Color constancy in a scene with bright colors that do not have a fully natural surface appearance

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Theoretical and experimental approaches have proposed that color constancy involves a correction related to some average of stimulation over the scene, and some of the studies showed that the average gives greater weight to surrounding bright colors. However, in a natural scene, high-luminance elements do not necessarily carry information about the scene illuminant when the luminance is too high for it to appear as a natural object color. The question is how a surrounding color's appearance mode influences its contribution to the degree of color constancy. Here the stimuli were simple geometric patterns, and the luminance of surrounding colors was tested over the range beyond the luminosity threshold. Observers performed perceptual achromatic setting on the test patch in order to measure the degree of color constancy and evaluated the surrounding bright colors' appearance mode. Broadly, our results support the assumption that the visual system counts only the colors in the object-color appearance for color constancy. However, detailed analysis indicated that surrounding colors without a fully natural object-color appearance had some sort of influence on color constancy. Consideration of this contribution of unnatural object color might be important for precise modeling of human color constancy.

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1. INTRODUCTION

A. Color Constancy and Color Appearance Mode

Color constancy is the effect whereby the apparent color of a surface remains constant despite extreme variation in the intensity and spectral composition of the illumination, which changes the light reflected from the surface [1]. To accomplish color constancy, the scene illuminant color needs to be discounted from the light reflected from the surface. A large number of theoretical and experimental approaches have proposed that color constancy involves a correction related to some average of stimulation over the scene [2–8]. Some studies including a previous study of our own showed that the average gives greater weight to surrounding bright colors (the bright-is-white assumption [9], specular highlights [10,11], and the chromaticity–luminance balance [12,13]). This is ecologically and physically reasonable, because a matte brighter surface having a high spectral reflectance ratio should reflect the color of the illuminant more reliably than a darker surface having a low reflectance ratio. However, increasing the luminance of a stimulus may cause a change in appearance from the surface-color to the illuminant-color mode [14–18], and in natural scenes, these bright colors do not necessarily carry information about the scene illuminant. For example, the chromaticity of lights from individual illuminants, fluorescent paints, and metallic lusters is physically independent of the scene illumination. On the other hand, specular highlights and bright white surfaces clearly reflect the chromaticity of the illumination. The question in our study is how the visual system deals with the bright colors in the illuminant mode to accomplish color constancy.

B. How do the Color Constancy Algorithms Deal with Illuminant-Color?

Most color constancy algorithms estimate the scene illuminant color by assuming that all colors in a scene belong to matte surfaces, or by excluding information from self-luminous colors. For instance, fluorescent surfaces are understood as a present problem for machine color constancy due to their violation of the assumptions [19,20]. Barnard (in 1999) mentioned that the presence of fluorescent surfaces degraded every algorithm not designed to deal with them and modified three leading machine color constancy methods to deal with fluorescent surfaces [19]. These algorithms require a mechanism that determines the appearance of colors (selecting illuminant- or surface-color mode), without information about the scene illuminant color, which needs to be discounted for color constancy. But this process seems mysterious, because the luminosity threshold is itself affected by scene illuminant color [17].

C. Past Studies Testing the Influence of Color Appearance on Color Constancy

In psychophysical studies, Ikeda and his colleagues investigated the effect of surrounding surface colors on the color appearance of a high-luminance test patch in the illuminant-color mode [21–23]. They measured the color appearance of a test patch in a natural scene with variable illuminations, and the results showed that color constancy gradually failed for the high-luminance test patch when the luminance became too high for it to appear as a natural object color [22]. This finding suggests that color constancy applies only for test patches that appear in the surface-color mode. However, the influence that surrounding bright colors in the illuminant mode show on a test patch in the surface mode has not been behaviorally investigated.

D. Past Studies Testing the Influence of Contextual Information from Surrounding Illuminant Colors

Some studies on color constancy have proposed or demonstrated the specific influence of specular highlights, which are one source surrounding bright colors in a scene. In 1986 D'Zmura and Lennie [10] and Lee [11] proposed that an estimate from a specular highlight is more likely to be reliable for color constancy. In 2001 Yang and Maloney [24] reported that the specular highlight cue did have a significant influence on color constancy, and in 2002 Yang and Shevell [25] showed that color constancy was reduced when specular highlights were eliminated. The color constancy mechanism seems to depend on specular highlights even though they do not appear as natural surface color. This is inconsistent with the theory that for color constancy, the surround should have an effect only if it and the test stimulus are both understood as surfaces [1]. However, it is reasonable that the visual system takes the color of specular highlights as a direct reflection of the color of illumination in most cases. Top–down information might affect the judgments of scene illuminant color from specular highlights. For example, if we find a specular component in a scene, the visual system may suppose the illuminant color should be the same and use it to discount the color in judging surface color appearances. This process might be different from the conventional color constancy mechanism, which counts only surface colors, and should be considered separately.

E. Purpose and Outline of this Study

We wanted to show how a surrounding color's appearance mode influences its contribution to the degree of color constancy when observers cannot use contextual information. To this end, we performed a series of psychophysical experiments. Unlike the color constancy studies that tested the effect of specular highlights, we eliminated the possibility of direct estimation of illumination color based on top–down contextual information and investigated the influence of the change in surrounding high-luminance elements' appearance of luminosity on color constancy. The results should suggest whether higher-level contextual information is necessary for the contribution of illuminant colors (e.g., specular highlights) to the degree of color constancy. The stimuli were simple geometric patterns, so they did not allow the observers to estimate the scene illuminant color from the context of the image, and the luminance of surrounding colors was tested over the range beyond the luminosity threshold at which appearance is modified from surface-color to illuminant-color mode. Normally, increasing the luminance of a color patch in a scene causes a shift of the discounted scene illuminant color toward the lightened patch because of the change in luminance balance [13]. On the other hand, if the change of the color patch's appearance into illuminant-color mode invalidates its effect on color constancy and the shift of the discounted scene illuminant color stops or reverses, this would suggest that all bright surround elements are identified as independent light sources, different from the general source of scene illumination, when there is no image context information. This might not require a top–down process derived from image context information, but it predicts a reduced effect in color constancy. If this is the case, image contexts would be required in order to recognize bright elements as an effective source of illuminant color (e.g., not independent light sources but specularities). Once the bright elements are identified as specularities, then they greatly contribute to color constancy. This mechanism can explain the effect of specular highlights on color constancy, which does not fit into the conventional color constancy algorithms.

2. METHODS

A. Apparatus and Stimuli

All stimuli were generated using a PC (EPSON MT7500) and presented on a 21 in. CRT monitor (SONY GDM-520) controlled by a ViSaGe graphic board (Cambridge Research System) with 14 bit intensity resolution for each phosphor. The monitor was calibrated by measuring the spectral power distributions of three phosphors using a PR 650 spectrophotometer (Photo Research Inc.), and then the transformation between the R, G, B values of the CRT monitor and the L, M, and S cone excitation values was calculated based on the 2 deg cone sensitivity function by Stockman *et al.* [26]. Subjects viewed the screen from a distance of 114 cm in a dark room. The position of a subject's head was fixed with a chin rest.

Figures 1 and 2 show examples of the stimulus configuration. Each hexagon subtended 2 deg diagonally, so that the whole stimulus subtended 14 and 15.6 deg in the vertical and horizontal directions, respectively. The center hexagon was used as the test field for a subjective response. The luminance of the test field remained constant at 2.86 cd/m^2 for the whole experiment. The observers were able to control the chromaticity of this field in the MacLeod and Boynton equiluminant chromaticity diagram [27], which corresponds to the location of the mouse pointer operated with a trackball. The resolution of chromaticity manipulation was 1280 steps for the *redness* from 0.65 to 0.73 and 1024 steps for the *blueness* from 0 to 3.0. Then the (*redness*, *blueness*) coordinate was converted into the nearest chromaticity representable by the 14 bit control of RGB phosphors. The surrounding 60 hexagons were composed of six groups according to color: bright and dark red (R_{bright} and R_{dark}), green (G_{bright} and G_{dark}), and

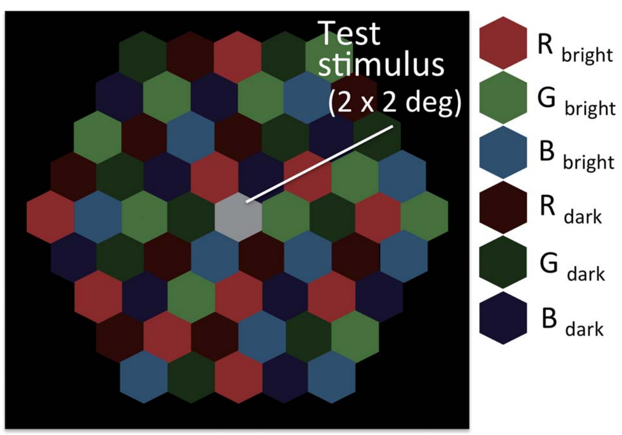

Fig. 1. Example of the stimulus configuration in 6500 K_N condition.

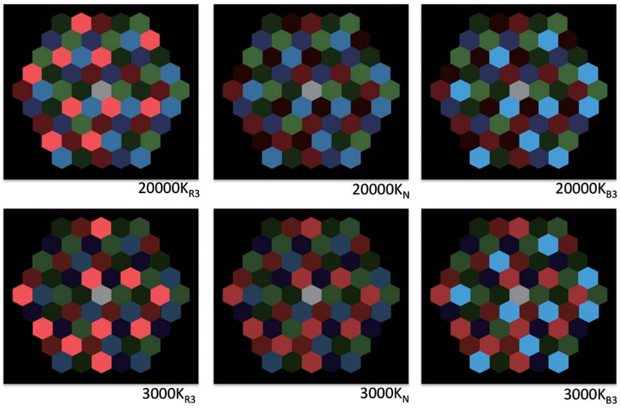

Fig. 2. Variations of the luminance condition. The upper panels show the stimuli in the $20,000\ K_{R3}$, $20,000\ K_N$, and $20,000\ K_{B3}$ conditions. The lower panels show the stimuli in the $3000\ K_{R3}$, $3000\ K_N$, and $3000\ K_{B3}$ conditions.

blue (B_{bright} and B_{dark}). Regarding the spatial arrangement of the six colors, each color was distributed equally according to the distance from the test field. For example, the 6 hexagons adjacent to the test field had different colors, and the 12 hexagons in the next periphery were composed of 2×6 colors, and so on. That is to say, there were 10 hexagons painted with each color. In the whole set of stimuli, any two hexagons of the same color did not appear side by side.

B. Stimulus Conditions

The luminance and chromaticity of each color were fixed for each condition. There were 3 optimal color conditions ($3000\ K_N$, $6500\ K_N$, $20,000\ K_N$) and 12 luminance increment conditions ($3000\ K_{B3,B2,B1,R1,R2,R3}$, $20,000\ K_{B3,B2,B1,R1,R2,R3}$), as listed in Table 1. In the optimal color conditions, the bright colors R_{bright}, G_{bright}, and B_{bright} were set to optimal colors under the illuminant of blackbody radiations at 3000, 6500, or 20,000 K, as shown in Table 1. The intensity of the simulated illuminant was determined, as it gives an ideal white surface the luminance of $3.0\ cd/m^2$. Its corresponding (*redness*, *blueness*) values in the MacLeod and Boynton chromaticity coordinate were (0.740, 0.38) for 3000 K, (0.701, 1.12) for 6500 K, and (0.681, 1.92) for 20,000 K conditions. In order to calculate the optimal colors, the spectral reflectance was set to 1 in the range of 350–425 nm and 565–800 nm for R_{bright}, 480–605 nm for G_{bright}, and 350–520 nm and 630–800 nm for B_{bright} for the $6500\ K_N$ condition and 0 for all other wavelengths [28]. The spectral reflectance for the other conditions, $3000\ K_N$ and $20,000\ K_N$, was determined, as they had similar chromaticity as much as possible for the three colors. (The actual chromaticities and luminances in the optimal color conditions are those designated by row N in Table 1.) The darker colors R_{dark}, G_{dark}, and B_{dark} were set to the same chromaticity but 1/5 the luminance value of the brighter colors R_{bright}, G_{bright}, and B_{bright}, respectively.

The luminance increment conditions were prepared in order to modify the appearance mode of the surrounding colors. In these conditions, the luminance of a color, R_{bright} or B_{bright}, was increased from that of the optimal color by the factors shown in Table 1. Therefore, for each of the 3000 and 20,000 K conditions, we obtained seven levels of different $L_{R\text{-}bright}/L_{B\text{-}bright}$ values. In conditions R1, R2, and R3 the luminances of the bright red surround elements were progressively increased from those for the optimal condition, as shown in Table 1. In conditions B1, B2, and B3 the indicated progressively increased luminances were applied to the blue surround elements. Before testing (and again in experiment 2 described below), we confirmed that increasing the luminance of a color resulted in the translation of color appearance from surface mode to illuminant mode for all observers.

C. Subjects

Four subjects participated in the experiments. All subjects had normal color vision, as determined with a book of Ishihara tests for color deficiency [29]. Subject KF is an author of this paper, and the others were naïve to the purpose of the study.

Table 1. Luminance and Chromaticity of Surrounding Colors in each Condition Represented in MacLeod–Boynton Color Space [27]

Stimulus Conditions		R_{bright}			G_{bright}			B_{bright}			$L_{R\text{-}bright}/L_{B\text{-}bright}$
		L (cd/m^2)	r	b	L (cd/m^2)	r	b	L (cd/m^2)	r	b	
	B3							17.4(×48)			0.12
	B2	2.03						4.36(×12)			0.47
	B1							1.45(×4)			1.40
3000 K	N		0.799	0.34	1.88	0.666	0.15		0.647	3.06	5.59
	R1	4.06(×2)						0.363			11.2
	R2	8.12(×4)									22.4
	R3	24.4(×12)									67.2
6500 K	N	1.34	0.805	0.29	2.42	0.672	0.17	1.16	0.636	2.90	1.16
	B3							17.5(×9)			0.06
	B2	1.12						7.76(×4)			0.14
	B1							3.88(×2)			0.29
20,000 K	N		0.799	0.27	2.53	0.673	0.15		0.636	2.96	0.58
	R1	4.48(×4)						1.94			2.31
	R2	8.96(×8)									4.62
	R3	26.3(×24)									13.6

3. EXPERIMENT 1

This experiment examined the effects of the luminance balance of the surrounding colors on the observer's achromatic setting. We measured the degree of color constancy using the subject's achromatic setting for the test field. Increasing the luminance of a color normally causes a shift of the achromatic point toward the color because of the change in luminance balance [13]. The question in this experiment is whether this trend is monotonic, or whether the shift reaches a maximum value beyond which further increments of the luminance reduce the shift. The latter result is expected if the transition to a luminous mode of appearance reduces the surround element's effect on color constancy.

A. Procedure

The observer's task was to adjust the chromaticity of the test field so that it appeared as an achromatic surface. Before the experiment started, observers performed a 3 min dark adaptation, then a 1 min equal-energy-white (2.86 cd/m^2) adaptation. In every test block, the stimulus of 6500 K_N appeared for 30 s before the first trial started, then 15 conditions were tested in random order. Each test trial started with the presentation of the surrounding stimulus for 15 s in advance, then the test field for the observer's task appeared at the center of the stimulus. Observers were instructed to move their eyes moderately during each trial to avoid local color adaptation and had unlimited time to perform their adjustment task. Every observer performed 10 blocks of this experiment, so that we had 10 repetitions for each stimulus condition.

B. Results and Discussion

In Fig. 3, filled plots show the mean of perceptual achromatic settings in each condition for an observer, and X marks indicate the calculated chromaticity of each illuminant condition (3000, 6500, 20,000 K). The abscissa and ordinate indicate logarithmic *redness* and *blueness* on the MacLeod–Boynton chromaticity diagram [27], where the coefficient of the S cone response is defined so that the log *blueness* of equal energy white becomes zero. Here, the linear regression of the blackbody radiation locus is Log *blueness* = −19.9 ∗ Log *redness* − 3.03(r^2 = 0.9996). The achromatic points vary with stimulus conditions and are mainly distributed along the blackbody radiation locus.

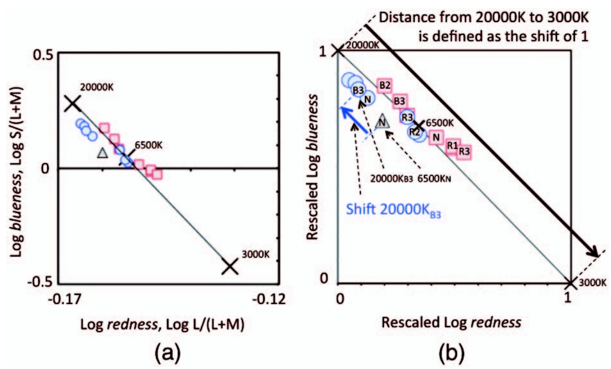

Fig. 3. (a) Example of the mean of the perceptual achromatic settings in each condition for an observer and (b) its enlargement. The X plots indicate the chromaticity of blackbody radiation (3000, 6500, and 20,000 K). The gray-triangle plot denoted "N" shows the result for the 6500 K_N condition. The red square and blue circle plots show the results for the 3000 and 20,000 K conditions, respectively. The degree of achromatic point shift for the condition 20,000 K_{B3}, for example, was defined as the ratio of "shift 20,000 K_{B3}" to "distance from 20,000 to 3000 K".

We then quantitatively evaluated the shift of the perceptual achromatic point among the stimulus conditions. Note that the slope of the blackbody radiation locus is −19.9 in Fig. 3(a), and the mean of the standard deviation for the achromatic point response obtained in each observer is 18.6 times larger in log *blueness* than log *redness*. In order to compensate this large difference in the scale and equalize the contribution of both axes, we rescaled them so that the slope of the blackbody radiation locus became −1 [see Fig. 3(b)] before calculating the shift of the perceptual achromatic point.

Figure 4 shows the effect of luminance change on perceptual achromatic point shift for the six luminance increment conditions regarding the 3000 K_N (dashed line and square plots) and 20,000 K_N (solid line and circle plots) conditions. The abscissa specifies the luminance increment condition, and the ordinate shows the degree of the perceptual achromatic point shift according to the position along the oblique line connecting 3000 and 20,000 K (see Fig. 3), in which the zero point is defined as the individual observer's result of the achromatic setting for the canonical condition in which the simulated illuminant was 6500 K_N. The scale was defined based on the distance in the rescaled (log *redness*, log *blueness*) coordinates from 3000 to 20,000 K. For example, the mean achromatic point for condition 20,000 K_{B3} was calculated by dividing "shift 20,000 K_{B3}" by "the distance between the plots from 20,000 to 3000 K" in Fig. 3(b). So, the sign of the values shows the direction of the achromatic point shift, positive values are reddish and negative values are bluish, and a larger absolute value indicates a larger shift of the achromatic point.

In Fig. 4 the ratio of red to blue luminance increases progressively from left to right. If the influence of the surround

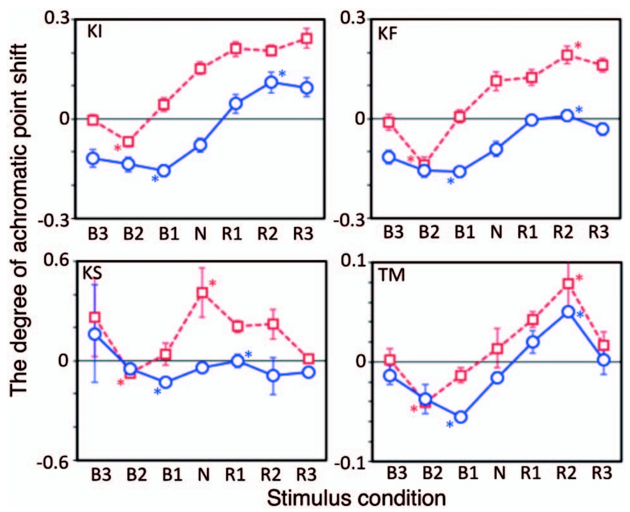

Fig. 4. Effect of luminance change on perceptual achromatic point shift for the four subjects. The abscissa is an index to the various luminance increment conditions, and the ordinate is the degree of the perceptual achromatic point shift. The red square and blue circle plots show the results for the 3000 and 20,000 K conditions, respectively. The error bars indicate intra-observer's standard deviation. The stars beside the plots indicate the conditions in which the curves show an extremum.

elements on the achromatic setting increased monotonically with element luminance, the R conditions should yield higher values. While this is roughly in accord with observation, most curves in Fig. 4 show a deviation from monotonicity: symmetric *N* shapes for both the 3000 and 20,000 K conditions. In other words, each curve had two extrema. For example, the curve of condition 20,000 K for observer KI had two extrema, a minimum at condition B1 and a maximum at R2, meaning that the increment of luminance B_{bright} and R_{bright} influences differently inside and outside this range. Inside this range, the increment of luminance B_{bright} and R_{bright} from the stimulus in the $20,000\ K_N$ condition caused a perceptual achromatic point shift of toward the chromaticities 20,000 K (bluish light) and 3000 K (reddish light), respectively. This result corresponds to the effect of the luminance ratio on color constancy shown in our previous study [13]. On the other hand, in the range beyond these extrema, the luminance increment of a color had the opposite influence. Notably, the luminance increment of the blue patch from conditions B1–B3 caused a shift of the achromatic point toward a reddish color for all observers. This result supports the theory that the change in the appearance of luminosity invalidates its effect on color constancy. However, in this experiment we have no evidence of whether the peaks in Fig. 4 relate to the change of the color appearance from surface color to illuminant color.

4. EXPERIMENT 2

In this experiment, we investigated the color appearance mode of the surrounding colors (surface color or illuminant color) for each stimulus condition in the previous experiment. Then we compared these results to the results of experiment 1, to show whether the extrema in Fig. 4 match to the change of color appearance mode.

A. Procedure

The stimulus and procedure in this experiment were the same as in experiment 1, except for the observers' task. In each trial, observers answered a question of whether all the surrounding colors of a stimulus were in complete-surface-color mode or not. If they said no, they reported the name of the color appearing as nonsurface-color mode and estimated the reliability of the illuminant-color impression within a scale from 1 to 10, so that the a magnitude of 1 to 9 was used when the appearance mode was ambiguous or unnatural surface color, for example, the perception of fluorescent surfaces. The magnitude was counted as 0 when all colors appeared as complete-surface-color mode. Thus, we obtained two types of responses with regard to observers' appearance mode for surrounding colors: (1) two-forced-choices responses of complete-surface-color appearance and (2) magnitude estimation of color appearance mode from 0 (complete-surface-color mode) to 10 (complete-illuminant-color mode). Observers waited for 15 s, with free eye movement every time, after a stimulus appeared, as in the procedure in experiment 1. Every observer performed 10 repetitions for each stimulus condition.

B. Results and Discussion

Figures 5 and 6 show the results in experiment 2 for each stimulus condition. The symbols and abscissa are determined as in Fig. 4. The ordinate in Fig. 5 shows the response ratio of

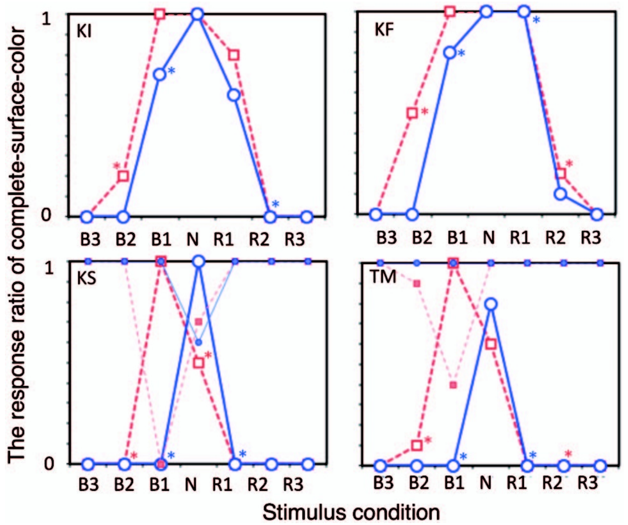

Fig. 5. Response ratio of complete-surface-color in the two-forced-choices task in each stimulus condition. The red squares with dashed lines and blue circles with solid lines show the results for the 3000 and 20,000 K conditions, respectively. The open symbols represent the responses for the bright color whose luminance was varied (for example, red for the R1–R3 conditions). The filled symbols for observers KS and TM represent the estimation for the other colors (for example, blue or green for the R1–R3 conditions). The stars beside the plots indicate the condition in which we have obtained an extremum of the achromatic point shift in Fig. 4 for each observer (critical luminance conditions).

complete-surface-color mode in the two-forced-choices task. The plots in Fig. 6 show the mean of the observer's magnitude estimation for the reliability of the illuminant-color appearance in the second task. Note that we expected that observers would report nonsurface-color appearance only for the bright color whose luminance was varied (e.g., red region in the

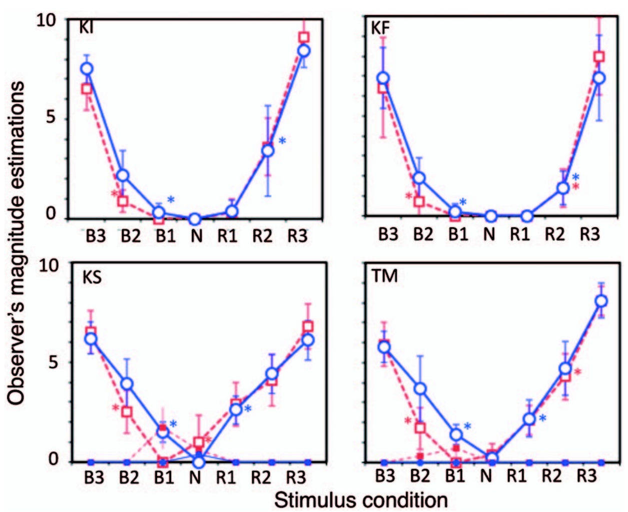

Fig. 6. Mean of the observer's magnitude estimations for the reliability of illuminant-color appearance for each stimulus condition. The red square and blue circle plots show the results for the 3000 and 20,000 K conditions, respectively. The open symbols represent the magnitude estimation for the bright color whose luminance was varied (for example, red for the R1–R3 conditions). The filled symbols for observers KS and TM are the estimation for the other colors (for example, blue or green for the R1–R3 conditions). The error bars indicate intra-observer's standard deviation. The stars indicate the condition in which we have obtained an extremum of the achromatic point shift in Fig. 4 for each observer (critical luminance conditions).

R1–R3 conditions and blue regions in the B1–B3 conditions). However, two of four observers, KS and TM, reported this appearance for other colors (e.g., the blue or green regions in the R1–R3 conditions) in 12.1% and 5.0% of all 150 trials, respectively. The responses for these expected and unexpected nonsurface-color appearance choices were shown as open and filled symbols, respectively.

As we expected, the magnitude estimations are nearly zero at the normal optimal color conditions 3000 K_N and 20,000 K_N (Fig. 6); the mean of magnitude at these conditions for all observers is 0.200 ($n = 80$; standard deviation, (SD) $= 0.604$; standard error of the mean, S.E.M. $= 0.068$), and the response ratio of complete-surface-color mode is 86.3% ($n = 80$), which is significantly larger than the chance level ($p = 0.00$ by the binomial test). For the luminance increment conditions R1–R3 and B1–B3, the magnitude increases remarkably with the luminance increment of a color, R_{bright} or B_{bright}. These results confirm that the observer's choice of appearance of surrounding colors surely changed from surface color to illuminant color with the luminance increment in our experiment conditions.

We then looked into the appearance mode judgment at the condition where we have obtained an extremum of the achromatic point shift in Fig. 4 for each observer. Here, we call the condition the "critical luminance condition." The stars besides the plots in Figs. 5 and 6 show the critical luminance conditions. The mean of observers' magnitude estimation for the critical luminance conditions was 1.87 ($n = 15$, SD $= 1.37$, S.E.M. $= 0.35$). The response of complete-surface-color mode (magnitude estimation, ME $= 0$) was obtained only in 20.7% of the trials in these conditions ($n = 150$), which is significantly smaller than the chance level of 0.5 ($p = 0.00$ by the binomial test). This result confirms that the observers saw some sort of luminosity in the surrounding colors in the critical luminance conditions. Our data also confirm that the observers' appearance choices of complete-surface-color mode were obtained up to the conditions whose luminance level is one step lower than that for the critical luminance conditions (e.g., conditions N and R1 for observer KI's blue solid curve, whose critical luminance conditions were B1 and R2). The mean of observers' magnitude estimation for these conditions was 0.38 ($n = 13$, SD $= 0.80$, S.E.M. $= 0.22$). The response of complete-surface-color mode (ME $= 0$) was obtained in 80.0% of the trials in these conditions ($n = 130$), which is significantly more than the chance level of 0.5 ($p = 0.00$ by the binomial test).

5. DISCUSSION

A. Summary of the Results and their Interpretation

We investigated how the appearance mode of the surrounding colors influences the effect of the luminance–chromaticity information on color constancy. In summary, the luminance ranges roughly matched: the range where the effect of luminance increment on color constancy was positive in experiment 1 was close to the range where observers reported complete-surface-color mode in experiment 2. Broadly, this result supports the assumption that the visual system counts only the colors in the surface-color mode for color constancy. However, detailed analysis indicated that the critical luminance for color constancy is beyond the range of complete-surface-color appearance, as shown in the responses

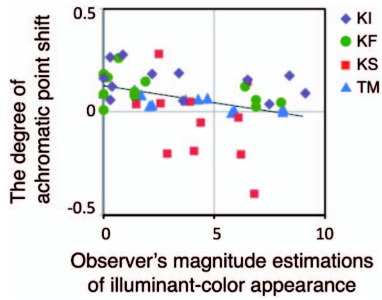

Fig. 7. Correlation diagram between the observer's magnitude estimations of illuminant-color appearance and the degree of perceptual achromatic point shift for the 3000 $K_{B1,B2,B3,R1,R2,R3}$ and 20,000 $K_{B1,B2,B3,R1,R2,R3}$ conditions. For the degree of achromatic point shift, we subtracted the data for the 3000 K_N or 20,000 K_N condition from the data for each condition shown in Fig. 4. The correlation coefficient is −0.37.

of appearance mode in experiment 2 at the critical luminance conditions. In addition, the bright colors gradually, not suddenly, lost their effect on color constancy after the luminance increment level passed over the critical luminance. Figure 7 shows the correlation diagram between the observer's magnitude estimations of illuminant-color appearance and the degree of perceptual achromatic point shift for 3000 $K_{B1,B2,B3,R1,R2,R3}$ and 20,000 $K_{B1,B2,B3,R1,R2,R3}$ conditions. For the degree of achromatic point shift, we subtracted the data for the 3000 K_N or 20,000 K_N condition from the data for each condition shown in Fig. 4. These results suggest that surrounding colors not in the complete-surface-color mode have some sort of influence on color constancy; this calls for some qualification of the conclusion that the visual system counts only the colors in the surface-color mode for color constancy. This might be a cause of the incomplete color constancy in natural scenes. Considerable numbers of objects in natural scenes have fluorescent constituents [19]. Considering this inappropriate contribution of unnatural surfaces to color constancy might be important for precise modeling of human color constancy. For example, finding a weighted function to represent the relationship between the appearance of a color in a scene and its contribution to color constancy will be required to improve the existing color constancy algorithms that use the luminance and chromaticity information in a scene.

Note that the steady decrements of color constancy effect beyond the critical luminance in experiment 1 strongly suggest that the much brighter colors whose luminance exceeds the range of unnatural object-color appearance are indeed neglected in the color constancy mechanism. This suggests that top–down information derived from image context is necessary for the contribution of brighter colors to color constancy. If the brightest surround elements were interpreted as specular highlights, they would certainly have additional influence on constancy, whereas when they are perceived as self-luminous, a reduced influence is expected. To consider the mechanism, we should perhaps assume two separate color constancy mechanisms: one a bottom-up conventional color constancy mechanism that gives a larger weight to surface colors of relatively high luminance, the other a top–down color constancy mechanism that can classify image features intelligently depending on the context. Our results correspond to the former case that the brightest elements are interpreted as self-luminous rather than as specularities.

B. Comparing with Previous Studies

In 2007 Pungrassamee *et al.* [22] demonstrated that color constancy gradually failed for the test patch with high luminance when the color mode became an unnatural object color and then a light source color. Our result is generally consistent with theirs, except that we tested color constancy for a low-luminance test patch surrounded by high-luminance colors. This agreement of the results reveals a common color constancy mechanism that degrades or ignores the bright colors in the illuminant-color or unnatural-object-color mode. Note that there is a difference in the results between these experiments. In Pungrassamee *et al.* [22], color constancy started to decline while the appearance of the test patch was in surface-color mode. In our experiment, color constancy did not decline while the appearance of the surrounding colors was in surface-color mode and started to decline only after the luminance exceeded the luminosity threshold. This difference might be caused by the location of the high-luminance color. The high-luminance color was the test patch in Pungrassamee *et al.* [22] but was in the surrounding colors in our experiment. Another possibility is the difference in their stimulus arrangement. The test patch was presented on a CRT monitor and viewed through an aperture in a real 3D scene in their experiment, but the test patch was surrounded by geometric patterns, both of which were presented on a CRT monitor, in our experiment.

Although theirs was not a color constancy study, Ikeda *et al.* [21] reported that surrounding colors in the light-source mode do not influence the limiting luminance for a test region's color appearance mode [30]. In their study, performed in a real scene, the border luminance was proportional to the luminance of the object with the highest lightness determined; however, there was no effect of the luminance of the object with the light-source-color mode. This is consistent with our results.

C. Implications for the Relationship between Color Constancy and Chromatic Induction

In 2011 Foster [1] stated in his review paper that the precise relationship between color constancy and chromatic induction remains to be determined. As far as we know, there is no evidence that color appearance mode affects chromatic induction. In other words, the higher the luminance of the induction color, the larger the effect of chromatic induction, regardless of whether the color appearance of the induction color is surface color or illuminant color. On the other hand, as we demonstrated in this study, the luminance increment does not affect the color constancy when the inducer is in the illuminant mode. This might help to determine the precise relationship between color constancy and chromatic induction.

D. Implications for the Color Constancy Mechanism and Color Appearance

We mentioned in the introduction the mysterious relationship of dependency between the color of the illuminant and the appearance of color (illuminant or surface color). The appearance of a color in illuminant-color mode or surface-color mode is affected by the illuminant color of the scene [17], and the maximum luminance of a surface color physically under a given illuminant is determined by the color and intensity of the illuminant (McAdam's limit [31]). On the other hand, our study showed that the color appearance of the surrounding colors, which is determined by the illuminant in the scene, is also a crucial factor in determining the scene illuminant color that is discounted for color constancy. This is comprehensible when the context of the scene is available for determining the dependence of each color [32]. However, our stimuli had only luminance and chromaticity information. These results suggest that there may be a preceding process of distinguishing illuminant colors from surface colors before estimating the scene illuminant color for the purpose of discounting it to accomplish color constancy.

6. CONCLUSION

This study showed the influence of the color appearance mode on color constancy. High-luminance elements in the illuminant-color mode have little effect on the estimation of scene illuminant color, which is discounted for color constancy. This qualifies the generalization that greater element luminance increases an element's influence in color constancy and suggests that a top–down process derived from image context information is necessary for the contribution of such high-luminance elements (e.g., specular highlight or direct view of illuminant) on color constancy. Our results also showed that the influence of colors that do not have a fully natural surface appearance could not be ignored for color constancy. The bright colors gradually, not suddenly, lose their effect on color constancy when their appearance transitions from surface-color to unnatural-surface-color and illuminant-color modes. Consideration of this inappropriate contribution of unnatural surface color to color constancy might be important for precise modeling of human color constancy.

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