions, manipulating the border around a test patch can influence its appearance.[36] The control experiments in which we removed the border show, however, that such border effects are minimal for our viewing conditions.

Our results differ from a number of studies in the literature in which local contrast decisively determined appearance.[9,40–42,54] A key difference between those studies and ours may be the richness of the stimulus conditions. In the lightness domain, Gilchrist and his colleagues have shown a number of rich stimulus conditions under which local contrast fails to determine appearance.[26,55,56] For simpler viewing conditions, Shevell and colleagues have also been able to demonstrate cases in which factors other than local contrast affect appearance.[38,39,57,58]

C. Role of the Spatial Average

A simple alternative to the idea that local contrast governs color appearance is that the visual system uses the spatial average of the cone photoreceptor responses to normalize its processing of color information.[22,24,43,44] This alternative does not require that local contrast be the key variable for predicting color appearance. The relatively small effect of adding a lot of red cloth to the scene while holding the illuminant fixed (particularly in Experiment 5, in which the local contrast was also held fixed) suggests that the spatial average is not the only variable governing appearance. On the other hand, this conclusion is not secure because, large as it was, the red cloth did not cover the majority of the visual field. If the visual system computes the spatial average over the whole field, our red cloth manipulation was not large enough to provide a decisive test. We are now pursuing experiments that manipulate the spatial average of the scene more vigorously.[59]

D. Effect of the Starting Rule

It is clear from our data that the rule used to determine the starting point of the adjustments has a systematic effect on the measured achromatic loci. In general, the measured locus is biased toward the chromaticity at which the adjustment started. This indicates that the test itself influences the visual system, which is perhaps not unreasonable: a visual system that attempts to estimate the illuminant at a location would probably do well to make use of the information available at that location as well as information provided by surrounding locations.

That the adjustment starting rule has an effect highlights a fundamental difficulty in measuring perceptual experience: the act of manipulating the test stimulus perturbs the state of the system we are trying to measure. A possible solution to this problem might be to flash the test patch briefly and allow the observer to adjust it between flashes. But even this procedure has the difficulty that something must be present at the test location during the interflash periods, and whatever is there may play a role in determining appearance. For studying appearance in natural scenes, we believe that our basic starting rule is an appropriate choice (see Section 3). For any particular application of our data, some attention should be paid to the effect of the starting rule.

E. Interaction of Illuminant and Scene Content

In our experiments, the effect of changing the background surface is small relative to the effect of changing the illuminant, especially when we use the basic starting rule. Nonetheless, it is clear that changing the background surface does have an effect on the achromatic loci. A complete theory of color appearance cannot be based solely on understanding how the visual system adjusts to the illuminant; the effect of the other objects in the scene must be taken into account. To develop such a theory, we will need to formulate and test simplifying principles that might govern the interaction between the illuminant and the surfaces that compose the scene.[6,11] Without such principles, the measurement problem becomes intractable: we would have to measure the effect of the background surface for every possible illuminant.

APPENDIX A: EQUIVALENT ILLUMINANT

The diagonal model of asymmetric matching is a formulation of von Kries's hypothesis[30] that the only effect of the illuminant is to change the gains of signals originating in the three classes of cones. Let $\mathbf{r}_t$ be a three-dimensional column vector that denotes the cone coordinates of the light reaching the observer from a test surface under a test illuminant. Similarly, let $\mathbf{r}_m$ represent the cone coordinates of the light reaching the observer from a match surface seen under a different illuminant. We use the symbol $\sim_{tm}$ to denote a visual asymmetric match across the illuminant change, so that when the test and match surfaces appear the same (when each is viewed under its respective illuminant) we have $\mathbf{r}_m \sim_{tm} \mathbf{r}_t$. The diagonal model of asymmetric matching[1,4] states that when $\mathbf{r}_m \sim_{tm} \mathbf{r}_t$, then

$$\mathbf{r}_m = \mathbf{D}\mathbf{r}_t, \tag{A1}$$

where $\mathbf{D}$ is a three-by-three diagonal matrix. The diagonal entries of $\mathbf{D}$ are parameters of the model that depend only on the contexts in which the test and match surfaces are seen. Thus within the diagonal model it is necessary only to specify the entries of $\mathbf{D}$ to predict what lights will match across the change of illumination.

When the achromatic locus is described by a line through the origin, we can describe the entire locus by specifying the cone coordinates of any stimulus on it. Let $\mathbf{a}_1$ be the cone coordinates of a stimulus on the locus measured under one illuminant. Let $\mathbf{a}_2$ be the cone coordinates of a stimulus on the locus measured under a second illuminant. Let $\mathbf{a}_m$ be a stimulus such that $\mathbf{a}_m \sim_{tm} \mathbf{a}_1$. Since $\mathbf{a}_1$ appears achromatic when seen under the first illuminant, we have that $\mathbf{a}_m$ appears achromatic when seen under the second illuminant (otherwise the asymmetric match would not hold.) Thus $\mathbf{a}_m = k\mathbf{a}_2$ for some scalar k, and from this we have $k\mathbf{a}_2 \sim_{tm} \mathbf{a}_1$. Given the diagonal model of matching, this leads to

$$k\mathbf{a}_2 = \mathbf{D}\mathbf{a}_1 . \tag{A2}$$

Inspection of Eq. (A2) tells us that we can determine the diagonal entries of $\mathbf{D}$ (and hence $\mathbf{D}$ itself) up to a free scalar:

$$(1/k)\ \mathrm{diag}(\mathbf{D}) = \mathbf{a}_2\ ./\ \mathbf{a}_1 , \tag{A3}$$

where the function diag( ) extracts the diagonal entries of its argument and the symbol ./ denotes entry-by-entry division. By convention, we set $k = 1$ to obtain a particular matrix $\mathbf{D}_0$ that differs from $\mathbf{D}$ only by an unknown scale factor.

Let $\mathbf{e}_1$ be the cone coordinates of the first illuminant when it is reflected from a perfect diffuser. The cone coordinates of the equivalent illuminant $\mathbf{e}_d$ are defined so that $\mathbf{e}_d \sim_{tm} \mathbf{e}_1$. Thus we have $\mathbf{e}_d = \mathbf{D}\mathbf{e}_1$. Let $\mathbf{e}_0 = \mathbf{D}_0\mathbf{e}_1$. Then $\mathbf{e}_0$ differs from $\mathbf{e}_d$ only by an unknown scale factor and thus has the same chromaticity as $\mathbf{e}_d$. Let $\mathbf{c}_d$ be the chromaticity of the equivalent illuminant. Then $\mathbf{c}_d$ is obtained as the chromaticity of $\mathbf{e}_0$.

In this paper we generally represent achromatic and illuminant chromaticities by using the CIE 1931 system of colorimetry.[28] In performing our equivalent illuminant calculation, we used a cone-excitation space consistent with this observer. We derived each of our L, M, and S-cone fundamentals as the linear combination of the 1931 *XYZ* color matching functions that provided the best least-squares fit to the corresponding Smith–Pokorny[60,61] cone fundamental.

ACKNOWLEDGMENTS

J. D. Tietz provided technical support and J. M. Spiegle helped with the initial construction of the apparatus. A. L. Gilchrist, J. M. Kraft, M. D. Rutherford, S. K. Shevell, and an anonymous reviewer provided critical comments on the manuscript. We thank W. A. Brunt, J. A. Doyle, J. P. Hall, R. L. Jones, K. Ishigami, and P. Wise for careful observing. M. D. Rutherford and J. M. Kraft kindly permitted me to include the data for Experiment 7 in this paper. These were collected as part of a larger project that will be presented elsewhere.[47] Data for observers KI and AMO were collected as part of a study of the appearance of colors presented on color monitors. This project is described in detail elsewhere.[42] Preliminary versions of this research were presented at the 1994 Association for Research in Vision and Ophthalmology Meeting[62] and the 1995 Trieste Encounter in Cognitive Science. The work was supported by National Eye Institute grant EY 10016.

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