Adaptive shift of visual sensitivity balance under ambient illuminant change

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Received November 24, 1997; revised manuscript received March 23, 1998; accepted April 16, 1998

We examined the relationship between the ambient illuminant chromaticity and changes in the sensitivity balance of the visual system, using illuminants of various chromaticities. The sensitivity of observers was measured in a room with a variable-chromaticity illuminant. The observer's state of chromatic adaptation was measured with unique-white settings. Our results showed that the change in visual sensitivity has a nonlinear correlation with the change in illuminant chromaticity; chromatic adaptation was nearly complete for desaturated illuminants, but the degree of chromatic adaptation became worse as the illuminant became more saturated. We defined a new index, relative cone weights, which represents this relationship well. To measure the role of chromatic induction from the immediate-surround area of the matching stimulus, we performed additional experiments by presenting the test inside a colored or black immediate surround. The results showed that the unique-white settings were not disturbed by the change in immediate-surround color. Our results imply that the room illuminant chromaticity was the primary factor in changing the observer's state of chromatic adaptation. [S0740-3232(98)02409-0]

OCIS codes: 330.0330, 330.1690, 330.1720, 330.5510, 330.7310, 330.7320.

1. INTRODUCTION

When we carefully observe an object color under various illuminants, we notice that there are two kinds of constancy in color perception. In the first case, the simple color appearance of an object is invariant. In the second case, the object itself appears unchanged, but the simple color appearance is changed under the change in illuminant. For example, a white paper appears white under an illuminant with a broadband spectrum, such as sunlight or a fluorescent lamp. However, the same white paper does not appear "colorless" under an incandescent lamp. The paper itself may appear as having a "white" surface, but the color may appear more yellowish than "white."

Such complications could be easily solved by introducing notions of two classes of color appearance: surface-color perception and apparent-color perception.[1] The term surface-color perception refers to the perception of an object color as an attribute of the object surface, and the term apparent-color perception refers to a simple apparent color. When we see white paper under whitish illuminant, the surface- and the apparent-color perceptions are identical, i.e., "white." When we see white paper under an incandescent lamp, surface-color perception is "white," but apparent-color perception is not (the color may appear slightly yellowish). These two classes of color perception have been pointed out by many researchers, but the number of observations is still small.[2–4]

If both surface- and apparent-color perception do not change under a change in illuminant condition, this state would be referred to as complete color constancy. If apparent-color perception shifts while surface-color perception remains constant, this state is referred to as partial color constancy. If surface-color constancy does not hold, there is no color constancy.[1,5]

In our previous study we found that surface-color constancy holds even under a highly chromatic illuminant but not under a monochromatic illuminant.[1] Our results also showed that the inconsistency between surface- and apparent-color perception became very small when the eyes were adapted to the illuminant and when a complex chromatic surround was presented. Although the inconsistency became larger as the illuminant chromaticity became saturated, we could not clearly categorize the two classes of color constancy. The primary purpose of our present study is to clarify the relationships of illuminant chromaticity and to clarify the border of consistency between surface-color and apparent-color perception.

The inconsistency between surface-color and apparent-color perception is regularly observed under chromatic illuminants but not under a whitish illuminant. Our previous data showed that the apparent-color perceptions for color chips start to deviate from complete color constancy under a nonwhitish illuminant, whereas surface-color perceptions for identical color chips remained constant under a wider range of illuminant chromaticities.[5] These facts imply that the outputs of the systems for apparent-color and surface-color perceptions become remarkably different as the illuminant becomes more chromatic.

If the adaptive shift is complete for whitish illuminants and starts to deviate as the illuminant becomes chromatic, and if the state of chromatic adaptation directly affects apparent-color perception but not surface-color perception, the discrepancy between apparent-color and surface-color perceptions might be solved in the following way. Under a whitish illuminant, the observer's visual system adapts completely to the illuminant, and the shift in sensitivity cancels out the change in chromaticity that corresponds to the illuminant-color change. As a result, the observer may report that the apparent color and the surface color are identical. Under a nonwhite illuminant, the observer's visual system adapts incompletely to the illuminant, and cancellation of the chromaticity change that corresponds to the illuminant change is not complete. As a result, the observer may report an inconsistency between surface- and apparent-color perception under a chromatic illuminant.

Chromatic adaptation has been raised as one of the key factors in color constancy, although it is known that the degree of adaptation is not complete.[6,7] If the photoreceptors change their sensitivity in inverse proportion to their own response to illuminants, as in the most basic von Kries system, the photoreceptor responses to objects under a new illuminant are expected to be nearly equal to the responses under the previous illuminant.[8] Fairchild and Lennie[6] pointed out that the chromatic adaptation is not complete enough to cancel out the effect of illuminant-color change. The observer's state of chromatic adaptation was measured in a unique-white setting, with the chromaticity of a color chip adjusted under various illuminant chromaticities on a CRT monitor. Arend[9] made unique-color settings for color chips in a mondrian pattern under various illuminant chromaticities simulated on a CRT monitor. These studies were quite useful for discussing the relationships between the change in visual sensitivity and the shift in matched colors. However, since these are separate studies, and data were collected with different apparatus and observers, it might be difficult to combine these results to derive a relationship between the degree of adaptation and the matched-color shift.

Both studies used relatively small stimuli, simulated on a CRT monitor, as an adapting field. In Fairchild and Lennie's study, the adapting field (including test stimulus) subtended 12 deg in most conditions. Similarly, Arend's stimulus subtended no larger than 5 deg. Generally, a computer-simulated stimulus on a CRT screen provides a stimulus smaller than the field of view in daily life. If the adapting field is not large enough in comparison with the size of the test stimulus, the test stimulus itself may affect the state of chromatic adaptation. It is true that computer-controlled CRT displays allow us to present stimuli under precise control in both intensity and chromaticity, but the size and spatial resolution of the CRT screen limit the scale of the stimulus.

In everyday situations, however, all of our surrounding field of view is effective as the adapting field. Brainard and his colleagues recently conducted studies in color constancy under realistic stimulus conditions by using a room with a chromatic illuminant.[10–12] Similarly, to provide a natural adapting environment and to stabilize the observer's state of chromatic adaptation, we used a Helson-type room apparatus[13,14] to present to the observer light from the illuminant reflected on the walls as an entire field-of-view adaptation field. The purpose of our study was to measure the observer's extent of chromatic adaptation and the inconsistency of apparent-color and surface-color perceptions by using unique-white settings.

2. METHODS

A. Use of a Unique-White Setting

We used unique-white settings to measure the observer's change in visual sensitivity. In many conventional studies on color constancy, the observer was asked to view two stimuli, successively or simultaneously, and the observer did asymmetric color matching between corresponding color chips. Arend[9] pointed out that unique-color settings are advantageous in terms of providing stable chromatic adaptation, because the observer has to see only a single stimulus.

The rationale for measuring the observer's state of chromatic adaptation with a unique-white setting is as follows. When the observer is exposed to a nonwhite illuminant, the visual system starts to adapt to the illuminant, and the state of chromatic adaptation becomes stable after several tens of seconds.[6,7] After the state of adaptation reaches an asymptote, the illuminant color may appear more whitish than at the beginning of the illuminant change. If the observer's state of chromatic adaptation is complete, the illuminant itself should appear colorless. However, previous studies pointed out that the simple color appearance (apparent color) of the current illuminant appears nonwhite. At the same time, a light of equal energy that appears white under no chromatic adaptation would appear to have a hue complementary to that of the illuminant. This implies that the chromatic sensitivity of the observer's visual system has changed and has stopped at some midway point, under which the light of the chromaticity between the equal-energy white and the nonwhite illuminant appears "white." This incomplete chromatic adaptation is prominent under an illuminant of relatively higher saturation.

In the unique-white experiment, the observer was shown a single color chip as a stimulus and adjusted its chromaticity until it appeared to be pure white. If the observer stayed under a highly saturated illuminant, neither the equal-energy white nor the current illuminant would appear pure white. Instead, the observer might match unique-white with the light of a chromaticity between the equal-energy white and the current illuminant color. This would imply that the observer's balance of sensitivity to color had shifted to a point such that the matched color, which was neither the equal-energy white nor the current illuminant, was seen as pure white. Thus the observer's state of chromatic adaptation could be derived in relation to the chromaticity of the adapting illuminant.

We ran a preliminary experiment with test stimuli of luminance lower than the luminances that we used in the formal experiment; the test stimuli were approximately the same as the luminance of the wall. The observer was not able to perceive the stimulus as completely colorless; for example, with yellowish illuminant, the observer experienced competing color perceptions between yellow and blue and with orange illuminant, between green and red. If the observer's visual system had fully adapted to the illuminant chromaticity, any "achromatic" object should appear "colorless." However, the observer's intuition was that a compromise was made to make neither of two opponent colors stronger. This implies that the "achromatic" setting at a modest luminance does not provide clear information about the state of observers' chromatic adaptation. When we raised the luminance of the test stimulus to appear "white," all observers were able to make adjustments more comfortably than with the test stimuli of lower luminance. Therefore we used luminance levels that appeared "white" to the observer.

We conducted two experiments. First we observed the effect of the illuminant on the change in the state of chromatic adaptation. Next we did an additional experiment to confirm whether simultaneous contrast (chromatic induction) affected the results. In the present section we will introduce the method of the first experiment; however, most of the methods are common to the two experiments. We will remark on several differences at the beginning of the second experiment section.

B. Apparatus and Stimulus

To provide stable chromatic adaptation, we used a room with a variable-chromaticity illuminant on the ceiling as an apparatus. Figure 1 shows a schematic view of the apparatus. The illuminant comprised five D_{65}-simulating fluorescent lamps (Toshiba FLR40S-D-EDL-D65/M), a checkerboard-patterned mask, and four checkerboard-patterned filter sets.

Figure 2 shows a schematic view of the variable-chromaticity illuminant. The size of each mask and filter was 10 cm $\times$ 10 cm, and they were placed in an array of 5 $\times$ 10. The filter array was made of a pair of neutral-density (ND) filters and a color filter. A pair of filters were placed in a checkerboard pattern in each cell of the 5 $\times$ 10 array. The mask was made of an aluminum frame and plastic boards. The plastic boards were cut into 10-cm $\times$ 10-cm squares to match the size of each filter and were placed in a checkerboard-pattern arrangement. This filter set was made for the pairs of ND filters and a blue, orange, green, or purple filter. The mask was a checkerboard-patterned 5 $\times$ 10 array of empty and opaque areas. When this mask was placed directly on the filter array, one color of the filters (i.e., ND or color) was covered with the opaque areas and the other color of the filter transmitted the light from the D_{65} fluorescent lamps. When the mask was slid gradually relative to the filter, the ratio between the areas of ND and colored filter through which the light was transmitted was gradually changed. As a result, the chromaticity of the light coming out of the empty areas of the mask changed gradually and continuously from D_{65} to the color of the filter. The hue direction of the illuminant variability was switched by replacing the filter set between the four (ND + blue, ND + orange, ND + green and ND + purple).

The reason the ND filter was paired with a color filter was to minimize the change in the intensities of the illuminant. Precise data are shown in Table 1.

Luminance (in cd/m^2) and x and y chromaticity data are shown for each filter set: blue, orange, green, and purple. Luminances were measured on a $BaSO_4$ white plate placed on the front wall adjacent to the matching stimulus. The blue filter set showed the lowest luminance among the four, but the other three sets showed smaller differences relative to one another (less than a factor of 2).

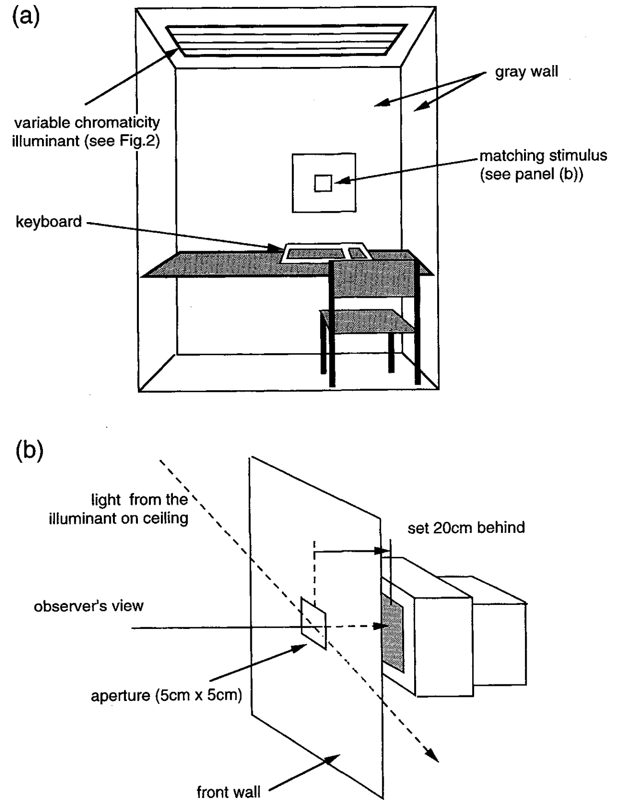

Fig. 1. Schematic view of the apparatus setup. (a) A small room (2.0 m $\times$ 1.5 m $\times$ 1.2 m) was equipped with a special illuminant on the ceiling. The illuminant was able to change its chromaticity in the way depicted in Fig. 2. Walls were painted with approximate N 5/ gray. An aperture was made on the front wall so that the CRT screen could be seen through it. The observer sat on the chair and manipulated a keyboard on the desk. (b) Arrangement CRT screen. The screen was set at ~20 cm behind the wall in an otherwise dark room.

The colors of the illuminants were chosen so that the distance on a $u'v'$ diagram would be divided into five equal-stepped saturation levels between D_{65} and the maximally saturated illuminant. The leftmost column shows filter position; position I corresponds to 100% D_{65}, and position V corresponds to 100% colored illuminant. The top row shows data for 0% illuminant, which stands for an almost-D_{65}-only illuminant, but there are slight differences between filter sets. Therefore each 0% illuminant was treated separately. The $u'v'$ chromaticities of the illuminants will be shown in the results (see Fig. 4 below).

Figure 3(a) shows the spectrum of the D_{65}-simulating fluorescent lamp, measured with spectroradiometer SR-1 (TOPCON, Tokyo). Figures 3(b), 3(c), 3(d), and 3(e) show spectral distributions of the maximum-saturation illuminant for each filter set: blue, orange, green and purple, respectively.

Figure 1(b) shows the arrangement of the CRT monitor (Apple 13-in. CRT color monitor), used as test stimulus.

The CRT surface was placed ~20 cm behind a 5-cm × 5-cm aperture on the front wall so that the illuminant from the ceiling would not be directly reflected on the CRT surface. This CRT surface was carefully calibrated under each room illuminant with the method proposed by Cowan.[15] The maximum intensity of any stray light that entered through the small aperture was 0.1 cd/m^2. This intensity was ~2.5 $\log_{10}$ units below the luminance of the matched stimulus. Therefore the light from the CRT surface was virtually independent of the room illuminant. The observer viewed the central part of the CRT surface through the aperture and made unique-white settings. Since the CRT surface was set ~20 cm behind the hole, the observer accommodated to the edge of the aperture, and the inside appeared to be a simple uniform square. At moderate luminances the small patch appeared as a small color chip on the wall. The observers viewed this mathing stimulus from 60 cm away from the wall. The matching stimulus subtended approximately 5 deg × 5 deg in visual angle.

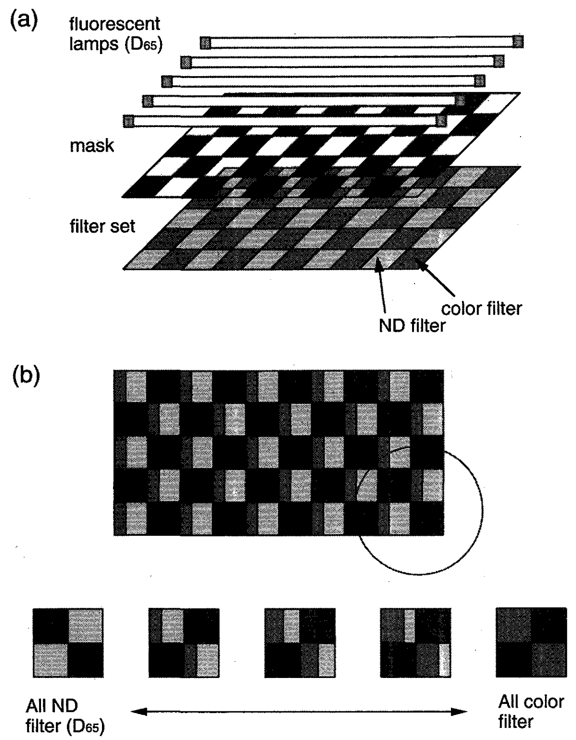

Fig. 2. Schematic view of the variable-illuminant system. (a) The illuminant consists of five D_{65}-simulating fluorescent lamps (TOSHIBA FLR40S-D-EDL-D65/M), a filter array, and a mask. (b) The filter array was a 5 × 10 matrix of color and ND filters (each 10 cm × 10 cm), arranged in alternating positions in a checkerboard pattern. The mask consisted of an array of opaque plastic boards and empty areas both (10 cm × 10 cm). (b) When the filter array was slid against the mask, the relative amount of light coming through the color filter and the ND filter changed continuously.

C. Procedure

The filter set was not changed throughout each session. The observer was asked to adapt to an illuminant for 5 min before starting the adjustment. The observer made five unique-white settings under each illuminant, one after another. In preliminary experiments we found effects of local adaptation in the form of strong afterimages. Therefore during the formal sessions we asked the observers to move their eyes as frequently as possible and to look away from the matching stimulus until the afterimage went away, especially before making any final decisions.

After each set of five settings, the experimenter changed the saturation of the illuminant and the observer adapted for an additional 5 min. The saturation was changed in random order, so that there were almost no progressive changes in the observer's state of adaptation from one saturation condition to the next. To reduce the effect of the order of saturation conditions, the observer repeated five sessions for each filter set with a randomized order of saturation conditions. The results of this experiment will be presented below with a mean value, averaged across 25 settings under each illuminant. Before every trial, the luminance of the matching stimulus was set to 35 cd/m^2 and the chromaticity was randomized around the D_{65} chromaticity.

We also measured unique-white under a cone-plateau condition. Under any kind of illuminant, the sensitivity of the human visual system is different from its completely neutral state. However, in order to discuss the change in the sensitivity of the visual system, we have to know the sensitivities of each cone class under a completely neutral condition. This state, adapted to nothing, might be defined as the origin of the state of sensitivity.

Table 1. Intensities and $u'v'$ Chromaticities of the Adapting Field[a]

	Blue			Orange			Green			Purple		
Filter Position	Luminance (cd/m^2)	u'	v'	Luminance (cd/m^2)	u'	v'	Luminance (cd/m^2)	u'	v'	Luminance (cd/m^2)	u'	v'
I	22.7	0.193	0.468	23.1	0.196	0.471	27.6	0.190	0.472	25.5	0.202	0.462
II	21.1	0.193	0.464	22.2	0.198	0.473	24.8	0.186	0.475	22.9	0.210	0.455
III	16.5	0.186	0.444	20.7	0.210	0.484	24.7	0.171	0.487	20.0	0.236	0.438
IV	13.3	0.179	0.422	19.9	0.219	0.493	24.6	0.157	0.499	17.0	0.264	0.420
V	8.95	0.164	0.373	19.2	0.236	0.509	25.2	0.148	0.507	15.5	0.283	0.408

[a] All data are measured on a $BaSO_4$ plate placed on the front wall adjacent to the matching stimulus. "Filter position" represents the filter's position relative to the mask. Position I represents the all-ND filter (D_{65}) condition. Position V represents the all-color filter condition, and the other positions represent intermediate points between positions I and V.

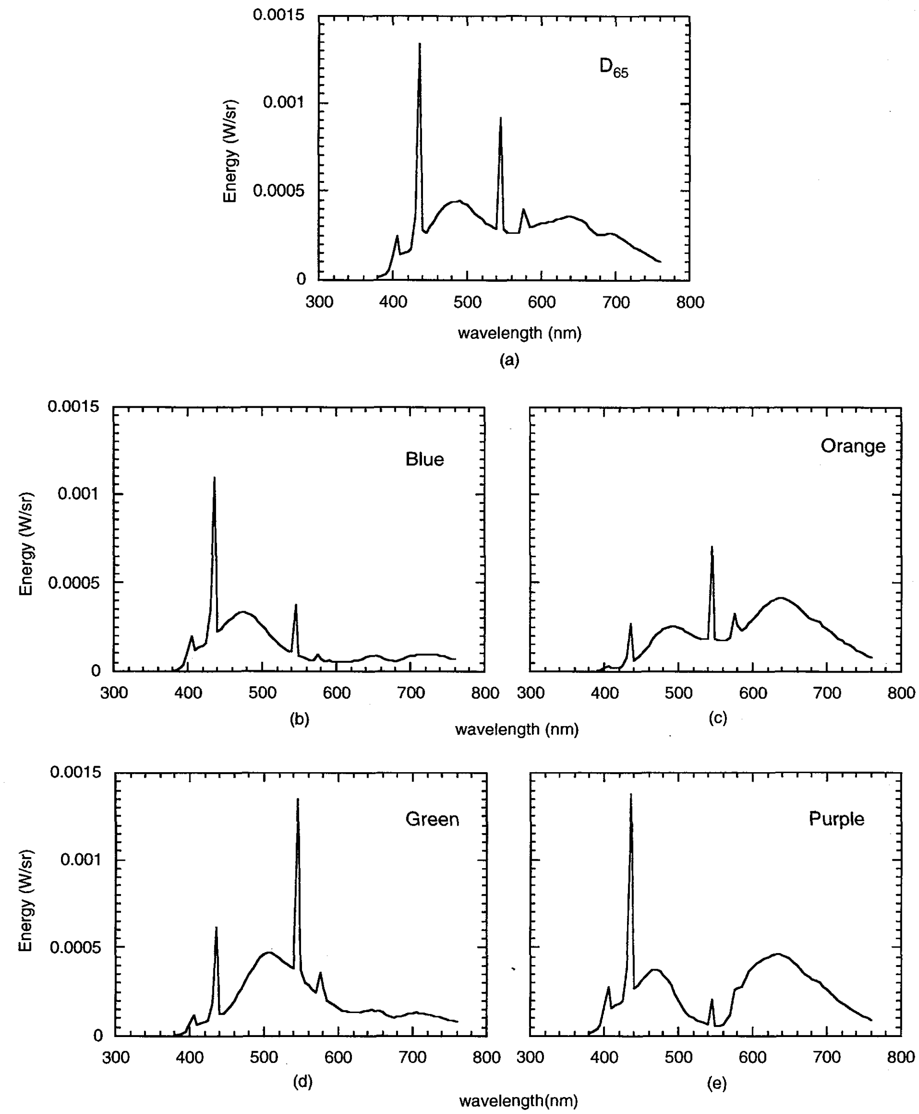

Fig. 3. Energy spectra of the illuminants. (a) D_{65}-simulating fluorescent lamp measured through a ND filter. (b) through (e) represent the spectral energy components of the transmittance of blue, orange, green, and purple filters, respectively. Each plot represents the result of measurement by a spectrophotometer (SR-1, TOPKON) for the maximally saturated condition.

Cone plateau is a state of adaptation of the visual system that is reached when a light-adapted eye spends 5–10 min in the dark. We asked the observer to start unique-white adjustments after 5 min of dark adaptation. The stimulus was presented repeatedly for 1 s between 5 s of blanks. The observer did as many settings as possible within 10 min from the start of dark adaptation. For simplicity we refer to the average of these unique-white settings under the cone-plateau interval as neutral unique-white.

D. Observers and Criteria

The two authors and one naïve observer served as observers in this experiment. The observers were asked to match unique-white, which does not appear to contain any kind of color (apparent-color matching criterion). In different sessions, two of the three observers (one author, one naïve) were asked to match as if a piece of white paper had been placed on the front wall (surface-color matching criterion).

3. EXPERIMENT 1

A. Results

The observers were allowed to adjust the luminance as well as the chromaticity, but they did not make any remarkable changes in luminance throughout the experiment. The luminance profiles will be discussed below. Figure 4 shows the results of unique-white settings on the $u'v'$ chromaticity diagram. Filled symbols represent the chromaticities of the illuminants, and open symbols represent observer's matches. The open cross in each panel represents neutral unique-white for each observer. Distributions of the observers' matches are shown by ± 1 standard deviation (SD) in both u' and v' directions, with error bars in a naïve observer (KS)'s results. The size of the error bars are very close to or twice as large as the size of the symbols. This means that the distributions of the observers' unique-white settings are very small across 25 repetitions for each illuminant condition.

It is remarkable that the observers' matches are quite stable and that they are distributed over a smaller range than the distributions of the illuminant chromaticities. Closer observations will be made in Subsection 3.B, but the present results show that the observer's state of chromatic adaptation does not follow exactly the change in illuminant chromaticity.

The results under the surface-color matching criterion are shown in Fig. 5. Representations of the symbols are the same as those in Fig. 4. Standard deviations (error bars) show that distributions of the observer's settings are larger than those in Fig. 4, especially for the matched results under a chromatic illuminant.

Figures 4 and 5 show that observers' settings differed according to their criteria, but they do not show clear correspondence between illuminant chromaticities and matched colors. We instructed the observer to make settings as if the matching stimulus appeared as a piece of "white" paper on the front wall. It must be mentioned that it was possible for the observer to make chromaticity matches between the adapting field (gray wall) and the matching stimulus to create a "white" surface at the matching stimulus, but there always existed differences in luminance. Therefore it might have been quite difficult for the observer to use the wall chromaticity as a cue to make a complete chromaticity match between the adapting field and the matching stimulus.

Figure 6 shows relationships between the illuminant and the matched results in $u'v'$ chromaticity difference from observers' neutral unique-white.

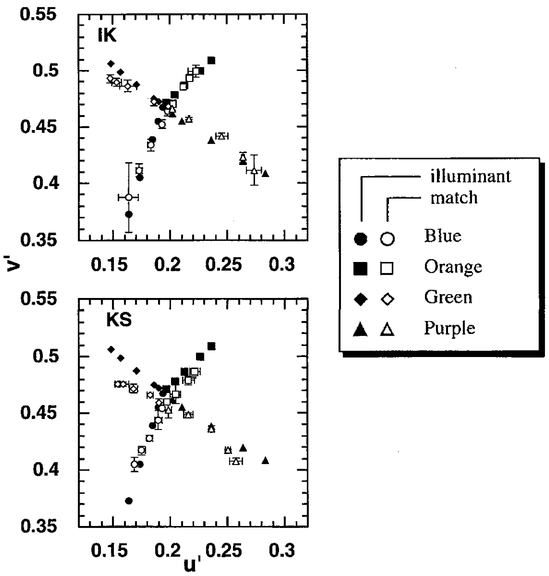

Fig. 5. Results of the surface-match criterion plotted on the CIE $u'v'$ chromaticity diagram, for observers IK and KS. Symbols are the same as those in Fig. 4. Error bars represent ±1 SD. The distributions the matched results (open symbols) cover a larger area than in Fig. 4.

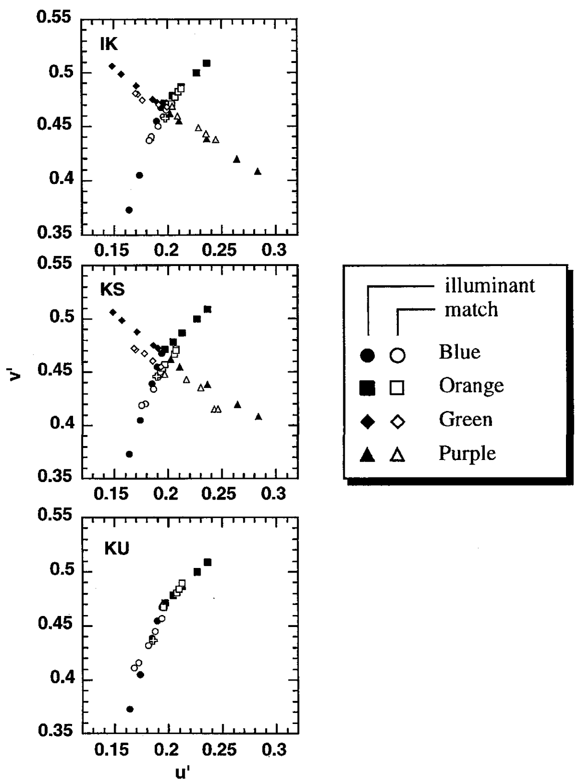

Fig. 4. Results of the apparent-match criterion plotted on the CIE $u'v'$ chromaticity diagram for observers IK, KS, and KU. KU conducted blue and orange filter conditions only. Filled symbols, illuminant chromaticity; open symbols, observers' matches; white cross, each observer's neutral unique-white. The distributions of the observers' matches are smaller than those of the illuminant chromaticity. The magnitudes of the SD's were smaller than or the same as the size of the symbols.

In Fig. 6, horizontal and vertical axes represent $u'v'$ distance from neutral unique-white to the illuminant chromaticity and to the chromaticity of the matched result, respectively. Open symbols represent the relationships between surface-color settings and illuminant chromaticity, and filled symbols represent the relationships between apparent-color settings (i.e., simple unique-white settings) and illuminant chromaticity. The open symbols show that the distances between unique-white under each illuminant and neutral unique-white are not equal to those between illuminant chromaticity and neutral unique-white.

B. Analysis and Discussion

Our results showed that the shift in observers' unique-white settings in $u'v'$ chromaticity became smaller as the room illuminant became saturated. In order to evaluate the change in color appearance and to discount intensity changes, we would have to evaluate the degree of chromatic adaptation. The basic idea of sensitivity change i.e., simple scaling of the responses of each cone class, was first proposed by von Kries[8]; however, the simplest application of the von Kries concept does not fully explain our data, so we define a new parameter—relative cone weights—in the following way.

First we converted all experimental data to L-, M-, and S-cone responses by using the Smith–Pokorny cone fundamentals.[16] The relative sensitivities among these three cone classes are determined arbitrarily; we rescaled the cone responses so that the responses to the neutral unique-white (i.e., unique-white under cone plateau) would be equal among the three cone classes:

$$L_{nw} = M_{nw} = S_{nw}.$$

L_{nw}, M_{nw}, and S_{nw} represent L-, M-, and S-cone responses, respectively, to the neutral unique-white. Using these scaled cone responses, we defined parameters that represent sensitivity balances among the three cone classes as follows:

$$\alpha = M_w/L_w, \qquad \beta = M_w/M_w = 1.0, \qquad \gamma = M_w/S_w.$$

L_w, M_w and S_w represent L-, M-, and S-cone responses, respectively, to the observers' unique-white match under a certain illuminant. If the relative magnitudes among L-, M-, and S-cone responses were the determinants of the color perceptions, changes in balances among L-, M-, and S-cone sensitivities might significantly affect simple apparent color of lights. Alpha and gamma could indicate the change in the sensitivities of L and S cones in comparison with the M-cone sensitivities.

Figure 7 shows the relationships between illuminant chromaticity and observers' settings with respect to alpha and gamma. Horizontal and vertical axes represent logarithms of alphas and gammas calculated from illuminant chromaticities and observer's unique-white results, respectively. The zero point on both axes represents alpha and gamma for neutral unique-white. If the balances between L- and M-cone or S- and M-cone classes have shifted from those of the cone-plateau condition (under which neutral unique-white was measured), alpha and gamma may deviate from 1.

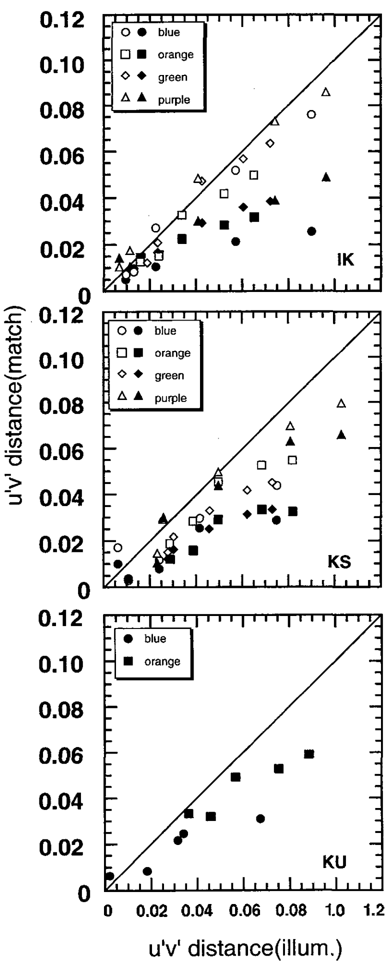

Fig. 6. Distance analysis. Horizontal and vertical axes represent $u'v'$ distance from neutral unique-white to the illuminant color and the matched color, respectively. Open and filled symbols represent results under surface-color and apparent-color settings, respectively. Different symbol shapes represent results in different filter-set conditions. The results for observers IK and KS are for all eight conditions. The results for observer KU's unique-white settings are for blue and orange illuminant conditions only.

Filled symbols represent results under blue and orange illuminant conditions, and open symbols represent results under purple and green illuminant conditions. Differences among panels represent differences between alpha and gamma and among three different observers. A particular pair of alpha or gamma represent a result calculated from a unique-white setting, under one illuminant chromaticity.

Compatible with the argument on the $u'v'$ distance analysis, if the visual system completely adapts to the illuminant, alpha and gamma for observers' settings should fall on a line through the origin with a slope of 1.0. The results show that both alpha and gamma coincide with the diagonal line near the origin, which represents alpha and gamma for neutral unique-white. As the value gets larger, the deviation of the plots from the diagonal line becomes larger. The entire shape of the plot is a shallow S-shaped curve. A comparison of open and filled symbols shows the direction of illuminant-chromaticity change. The two types of symbols show similar shallow S-shaped curves, implying that the direction of the change in illuminant color does not affect the change in the relative cone weight and that relatively low illuminance in the blue-filter-set condition did not have a destructive effect on the experiment.

The relative cone weights represent the balances among L-, M-, and S-cone sensitivities. If the ratios among these three cone classes are the primary factor in the shift in apparent color under chromatic adaptation, the relative cone weights might be able to explain the shift in the apparent color of a colored surface under a colored illuminant.

C. Effect of Luminance Variability

The luminance range of the wall was relatively small, except for the blue filter condition (see Table 1 for details). This was because the D_{65}-simulating fluorescent lamp had less energy in the short-wavelength spectra. Since brightness efficiency is higher for blue than for other colors, the difference in the luminance of the wall did not make a difference in the observers' brightness perception of the wall in the room. The luminance range of the settings was far smaller than the change in adapting field luminance for both apparent and surface matches.

Previous studies[17–19] have reported desaturation of the chromaticities of light, which yielded an achromatic appearance, when the luminance of a test stimulus was raised with respect to the background (adapting stimulus). This effect may cause some desaturation of the unique-white settings of our data. The green and orange illuminants provide nearly constant luminance at the wall, so these conditions are clearly not affected by luminance ratio. However, our results under blue and purple conditions sometimes contain a relatively large luminance-ratio change between the saturation conditions, which may introduce a Helson–Judd effect.

The primary problem was that the luminance ratio between the wall and the test stimulus changed from 7.0 to 17.5 in the blue condition. If a simple relationship between the luminance ratios of the test stimulus and the adapting stimulus determines achromatic appearance, as suggested by Helson and Michels,[18] this relationship could cause the desaturation of unique-white settings at the higher illuminant-saturation levels in our results. In our experiment, luminance ratios between the test stimulus and the wall changed from 7.0 to 17.5 (blue), from 7.0 to 9.0 (orange), from 7.0 to 7.0 (green) and from 7.0 to 11.2 (purple) as the saturation level increased. The orange and the green illuminant conditions contained less change in luminance ratio than did the blue and purple illuminant conditions (or no change), but all hue conditions showed the same degree of desaturation, as shown in Fig. 4. Also, the alpha and gamma plots in Fig. 7, which represent a shift in sensitivity balance among the three cone classes, show identical shallow S-shaped curves in all illuminant directions.

We conducted a supplemental experiment to clarify that our result was not determined primarily by the luminance-ratio change. We fixed the luminance ratio between the wall and the test stimulus to 7.0 at every saturation level of illuminant and measured unique-white settings with one author (IK) and two naïve observers.

Figure 8 shows the results of a new naïve observer, KM, under all four hue directions and five saturation levels of illuminant. Figures 8(a) and 8(b) represent relative cone weights for L-cone (alpha) and S-cone (gamma) classes, respectively. In both panels, horizontal and vertical axes represent illuminant chromaticity and matched unique-white, respectively, as a logarithm of the relative cone weight. These results show the similar shallow S-shaped curves, which indicate desaturation of unique-white settings under higher illuminant-saturation conditions. The general tendency of the results was the same for the other two observers. This implies that the effect of desaturation of unique-white, which appeared as a shallow S-shaped curve in the relative cone weights (Fig. 7), was not affected primarily by luminance variability.

4. EXPERIMENT 2

When the illuminant color was changed, the light reflected on the gray wall was necessarily changed at the same time. Consequently, the color of the wall immediately surrounding the matching stimulus changed. It is

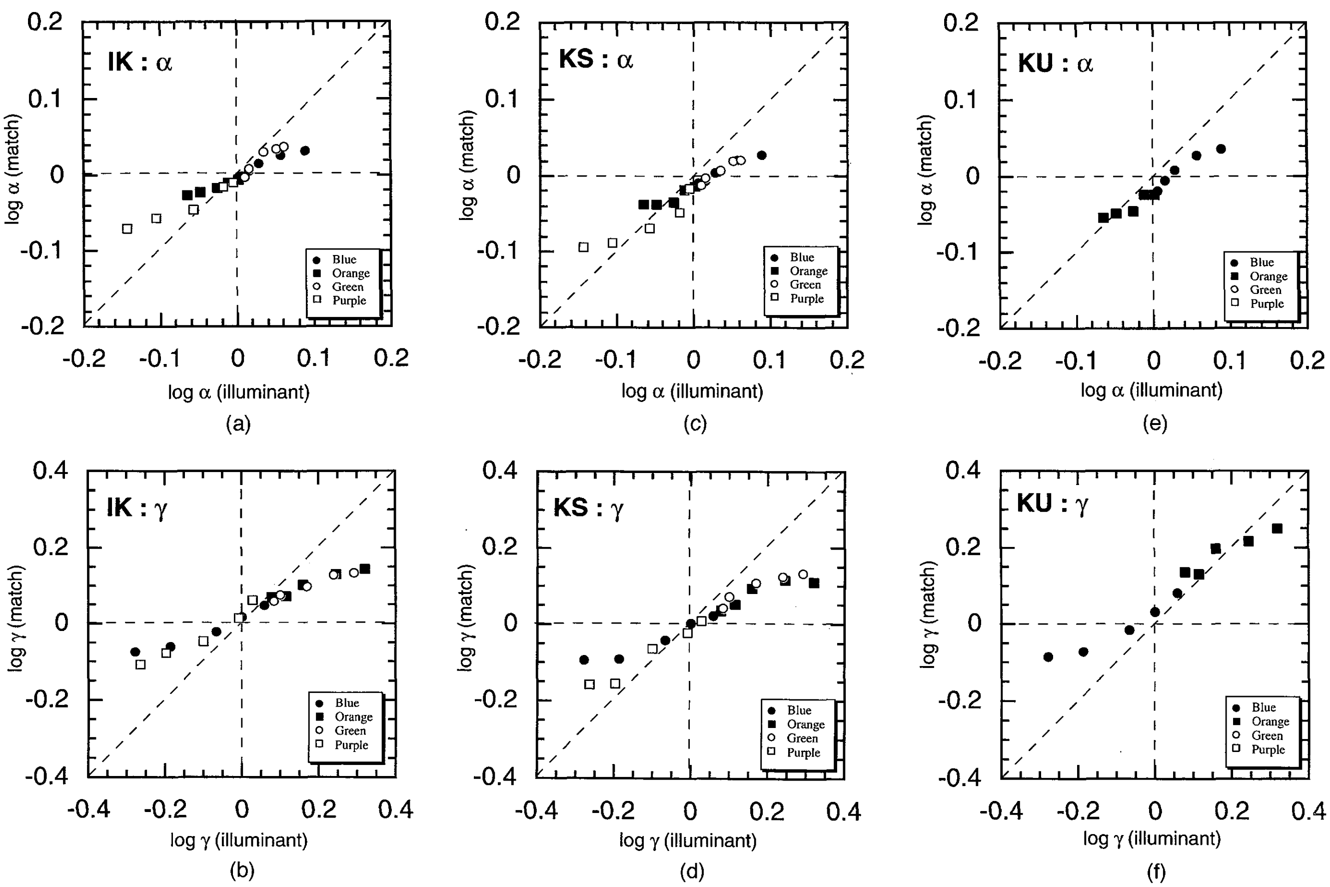

Fig. 7. Relative cone weights with respect to alpha and gamma for three observers: (a), (b) IK; (c), (d) KS; (e), (f) KU. Horizontal and vertical axes represent alpha and gamma derived from illuminant chromaticity (measured at an area adjacent to the test stimulus) and those derived from matched results, respectively. Filled circles and squares represent results under illuminant changes in the D_{65}-blue and D_{65}-orange directions, respectively. Open circles and squares represent results under illuminant changes in D_{65}-green and D_{65}-purple directions, respectively. Both the alpha and the gamma plots show a shallow S-shaped curve. This nonlinearity was common to all three observers.

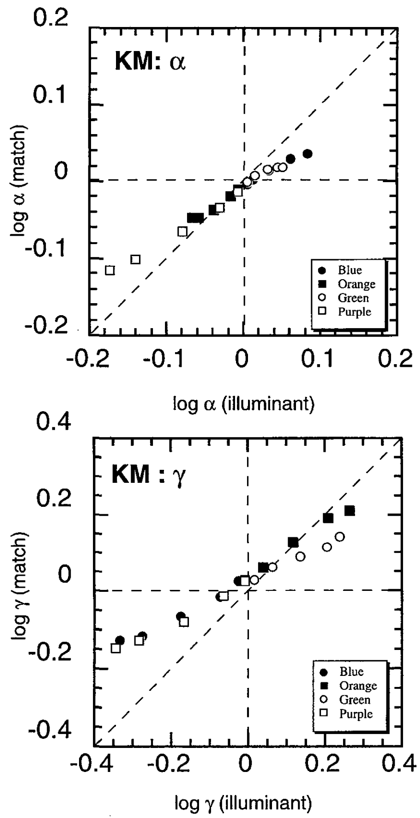

Fig. 8. Alpha and gamma plots for a naïve observer (KM). The axes and the symbols are the same as for Fig. 7. The luminance ratio between the wall and the test stimulus was fixed, but the shallow S-shaped curve still remains.

well known that the chromaticity or the existence of a surround field affects the color appearance of an object's surface at the center of the field.[20,21] In Experiment 1 the change in illuminant introduced a change in color of the immediate surround, and it is quite possible that the change in color of the immediate surround affected the appearance of the central matching stimulus. If a mechanism that uses local contrast information is responsible for the appearance of the test color chip, this might be the primary factor in the shift of unique-white under illuminant-chromaticity change.

To confirm whether the chromaticity of the adjacent area was the primary factor, we conducted another experiment. We presented the observer with one of four kinds of color and a black annulus stimulus as the immediate surround field of the matching stimulus. Each annulus stimulus was a uniformly colored Munsell 15-cm × 15-cm paper (subtended 14 deg × 14 deg of visual angle) with a 5-cm × 5-cm hole (subtended 5 deg × 5 deg) at the center, through which the matching stimulus was viewed. Color-surround stimuli were selected from Munsell papers: 5B 5/8 (blue), 5YR 5/10 (orange), 5G 5/10 (green) and 5PB 5/10 (purple). They were selected so that the chromaticities under D_{65} would be close to the illuminants in Experiment 1 at the maximum saturation of the corresponding hue filter set. The chromaticities of the color-surround stimuli under D_{65} illuminant will be shown below.

When any of the color-surround stimuli (color-surround condition) was presented, the illuminant was fixed to D_{65}; when black (Munsell N 1/) paper was presented as a surround stimulus (black-surround condition), the illuminant was changed in the same manner as in Experiment 1. The black surround was presented for the purpose of measuring the effect of the change in the illuminant on a unique-white hue shift when the effect from the immediate surround was minimized.

Fairchild and Lennie[6] reported that unique-white chromaticities showed little change when the size of the immediate surround was changed from 12 deg to 180 deg. If the effect of the chromaticity of the immediate surround were the primary cause of the shift in the unique-white chromaticity, a 14-deg × 14-deg surround should be large enough to affect the chromaticities of the unique-white settings, and it could be predicted that the amount of unique-white shift on the $u'v'$ chromaticity diagram would be almost the same as under the condition with the most saturated illuminant in Experiment 1.

We used the same apparatus and procedure as in Experiment 1 except that the immediate surround was changed. In the chromatic-surround conditions, the illuminant was fixed to D_{65} and the annulus-surround stimulus was changed among the four colors. Under the black-surround condition, the surround stimulus was fixed to N 1/ but the illuminant was changed in four directions, as was the case in Experiment 1. Two observers, IK and KS, served in both conditions.

A. Results

Figure 9 shows the results of unique-white settings under D_{65} illuminant with four chromaticities of surround

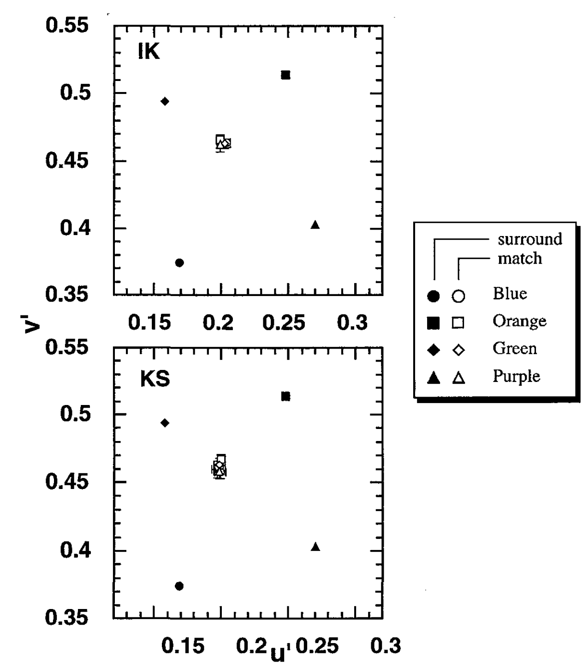

Fig. 9. Unique-white settings (apparent-color settings) of observers IK and KS with color-surround stimulus under D_{65} illuminant. Filled symbols represent chromaticities of blue, orange, green, and purple surround under D_{65} illuminant. Open symbols represent chromaticities of the matched results under the corresponding color-surround stimulus. Error bars represent SD of the average across 25 settings under each illuminant condition.

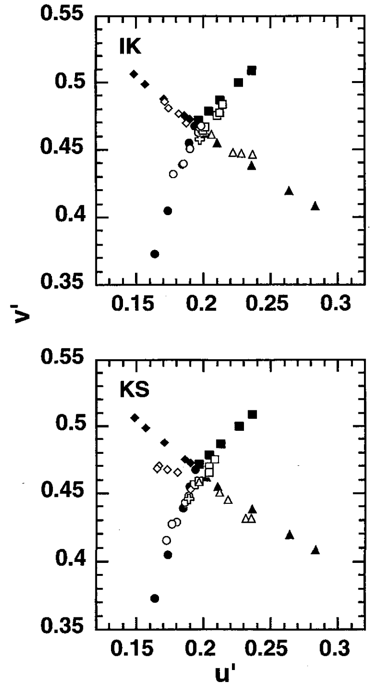

Fig. 10. Unique-white settings with black-surround stimulus under various colors of illuminant for observers IK and KS. Filled symbols represent chromaticities of illuminants in the blue, orange, green, and purple directions. Open symbols represent chromaticities of the matched results under the corresponding illuminant color. Error bars represent the SD of the average across 25 settings under each illuminant condition.

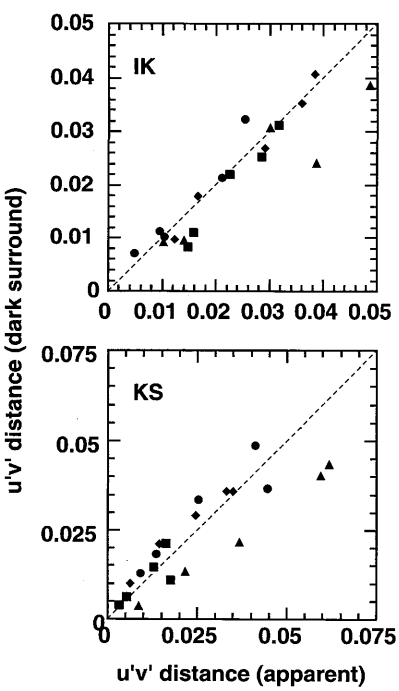

Fig. 11. Distance-analysis results under the black-surround-condition, for comparison with those under the normal condition (Fig. 4) for observers IK and KS. The results showed no significant statistical difference ($p > 0.05$) for either observer.

stimulus, i.e., the chromatic-surround condition, on the $u'v'$ chromaticity diagram. Open symbols show the chromaticities of the results matched with the four chromatic-surround stimuli, and filled symbols show the chromaticities of the surround stimuli. The error bars show ± 1 SD of 15 settings for each surround stimulus.

When Fig. 9 is compared with Fig. 4, we see that the effect on the change in the unique-white setting by the change in the immediate-surround chromaticity is far smaller than the change in the chromaticity of the wall that is produced by the illuminant-chromaticity change.

Figure 10 shows the results of unique-white settings with the black-surround stimulus under various chromaticities of illuminants on the $u'v'$ chromaticity diagram. The meanings of the symbols are the same as those in Fig. 4.

The results of the unique-white settings under the black-surround condition are generally similar to the previous results, where the effects of the immediate surround were not minimized (Fig. 4). Figure 11 compares the results in $u'v'$ distances of unique-white and neutral unique-white settings.

It has been statistically confirmed by analysis of variance that there is no significant difference between the conditions with and without black-surround stimulus ($p > 0.05$ for both observers). Figures 10 and 11 displayed results under different stimulus arrangements; however, both results suggest that regardless of the immediate-surround color of the test color chip, the observer's unique-white settings were determined mainly from the chromaticities of the illuminant.

B. Discussion

In chromatic-surround conditions the results showed that the change in the immediate-surround chromaticity under a constant illuminant did not change unique-white perception. We can derive two facts from these results. First, under our experimental condition, the effect of chromatic induction from the immediate-surround stimulus to the unique-white settings was quite low. The corollary is that the change in illuminant color, not the change in the color of the adjacent area, was the primary factor affecting the change in unique-white settings that we measured in Experiment 1. This implies that the change in illuminant color was effective for the change in sensitivity of the visual system, and it was measured with the stimulus conditions that we employed.

5. GENERAL DISCUSSION

A. Previous Studies

Many studies have been conducted on the establishment of corresponding color models, and most of them dealt with shifts in color appearance after the changes in illuminant colors. The models by Hunt[22] and Nayatani *et al.*[23] are among the most well-known ones. However, their models assumed *complete* adaptation, i.e., a white object appears white under any kind of illuminant; but incomplete chromatic adaptation, as observed in our experiment, was not taken into account. Fairchild proposed a modified version of the Hunt model by introducing partial chromatic adaptation, named RLAB.[24] Nayatani's model also introduced a term defining incomplete chromatic adaptation after recent modification. These models are basically designed to predict corresponding colors between two illuminant conditions. The parameters are defined to minimize the rms error for previously measured data, and these authors scarcely mention mechanistic aspects of color constancy.

B. Difference between Two Classes of Color Constancy

We introduced the notion of two classes of color constancy in this paper: partial color constancy and complete color constancy. We simplified the definitions of these two classes of color constancy by using two kinds of color perception, specifically, simple apparent color perception (i.e., apparent-color perception) and color perceived as a surface attribute (i.e., surface-color perception) of an object. These two kinds of color perception have been reported by some researchers for many years. The most well-known examples were termed hue/saturation match and paper match in the experiments by Arend and Reeves.[2] We might assume that a boundary between these two classes of color constancy can be defined by measuring the extent of chromatic adaptation of the visual system. If the visual system were able to adapt completely to the chromaticity of an illuminant, the observer's apparent-color perception and surface-color perception of an object would be consistent; otherwise, they would be inconsistent. We suggest that the discrepancy between the two classes of color perception caused the difference between the two classes of color constancy. This notion might be quite useful in explaining some of the arguments about the results of color-constancy experiments in previous studies.

C. Effect of Illuminant

The results of Experiment 2 showed that the room illuminant was a stronger factor than the chromaticities of the immediate surround. It seems reasonable to assume that areas closest to a test stimulus should exert the strongest effect on the color appearance of the stimulus. However, our results showed that the immediate surround had little effect on unique-white settings. This might be partly because the adapting field (the walls, in our case) had a larger area than the surround stimulus ($14 \text{ deg} \times 14 \text{ deg}$). But this could explain our data only if an area could affect the color appearance of the test stimulus equally, regardless of the distance from the test stimulus.

If there were a mechanism that accumulated chromatic information evenly across the view field, it would take into account any changes in color or luminance at the far periphery. Land's retinex algorithm[25,26] could be a candidate for this kind of mechanism. The very early version of Land's retinex model applied equal weight to changes at each edge in the visual field when luminance contrasts at these edges were accumulated to produce an output.[25] Later to make the retinex model consistent with physiological data, he introduced a weighting function to give a larger weight to the closer object.[26] Some recent studies have reported that adjacent chromatic objects and objects with larger areas are not the only factors in the shift in color appearance.

Therefore it may be quite unnatural to attempt to explain color appearance only as a function of immediate-surround colors. In daily circumstances, every incident light from the whole field of view to the retina might be taken into account when we perceive the color of an object. In the apparatus of the present study, observers were provided with more-general lighting, simulating more closely everyday circumstances, in comparison with experiments with smaller stimuli presented in an otherwise completely dark room.

Recently Brainard and his colleagues reported on many aspects of the effects of an illuminant on color appearance,[10,11] and Brainard proposed a model that provides *estimation of illuminant*, not individual color chip, as an output.[11] These studies share some common ideas with the work of Ikeda and his colleagues[27,28] and our own. Since the human visual system is not able to measure the precise spectrum of the illuminant or of reflected light, the observer has to make an estimate of the illuminant and of any objects, that would be maximally plausible to the observer. However, this process contains a somewhat circular problem. The color appearance of object surfaces would be recognized after the illuminant was determined in the observer's visual system, but the illuminant might itself be estimated, on the basis of the color of the lights from the objects in the field of view. The point is that the color appearance of the object surfaces would be determined after illuminant estimation, but illuminant estimation must be based on the color of the object surfaces. We do not have enough data to address this problem, but Brainard's equivalent illuminant model,[11] or its extension, could be a solution.

It might be reasonable to assume that the lights in the observer's field of view may affect the state of the observer's visual system. In our experiments the luminance distributions should show little change across the visual field among filter sets, because the ratios of the intensities are determined only by the ratio of the reflectance of the object surfaces and the spatial arrangement of objects and the illuminant. Therefore the only factor that changed drastically across the conditions was the illuminant color. We characterized these lights with a single parameter, the chromaticity of the illuminant. This may not be the only factor, but it represented well the characteristics of the shift in the unique-white setting of the observer after a considerable period of adaptation to the illuminant chromaticities. However, our study is still far from providing conclusive information on how observers went about estimating illuminants.

6. CONCLUSIONS

First we succeeded in stabilizing the observer's state of chromatic adaptation by using a whole-room stimulus as an adapting field. Second, the results of the unique-white settings showed that the observer's state of chromatic adaptation did not follow the change in illuminant color completely. Finally, the change in the observer's state of adaptation was analyzed by using balances among three cone classes, and the results showed that a shallow S-shaped curve depicts a general tendency in the relationship between the observer's state of chromatic adaptation and the illuminant chromaticity.

ACKNOWLEDGMENTS

We thank David H. Brainard, James Bebko, and two anonymous reviewers for their helpful feedback on our manuscript.

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