Estimating illuminant color based on luminance balance of surfaces

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To accomplish color constancy the illuminant color needs to be discounted from the light reflected from surfaces. Some strategies for discounting the illuminant color use statistics of luminance and chromaticity distribution in natural scenes. In this study we showed whether color constancy exploits the potential cue that was provided by the luminance balance of differently colored surfaces. In our experiments we used six colors: bright and dim red, green, and blue, as surrounding stimulus colors. In most cases, bright colors were set to be optimal colors. They were arranged among 60 hexagonal elements in close-packed structure. The center element served as the test stimulus. The observer adjusted the chromaticity of the test stimulus to obtain a perceptually achromatic surface. We used simulated black body radiations of 3000 (or 4000), 6500, and 20000 K as test illuminants. The results showed that the luminance balance of surfaces with no chromaticity shift had clear effects on the observer's achromatic setting, which was consistent with our hypothesis on estimating the scene illuminant based on optimal colors. © 2012 Optical Society of America

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1. INTRODUCTION

The human visual system can perceive an invariant surface color despite changes of the illuminant. This ability of human color vision is known as color constancy. Recently Foster reviewed most of previous studies on color constancy [1]. To accomplish color constancy the human visual system must in some sense discount the illuminant color's influence on the light reflected from the surface.

A variety of strategies have been proposed for discounting the illuminant using the chromaticity and luminance distributions of natural scenes [1]. The 'Gray World' hypothesis [2,3] is a typical theoretical framework. In one form of this hypothesis, the chromaticity of the average spectral energy distribution over all of the scene surfaces is considered as a cue for estimating the illuminant. This amounts to assuming that the spatial average of the scene reflectances is the same for all scenes, for example a fixed spectrally neutral gray. The chromaticity of the average of the retinal image therefore follows the chromaticity of the scene illuminant. Hence, it could be a cue for the scene illuminant. But this method using the chromaticity of the average of the retinal image fails when the 'Gray World' assumption fails [4]. For instance, the average reflectance across a scene made up of reddish surfaces is not neutral. Therefore this scene under a white illuminant and a scene with neutral surfaces under a reddish illuminant may generate the same chromaticity of the average in the retinal image.

Golz and MacLeod proposed a solution for this problem [5]. They pointed out that not only the chromaticity of natural scenes but also the relative luminance of different colors within the scene could be a cue for illuminant estimation. They analyzed the chromaticity and luminance distribution of a set of 12 natural scenes collected by Ruderman *et al.* [6] They found that the luminance-chromaticity correlation, assessed for the set of surfaces within the scene, varies systematically between those scenes that have predominantly greenish surfaces and those that have predominantly reddish surfaces, yet, it typically remains almost constant despite changes of scene illuminant.

Thus if a predominantly reddish scene and a predominantly greenish one, under differently colored illumination, happen to produce retinal images of the same mean chromaticity, we can still expect to distinguish between them on the basis of their luminance-correlation values. Golz and MacLeod showed experimentally that the human visual system made appropriate use of these scene statistics for illuminant estimation [5].

Many other models have been proposed for illuminant color estimation based on statistics of the surface reflectances and the illuminant. Maloney and Wandell showed that a trichromatic visual system can exactly recover surface reflectances when reflectances in the visual environment are drawn by a linear model with two degrees of freedom [7]. In Bayesian models, internalized assumptions about the statistical structure of scenes are used to find the illuminant that maximizes the likelihood of the totality of image data [8]. Forsyth [9] and Finlayson *et al.* [10] proposed gamut matching methods that exploited the distribution statistics of surface colors in the image.

The gamut attainable for a particular illuminant is defined by optimal colors. Optimal colors, more exactly termed optimal surfaces or optimal spectral reflectance functions, have two abrupt spectral transitions between zero and 100% reflectance, and hence have the maximum luminance attainable at their chromaticity [11,12]. The actual chromaticities of the proximal stimuli associated with optimal colors shift with the chromaticity of the illuminant, with ideal white surface as a special case taking on exactly the chromaticity of the illuminant.

Optimal colors, if present, are in principle especially helpful for estimating the illuminant. The simplest algorithm of all is to identify the brightest scene element as white [13–15]. If a white is not guaranteed to be present, an alternative simple algorithm based on optimal colors is to fit the optimal color surface to three candidate optimal colors in the scene. In cone excitation space, the optimal color surface is roughly conelike and is moved around without drastic change of shape by a change of illuminant. This cone can be translated in chromaticity and 'dropped' by lowering the assumed illuminance, until it is supported at three points by three of the surface colors in the given image, which (leaving aside ties) are the only three candidate optimal colors. Sources and highlights have to be first rejected, a process necessary in any algorithm of this general sort. The observer can estimate three parameters of the optimum luminance surface from the luminance at these three limiting (presumed optimal) color points.

The 'three-surface' algorithm is very much like the well-known proposal in Land's early Retinex model [15], where the highest luminance in the image received by each cone type is taken to represent 100% reflectance in a corresponding spectral band. It works perfectly provided there are three or more optimal colors, but if there are not, and nonoptimal colors are used in place of optimal ones, the resulting estimate will be in error.

Figure 1 shows the chromaticity and luminance distribution of all optimal colors, under 20000 K, 6500 K, and 3000 K illuminants, in a luminance-redness cross-section of cone excitation space. The stimuli were generated by incrementing each of the two spectral transition wavelengths in steps of 5 nm and plotting a point for each surface so generated. We adopted Stockman, MacLeod, and Johnson spectral sensitivity of L, M, S cones (1993) to calculate MacLeod–Boynton (M-B) chromaticity coordinates and luminance [16,17]. With suitable scaling of the cone excitation values L and M, luminance is defined as $L+M$ and a chromaticity coordinate corresponding (loosely) to redness can be defined as $L/(L+M)$; a second chromaticity coordinate capturing blueness is given by $S/(L+M)$ in the M-B chromaticity diagram. With the blueness coordinate (or the S cone excitation) appropriately normalized to white, these equations give the chromaticity coordinates of (0.7, 1) to the equal-energy white.

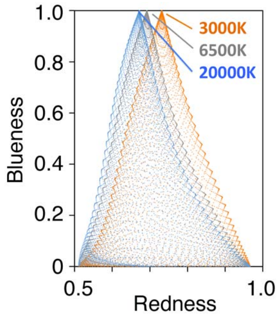

Fig. 1. (Color online) The chromaticity and luminance distribution of all optimal colors under 20000 K, 6500 K, and 3000 K illuminant. The abscissa represents redness in the MacLeod–Boynton chromaticity diagram.

The projections of optimal colors onto the luminance-redness plane fill a cone-shaped region. Under a change of illuminant, the peak, representing full white, follows the chromaticity of the illuminant, while the envelope formed by more colorful and less luminous colors undergoes a similar but lesser shift, as if anchored at two points on the horizontal axis, which are the luminance-invariant chromaticities of monochromatic reflectances at the wavelengths of greatest and least redness.

This helps to clarify the basis for the illumination-invariant luminance-chromaticity correlation noted above: for colors of not too low reflectance and luminance, the window across which this correlation is computed shifts along with the illuminant chromaticity; to a first approximation a change of illuminant causes a uniform chromaticity shift, leaving the correlation unaffected. Here, we note that if the chromaticity and luminance distribution of natural scenes behaves in approximately the same way as those of optimal colors, the visual system can usefully refer to the corresponding optimal-color distribution to estimate the chromaticity of illuminant, applying the 'three-surface' algorithm described above. Even if the three candidate colors are not in face optimal ones, they may fall below the optimum luminance in a statistically predictable way and the basic three-surface algorithm can be amended accordingly.

To assess the feasibility of such an algorithm, we investigated the relation between the luminance versus chromaticity distribution of natural surfaces and that of optimal colors. We used a database of spectral reflectance of 574 haphazardly selected natural objects measured by Brown [4]. This database consists mainly of flowers, leaves, barks, and ground samples. The results are shown in Figs. 2(a), (b), and (c). For near-whites and reddish colors, the distributions for natural colors approach the envelope of optimal colors closely, but for colors of lower redness value the natural colors drop away considerably below the envelope. Notably, however the distribution of natural colors in this cone excitation space resembles that of optimal colors in being invariant with illuminant chromaticity except for a shift.

From these results, it seems that the joint distribution of chromaticity and luminance in natural scenes has a somewhat predictable relationship to that of optimal colors. Uchikawa *et al.* suggested that the visual system might make an estimate of the optimal-color luminance and they found this to be closely related to the upper limit of luminance of a colored light to be perceived as a surface [18]. Speigle and Brainard tested whether the visual system could estimate a reflectance spectrum that was outside the optimal-color surface and proposed a simple linear-model to predict that a color stimulus appears self-luminous when it is not consistent with any physically realizable surface [19]. Hence, there is a possibility that visual system implicitly internalizes and uses the environmental regularities that are reflected in the optimal-color distribution for illuminant estimation with natural scenes.

In an analysis similar to ours, Tominaga *et al.* described an algorithm that classified scene illuminants in color images [20]. They created illuminant gamuts for various blackbody radiations with a database of surface spectral reflectances in the (R, B) sensor plane. This (R, B) plane preserves not only one dimension of chromaticity, but also relative intensity information of the surfaces in the image. It was shown that the

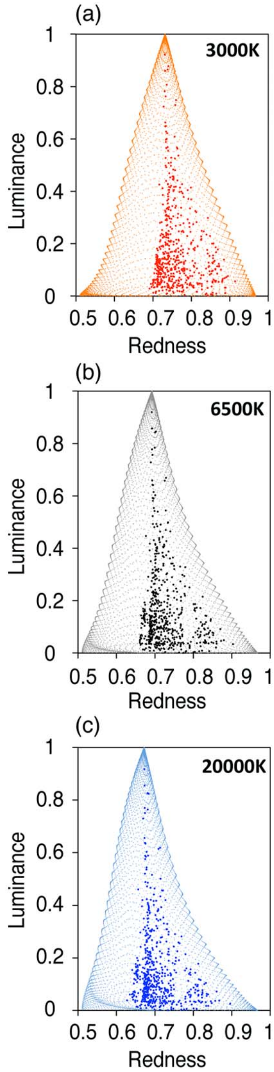

Fig. 2. (Color online) The chromaticity and luminance distribution of optimal colors and 574 natural objects measured by Brown under (a): 20000 K , (b): 6500 K, and (c): 3000 K illuminant. The abscissa represents redness in the MacLeod–Boynton chromaticity diagram.

correlation between image data and an illuminant gamut, calculated in the (R, B) plane, could be used as a good index for identifying the illuminant in the image. The simulated image data showed that the brighter regions in an image are in principle more diagnostic than the dimmer regions for classifying the illuminant color. This is consistent with their (and our) theoretical framework, since the brighter scene elements constrain the gamut more tightly than the dimmer ones.

What remains to be seen is whether human subjects act in accordance with these statistical constraints. We performed experiments to investigate this. We asked whether the visual system can exploit the luminance balance of surface colors as the sole cue for illuminant estimation and to what degree the luminance balance affects illuminant estimation when both chromaticity and luminance are allowed to vary with illumination in a natural way.

We based our choice of stimuli on optimal colors as described below and controlled their chromaticity and luminance to simulate the consequences of changing illuminants. In experiment 1 we changed the luminance balance of surrounding colors to reflect various illuminant conditions, but with their chromaticities kept constant. In experiment 2 we changed the chromaticities of surrounding colors to reflect various illuminant conditions, but with their luminance balance kept constant. The results indicated that the visual system's estimate of illuminant color could be influenced by luminance balance alone to some degree, but less markedly than by chromaticity shift only. In experiment 3, as a control condition, both the chromaticity and the luminance of surrounding colors were changed with simulated illumination. Experiment 4 was designed to tested a simple alternative hypothesis often identified with the 'Gray World' assumption: that the visual system evaluates the mean of the L, M, S cone responses to the surrounding colors and bases its illuminant estimate on that alone instead of making computations based on the luminances and chromaticities of the context colors. In all experiments, we use the test chromaticity chosen as achromatic as a proxy for estimated illuminant chromaticity.

2. METHODS

A. Apparatus and Stimuli

The stimulus was presented on a 22" CRT monitor (Iiyama, HM204DT A, 1024×768) controlled by the CRS VSG2/4f graphic board. The stimulus simulated surface colors. We used six context colors, bright and dim red (R), green (G), and blue (B) colors, the luminance and chromaticity of which were systematically chosen in the experiments, in order to evaluate separately luminance and chromaticity effects of surrounding colors on illuminant estimation.

Figure 3 shows an example of the stimulus spatial configuration used in the experiments. The surrounding field consisted of 60 hexagons of bright and dim R, G, B context colors. Ten of each bright and dim R, G, B colors were arranged so that the same color was not aligned in adjacent positions with the same eccentricity from the center. The center hexagon was used as the test field. The observer controlled the chromaticity of this field. Each hexagon subtended 2 deg diagonally, and the whole stimulus subtended 14 deg and 15.6 deg in the vertical and horizontal directions, respectively. The maximum luminance used for the stimulus was 28.6 cd/m^2 for the equal-energy white. This luminance was a half of the maximum luminance available of the CRT monitor. We designated hereafter the stimulus luminance as the ration to the CRT maximum luminance, i.e., 28.6 cd/m^2 as

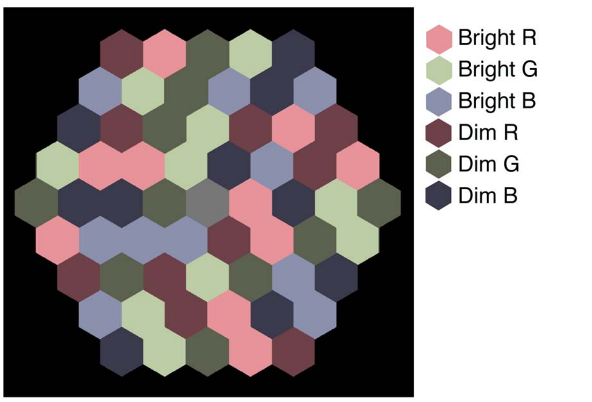

Fig. 3. (Color online) An example of the stimulus spatial configuration used in the experiments. The surrounding field consisted of 60 hexagons of bright and dim R, G, B colors. The center hexagon was used as the test field.

Table 1. Combination of Test Illuminants for Separately Illuminated Surrounding Bright and Dim R, G, B Colors, with Numbers Representing the Conditions of Illuminants for Bright and Dim R, G, B Colors

		Bright R, G, B colors		
		20000 K	6500 K	3000 K
Dim R, G, B colors	20000 K	1	2	3
	6500 K	4	5	6
	3000 K	7	8	9

0.5. The observer saw the stimulus in a dark room with the viewing distance of 114 cm.

B. Procedure

The observer's task was to adjust the chromaticity of the test field so that it appeared as an achromatic surface. We used simulated 3000, 6500 and 20000 K black body radiations as test illuminants. The test illuminants were chosen independently, and applied separately, to the bright R, G, B colors and the dim R, G, B colors. Table 1 shows the combinations of illuminants, indicated by the numbers, for bright and dim R, G, B colors. Number. 2, for instance, represents the condition where bright R, G, B colors are illuminated by 6500 K and dim R, G, B colors are illuminated by 20000 K.

We selected and fixed the luminance and chromaticity of surrounding R, G, B colors in each experiment. The luminance of the test field was chosen from three fixed levels, 0.1, 0.25, and 0.5.

In a session, the observer adapted to the equal-energy white with luminance 0.5 for 2 min before the first trial started. In a trial, the stimulus was steadily presented while the observer adjusted the chromaticity of the test field. One of the three luminance levels of the test field was chosen at random for a trial. In a block, the same six R, G, B colors were presented, but with different spatial arrangements. A block consisted of 15 trials (three test luminance level $\times$ 5 repetitions). The observer adapted to the white between blocks. Nine blocks were carried out with different combinations of illuminants in a session. The observer performed four sessions in an experiment with the total of 20 repetitions for the same stimulus condition.

C. Observers

Two observers participated in experiments 1, 2, and 3 and four observers participated in experiment 4. All observers were males with normal color vision, as tested by Ishihara plate.

3. EXPERIMENT 1

A. Surrounding Stimulus Condition

In experiment 1, we examined the effects of luminance balance of surrounding colors on the observer's achromatic setting. The chromaticities of the surrounding R, G, B colors were kept constant for all illuminant conditions. Table 2 shows *M-B* chromaticity coordinates and luminances of the R, G, B colors. The chromaticities were the same for bright and dim colors. The mean chromaticity of the six colors was (0.7, 1.0). The luminances of the bright R, G, B colors were set in proportion to those of optimal colors under the

Table 2. MacLeod–Boynton Chromaticity Coordinates and Luminance of R, G, B Colors Used in Experiment 1 (Luminance: 0.5 = 28.6 cd/m^2)

		M-B Chromaticity		Luminance		
				Illuminant		
		Redness	Blueness	20000 K	6500 K	3000 K
Bright colors	R	0.800	0.350	0.173	0.219	0.317
	G	0.670	0.150	0.434	0.418	0.351
	B	0.630	2.50	0.383	0.224	0.0747
Dim colors	R	0.800	0.350	0.0345	0.0439	0.0634
	G	0.670	0.150	0.0869	0.0837	0.0702
	B	0.630	2.50	0.0765	0.0448	0.0149

test illuminant. The luminances of dim R, G, B colors was set at 20% luminance of bright R, G, B colors.

Figure 4 shows the *M-B* chromaticities of illuminants, 20000 K (open diamond), 6500 K (open circle), and 3000 K (open square); the mean chromaticities of the surrounding R, G, B colors, which overlap at the white point (redness, blueness) = (0.7, 1) and the chromaticities of the means of L, M, S responses of those surrounding colors.

B. Results

Figures 5(a) and (b) show the mean achromatic settings for observers KU and YK, respectively, shown in the *M-B* chromaticity diagram, in conditions 1 (diamond), 5 (circle) and 9 (square). The small dots show the observer's settings for each trial. The open symbols represent the positions of illuminants, 20000 K (diamond), 6500 K (circle), and 3000 K (square). Left, middle, and right panels in Figs. 5(a) and (b) correspond to the test luminances $L = 0.1$, 0.25, and 0.5, respectively. It is shown in Figs. 5(a) and (b) that the achromatic setting points consistently shift with the illuminants for both observers. These shifts are less than the physical illuminant differences, but they clearly indicate that the visual system's estimate of the illuminant color can be influenced to some degree by a change in luminance balance of surrounding colors alone, even when the chromaticity of surrounding colors does not change.

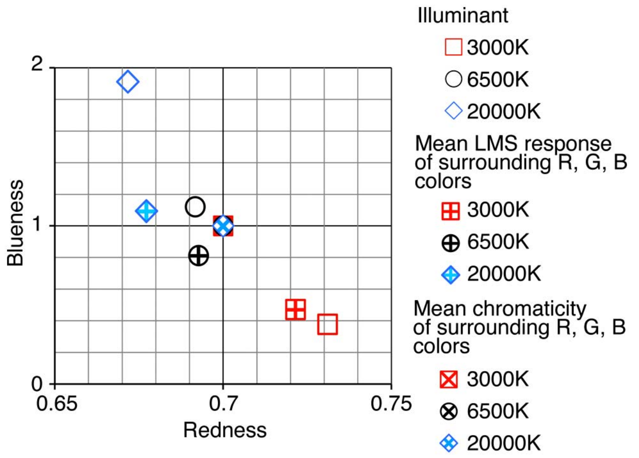

Fig. 4. (Color online) Chromaticities of test illuminants, mean chromaticities of surrounding R, G, B colors and means of L, M, S cone responses of surrounding R, G, B colors used in experiment 1. Stimulus condition: 1 (20000 K), 5 (6500 K) and 9 (3000 K).

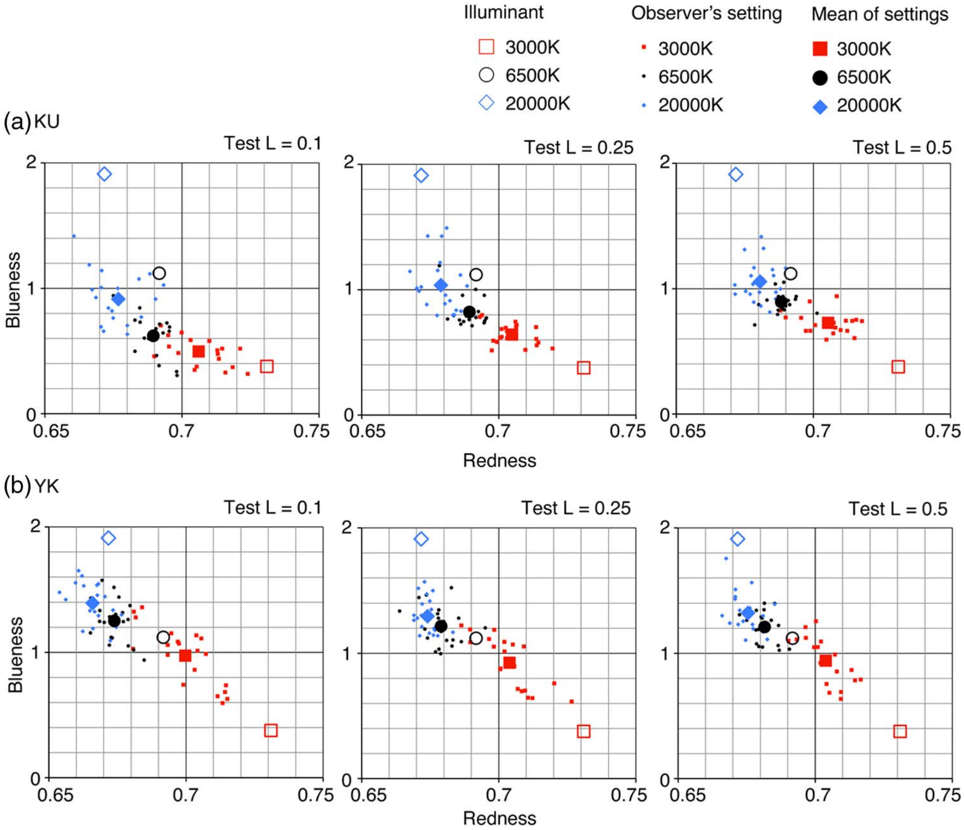

Fig. 5. (Color online) Observer's achromatic settings obtained in experiment 1 in three test luminance conditions ($L = 0.1$, 0.25, and 0.5) for observer (a) KU and (b) YK. Closed symbols represent means of settings and small dots show settings for each trial. Stimulus conditions: 1 (diamond), 5 (circle), and 9 (square). Positions of illuminant: 20000 K (open diamond), 6500 K (open circle), and 3000 K (open square). Stimulus condition: 1 (20000 K), 5 (6500 K) and 9 (3000 K).

Effects of test luminance are small or absent. With increasing test luminance the mean settings are shifted slightly, but significantly, in the blueness direction for KU, and in the redness direction for YK, except in condition 1 for YK (MANOVA, $p < 0.01$ for conditions 1 and 5 (KU) and conditions 5 and 9 (YK), $p < 0.05$ for condition 9 (KU)). However, the mean settings in conditions 1 and 9 do not differ significantly from those in condition 5 (MANOVA, $p > 0.1$ in all conditions for both observers). This might indicate that the shifts of observer's settings with test luminance are not caused by differences in estimated illuminant color but merely by some observer's criterion shift. It is likely that the test stimulus luminance does not have any considerable effect on the observer's achromatic setting. In other stimulus conditions we found similar results with no systematic shift of observer's settings in the test luminance conditions.

In Fig. 4 it is shown that the change in luminance balance causes a shift in the chromaticities of the means of L, M, S cone responses to the context colors in the direction of the simulated illuminant chromaticity, but of lesser amount (while the mean chromaticities of the surrounding R, G, B colors are constant by design). The observer's mean achromatic settings are close to, but not coincident with, the chromaticities of the mean cone responses. This could suggest that the observer does not use the luminance balance of R, G, B colors, but rather the means of L, M, S cone responses to obtain the illuminant estimate and determine the achromatic setting. This possibility will be examined later in experiment 4.

In order to make the M-B diagram approximately uniform, so that equal chromatic differences are perceived in equal steps in any direction in the diagram, we normalized the redness and blueness axes by using the standard deviation, SD, of observer's settings along each axis. The chromaticity coordinate, redness and blueness, of the mean was divided by SD along redness and blueness axis, respectively. We used this normalized M-B chromaticity diagram to calculate color constancy index, CI. The CI is defined by the Euclidean distance, d_s, between the mean setting under a test illuminant, ST (= 20000 K or 3000 K), and that under the white illuminant, 6500 K, divided by the distance, d_i, between the position of a test illuminant, PT (= 20000 K or 3000 K), and that of the white illuminant, 6500 K, shown by the equation as follows:

$$\mathrm{CI} = d_s(\text{ST-6500 K})/d_i(\text{PT-6500 K}).$$

Figure 6 shows CIs, averaged across all test luminance conditions, for two observers. The surrounding stimulus conditions are 1-5-9 (filled circle), 4-5-6 (filled triangle) and 2-5-8 (open triangle). When the luminance balance changed in both bright and dim colors (conditions 1-5-9), CIs were highest (approximately 0.3 for KU, 0.5 at 3000 K, and 0.2 at 20000 K for YK). CIs became smaller in the condition that the luminance balance changed in bright colors only (conditions 4-5-6) and they were smallest when the luminance balance changed in dim colors only (conditions 2-5-8). These results indicate that the luminance balance cue was most effective when applied

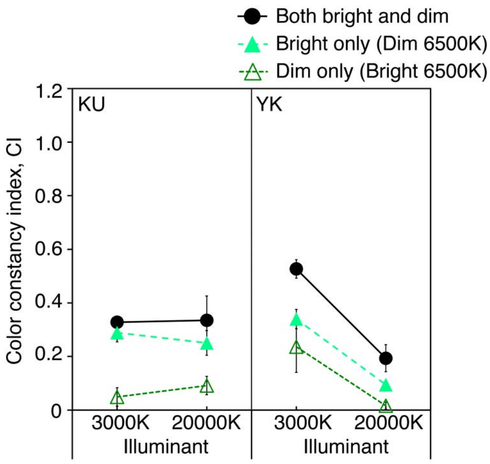

Fig. 6. (Color online) Constancy indexes (CIs) for two observers obtained in experiment 1. Conditions: 1-5-9 (filled circle), 4-5-6 (filled triangle) and 2-5-8 (open triangle).

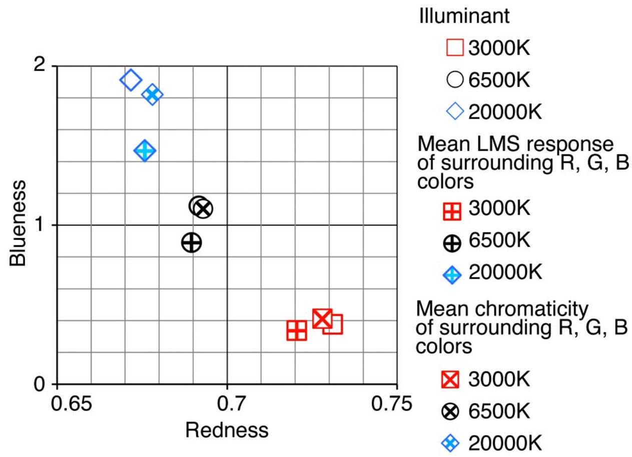

Fig. 7. (Color online) Chromaticities of test illuminants, mean chromaticities of surrounding R, G, B colors and means of L, M, S cone responses of surrounding R, G, B colors used in experiment 2. Stimulus condition: 1 (20000 K), 5 (6500 K), and 9 (3000 K).

consistently to bright and dim colors and was more effective when applied to bright colors only than when applied to dim colors only.

4. EXPERIMENT 2

A. Surrounding Stimulus Condition

In experiment 2, we studied effects of chromaticity on observer's achromatic settings while the luminance balance of surrounding colors was kept constant. The R, G, B samples were determined in such a way that they had optimal-color reflectance with *M-B* chromaticities, (0.780, 0.490), (0.665, 0.270), and (0.655, 2.24), respectively, under the equal-energy white. When these R, G, B samples were placed under the test illuminants both their chromaticities and luminances changed. We used these chromaticities for the R, G, B colors under the corresponding test illuminants. To make the luminance balance constant across all illuminant conditions we adjusted the luminance of bright R, G, B color so that each of them took the lowest value in all values calculated above under the three illuminants. This is because if we did not use the lowest luminance value, then their luminances might exceed the optimal-color luminance when the test illuminant changes. Table 3 shows the chromaticity and luminance of the R, G, B colors used in experiment 2.

Figure 7 shows the mean chromaticities of the surrounding R, G, B colors and the chromaticities of the means of L, M, S responses of those context colors in experiment 2 in addition to the *M-B* chromaticities of the illuminants, 20000 K (open diamond), 6500 K (open circle,) and 3000 K (open square).

B. Results

We calculated CIs using the mean chromaticity of the observer's achromatic settings in the same way as in experiment 1. Figure 8 shows CIs obtained in experiment 2. The symbols represent the same stimulus conditions in experiment 1 (Fig. 6). The results indicate that CIs obtained in the chromatic shift condition are larger than CIs in luminance balance condition in most cases. It is also shown that the bright colors are more influential in illuminant estimation than the dim colors. When both bright and dim colors changed the effect was largest.

5. EXPERIMENT 3

A. Surrounding Stimulus Condition

In experiment 3, both the chromaticity and the luminance of the surrounding R, G, B colors changed with the test illuminant. This condition can be considered as a natural condition, or a control condition, because this condition simulates the effects of a change in illuminant color temperature on both chromaticity and luminance balance in a natural and mutually consistent way. The R, G, B samples were determined in the same way as in experiment 2, but the R, G, B optimal-color

Table 3. MacLeod–Boynton Chromaticity Coordinates and Luminance of R, G, B Colors Used in Experiment 2 (Luminance: 0.5 = 28.6 cd/m^2)

			M-B chromaticity					
			Illuminant					
			20000 K		6500 K		3000 K	
		Luminance	Redness	Blueness	Redness	Blueness	Redness	Blueness
Bright colors	R	0.233	0.765	1.351	0.775	0.579	0.794	0.106
	G	0.381	0.651	0.400	0.661	0.297	0.682	0.157
	B	0.194	0.619	3.712	0.643	2.433	0.708	0.972
Dim colors	R	0.0465	0.765	1.351	0.775	0.579	0.794	0.106
	G	0.0762	0.651	0.400	0.661	0.297	0.682	0.157
	B	0.0387	0.619	3.712	0.643	2.433	0.708	0.972

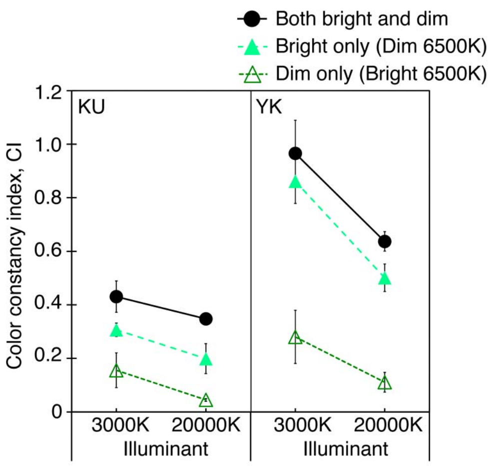

Fig. 8. (Color online) CIs for two observers obtained in experiment 2. Conditions: 1-5-9 (filled circle), 4-5-6 (filled triangle), and 2-5-8 (open triangle).

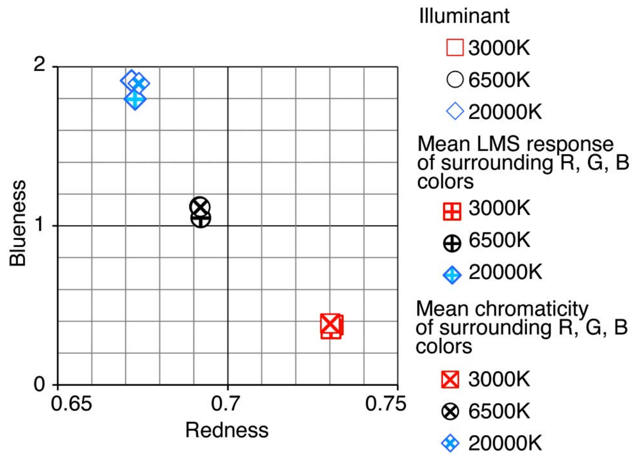

Fig. 9. (Color online) Chromaticities of test illuminants, mean chromaticities of surrounding R, G, B colors and means of L, M, S cone responses of surrounding R, G, B colors used in experiment 3. Stimulus condition: 1 (20000 K), 5 (6500 K), and 9 (3000 K).

reflectances with *M-B* chromaticities, (0.740, 0.745), (0.683, 0.635), and (0.678, 1.62) were used, respectively, under the equal-energy white. Table 4 shows the chromaticity and luminance of R, G, B colors used in experiment 3.

Figure 9 shows the mean chromaticities of the surrounding R, G, B colors and the chromaticities of the means of the L, M, S responses for the surrounding colors in experiment 3, together with the *M-B* chromaticities of the illuminants, 20000 K (open diamond), 6500 K (open circle), and 3000 K (open square).

B. Results

When both the chromaticity and the luminance balance changed in consistent manner with the test illuminant, we obtained fairly good CIs as shown in Fig. 10.

In order to obtain the degree of the shift of observer's settings in the luminance balance condition (experiment 1) and that in the chromaticity shift condition (experiment 2) we took the ratio of the CIs in experiment 1 (Fig. 6) and that in experiment 2 (Fig. 8) to the CI obtained in experiment 3 (Fig. 10). The CIs obtained in the 1-5-9 condition (both bright and dim colors change), were used here. Figure 11 shows the ratio of CI for luminance balance and chromaticity shift. They are 0.52 and 0.86, respectively, on average of two illuminants and two observers. Thus luminance balance alone caused a substantial shift—roughly halfway to full constancy, but less than the chromaticity shift.

6. EXPERIMENT 4

A. Purpose

Changing the luminance balance of surrounding colors of fixed chromaticity yielded significant effects on observer's achromatic settings, as shown in experiment 1 (Fig. 5). The mean chromaticity of the R, G, B colors was fixed at (0.7, 1.0) and their luminances varied as those of optimal colors under test illuminants. This result seems to indicate that the luminance of a context color might be effective in achieving color constancy independent from its chromaticity. However, for this stimulus set, the means of the L, M, and S cone responses of the context colors and the chromaticity of that mean stimulus, also changed with test illuminants, even though there was no change in the mean chromaticity averaged over individual surfaces (Fig. 4). This happens because the individual surface chromaticities are weighted by surface luminance when the mean L, M, and S cone excitations are taken. The data of Fig. 5 could suggest that the observer does not use the luminance balance of R, G, B colors, but rather the means of the L, M, S cone responses as a cue to obtain the achromatic setting. In experiment 4, we aimed at testing this

Table 4. MacLeod–Boynton Chromaticity Coordinates and Luminance of R, G, B Colors Used in Experiment 3 (Luminance: 0.5 = 28.6 cd/m^2)

		Illuminant								
		20000 K			6500 K			3000 K		
		M-B chromaticity			*M-B* chromaticity			*M-B* chromaticity		
		Redness	Blueness	Luminance	Redness	Blueness	Luminance	Redness	Blueness	Luminance
Bright colors	R	0.719	1.747	0.343	0.733	0.857	0.372	0.760	0.203	0.420
	G	0.661	1.070	0.468	0.677	0.705	0.464	0.706	0.295	0.443
	B	0.641	2.870	0.333	0.666	1.791	0.313	0.724	0.659	0.286
Dim colors	R	0.719	1.747	0.069	0.733	0.857	0.074	0.760	0.203	0.084
	G	0.661	1.070	0.094	0.677	0.705	0.093	0.706	0.295	0.089
	B	0.641	2.870	0.067	0.666	1.791	0.063	0.724	0.659	0.057

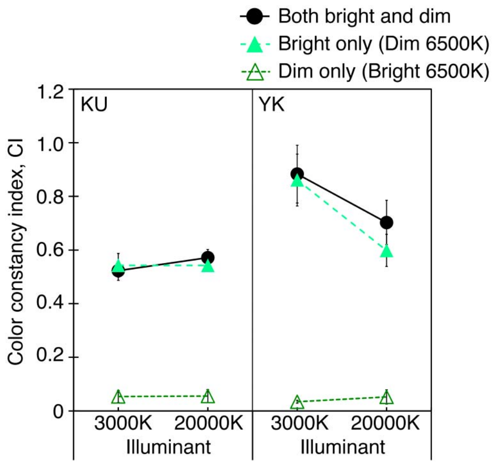

Fig. 10. (Color online) CIs for two observers obtained in experiment 3. Conditions: 1-5-9 (filled circle), 4-5-6 (filled triangle), and 2-5-8 (open triangle).

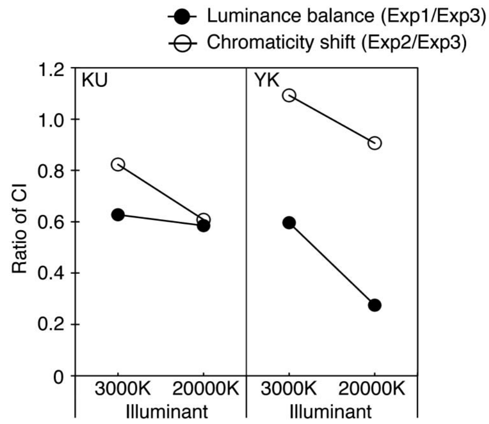

Fig. 11. Ratio of CI for luminance balance and chromaticity shift obtained in experiment 1, 2, 3 in the condition of 1-5-9.

possibility that the visual system utilizes the mean of L, M, S cone responses of surrounding colors for estimating an illuminant.

B. Surrounding Stimulus Condition

We used two test illuminants, 20000 K and 4000 K, in experiment 4. The R, G, B colors were determined in the same way as in experiment 2, except that their luminances varied so that the mean L, M, S cone responses of the R, G, and B context colors did not change under the two test illuminants. The same test illuminant was used both for bright and dim R, G, B colors. Table 5 shows chromaticity and luminance of the R, G, B colors used in experiment 4. The chromaticity and luminance of the mean L, M, S cone responses, (redness, blueness, luminance), were fixed at identical values for both conditions. Thus in this condition, the expected influences of mean surface chromaticity and luminance balance were pitted against one another, while if the mean cone excitation is what matters, the achromatic setting should not shift at all.

C. Results

Figure 12 shows the results for four observers. The filled symbols represent means of observer's achromatic settings for two test illuminants, 20000 K (diamond) and 4000 K (square), respectively. In Fig. 12 it is found that the means are significantly separated in the chromaticity diagram, $p = 0.000$ ($p < 0.01$) for KU, $p = 0.009$ ($p < 0.01$) for YK, $p = 0.013$ ($p < 0.05$) for MS, $p = 0.013$ ($p < 0.05$) for KF by MANOVA. This suggests some independent role for luminance balance, independent of the mean cone responses, in the estimation of the illuminant color.

We calculated CIs in experiment 4. They are shown in Fig. 13. Since the white illuminant of 6500 K was not used in experiment 4 the CI was defined as the ratio of the distance between the means of the observer settings under 2000 K and 4000 K and the distance between the positions of illuminants 20000 K and 4000 K. The CI in experiment 4 corresponds to the mean of CIs obtained under two illuminants, as defined in experiments 1, 2, and 3. The CIs in Fig. 13 turned out to be much smaller than those in the same stimulus condition (both bright and dim) in experiments 1, 2, and 3. Moreover they are consistently negative for all observers, which indicates that the observer's settings shifted in the opposite direction to the illuminant direction (which is also the direction of the shift in mean surface chromaticity). Apparently in this condition, the influence of mean surface chromaticity is slightly outweighed by the greater opposing influence of luminance balance.

7. DISCUSSION

We performed four experiments to investigate effects of luminance balance of surface colors on observer's achromatic setting. In experiments 1–3, we found that the visual system's estimate of illuminant color could be influenced by luminance balance alone, but the luminance balance cue was less effective than the naturally associated shift in mean surface chromaticity. The ratio of CI was 0.52 in the luminance balance

Table 5. MacLeod–Boynton Chromaticity Coordinates and Luminance of R, G, B Colors Used in Experiment 4 (Luminance: $0.5 = 28.6\ \mathrm{cd/m^2}$)

		Illuminant					
		20000 K			4000 K		
		M-B Chromaticity			*M-B* Chromaticity		
		Redness	Blueness	Luminance	Redness	Blueness	Luminance
Bright colors	R	0.765	1.351	0.328	0.785	0.236	0.133
	G	0.651	0.400	0.535	0.672	0.213	0.288
	B	0.619	3.712	0.049	0.675	1.518	0.491
Dim colors	R	0.765	1.351	0.066	0.785	0.236	0.027
	G	0.651	0.400	0.107	0.672	0.213	0.058
	B	0.619	3.712	0.010	0.675	1.518	0.098

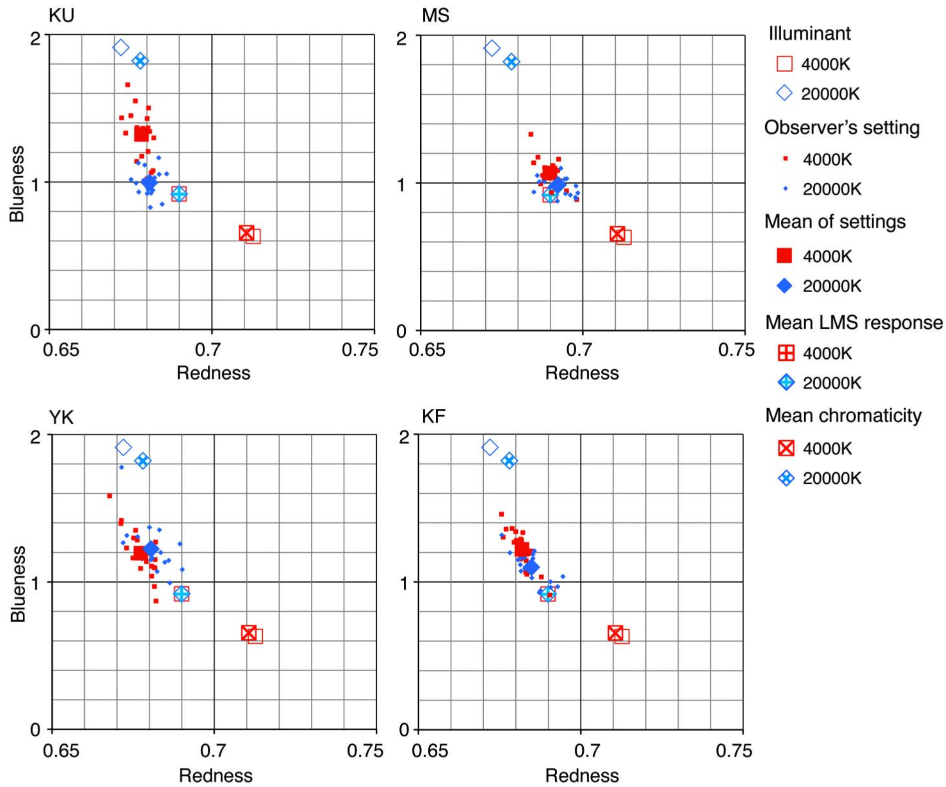

Fig. 12. (Color online) Observer's achromatic settings obtained in experiment 4 for four observers. The same test illuminant was used both for bright and dim R, G, B colors. Test luminance was 0.25.

condition and 0.86 in the chromatic shift condition when expressed as a fraction of CI obtained in the natural change condition. Brighter surface colors were found to be more effective than dimmer surface colors. In experiment 4, it was confirmed that the visual system utilized the luminance balance independent of the mean of L, M, S cone excitations of surrounding colors. All these results support our hypothesis on illuminant estimation.

Our hypothesis is consistent with the general view that when the distribution of chromaticity and luminance in a scene is given, the visual system selects the illuminant most likely to have given rise to that distribution by taking account of the ways in which natural color distributions relate to the distribution of optimal colors. For each surface and for given illuminance, there is a possible range of illuminant chromaticities. The peaked form of the optimal-color surface and its roughly rigid translation with changing illuminant chromaticity imply that this range is narrower the higher the surface luminance. Therefore the brighter scene elements will be more diagnostically useful than the dimmer elements. Practically, this means that low luminance surfaces may be almost ignored, but nearly equally bright ones will carry nearly equal weight.

These predictions were experimentally supported in the present study. Brighter samples were more effective than dimmer samples in all experiments. It is noticed in Fig. 10 that CIs in the 4-5-6 (bright only) condition are almost equal to those in the 1-5-9 (both bright and dim) condition and that CIs in 2-5-8 (dim only) condition were almost zero. This means that, in experiment 3 where surrounding colors changed their luminance and chromaticity in the same way as in the natural scene under different illuminants, the visual system estimates the illuminant color mainly on the basis of the bright (optimal) colors.

We investigated whether the variability of the observer's settings is different across surrounding stimulus conditions, since it might be an indication that some conditions are less natural and less amenable to reliable processing than others. Figure 14 shows standard deviations (SDs) of observer's settings in all experiments. The SD was calculated separately in the redness and blueness directions of the M-B chromaticity diagram for each test luminance level. The SD is significantly smaller in experiment 4 than in other experiments in the redness direction (ANOVA, $p < 0.05$), but not in the blueness direction (ANOVA, $p > 0.1$). Since the surrounding colors are generated in a relatively natural way in experiment 3, but not in experiment 4 where luminance balance and mean surface chromaticity cues are in conflict, the results give no support to the proposal that the variability of the observer's settings reflects the naturalness in the change of the surrounding colors.

In experiment 4, the observer's achromatic settings moved in the opposite direction from the chromaticities of

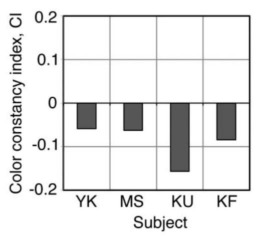

Fig. 13. CIs for four observers obtained in experiment 4. Illuminants: 20000 K and 4000 K.

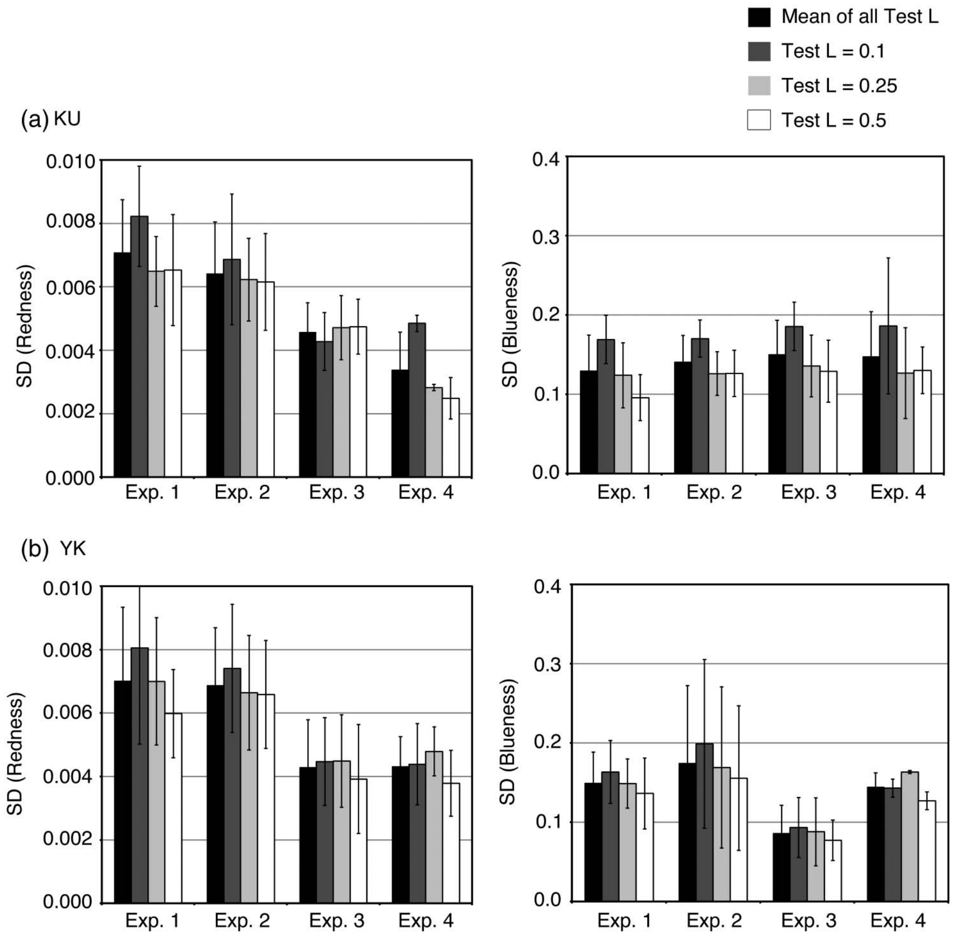

Fig. 14. Standard deviations (SDs) of observer's settings in all experiments. (a) Observer KU. (b) Observer YK. The SDs are separately shown in redness and blueness directions, for each test luminance, averaged across all stimulus conditions.

the simulated illuminant and surround colors (Fig. 12). Here the mean chromaticity of the surround colors almost completely shifted to the test illuminant chromaticity, while the achromatic setting varied in a manner consistent with the opposite illuminant shift (and with the applied luminance balance). In this cue-conflict situation the visual system's estimate of the illuminant color was influenced more by the luminance balance than by the chromaticity shift of the individual surfaces*.

Nevertheless, the results of all the experiments, especially experiment 4, are fairly close to the predictions of the simple 'Gray World' scheme in which achromatic settings are determined by the chromaticity of the average of the surround reflectances or cone excitations. Such a model has an attractive formal simplicity, but lacks a plausible mechanistic basis since observers are not thought to have subjective access to the cone excitations from a surface, still less to the average of the cone excitations for a set of surround surfaces. Surface luminance and chromaticity, however, do seem to have psychological and physiological reality. An equivalent to the 'Gray World' scheme can be constructed by weighting each surface chromaticity by its luminance before the average is taken. This is roughly an appropriate weighting to account for our data and other data compatible with the simple 'Gray World' scheme. But the shift seen in experiment 4 suggests that a weighting by luminance is not quite enough. A more accurate model might be constructed on the supposition that surface chromaticities are weighted by a power function of surface luminance, with an exponent slightly greater than 1, before the average is taken. In the introduction, we noted (as did Tominaga *et al.* [20]) the greater diagnostic value of bright surfaces in the estimation of illuminant color; a weighting by a suitable function of luminance would allow the visual system to exploit this.

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