Color constancy influenced by unnatural spatial structure

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The recognition of spatial structures is important for color constancy because we cannot identify an object's color under different illuminations without knowing which space it is in and how that space is illuminated. To show the importance of the natural structure of environments on color constancy, we investigated the way in which color appearance was affected by unnatural viewing conditions in which a spatial structure was distorted. Observers judged the color of a test patch placed in the center of a small room illuminated by white or reddish lights, as well as two rooms illuminated by white and reddish light, respectively. In the natural viewing condition, an observer saw the room(s) through a viewing window, whereas in an unnatural viewing condition, the scene structure was scrambled by a kaleidoscope-type viewing box. Results of single room condition with one illuminant color showed little difference in color constancy between the two viewing conditions. However, it decreased in the two-rooms condition with a more complex arrangement of space and illumination. The patch's appearance under the unnatural viewing condition was more influenced by simultaneous contrast than its appearance under the natural viewing condition. It also appears that color appearance under white illumination is more stable compared to that under reddish illumination. These findings suggest that natural spatial structure plays an important role for color constancy in a complex environment.

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1. INTRODUCTION

Color constancy has been studied by many researchers over the years [1]. It is often explained by mechanisms in lower levels of visual processing, such as an adaptation of the photoreceptors on the retina, known as the von Kries adaptation [2], and adaptation to the averaged color of a visual field [3,4]. Various factors affecting color constancy are also suggested; for example, the clue of specular highlight [5], the recognition of 3D shape and mutual illumination [6], correlations between spatially local chromatic signals across illuminants [7], changes in surface position and illuminant [8], and characteristics of scene statistics [9,10]. Many models and theories have been proposed: Retinex theory [11], statistical approach such as Bayesian approach [12], and physics-based approaches [13], and so on. However, we still do not have a consensus regarding what the mechanisms of color constancy are. The degree of constancy depends on which research is examined. This is most likely due to the differences in the experimental environments. One study using a nearly natural environment showed a high degree of color constancy [14,15] and another using a simple stimulus; for example, a Mondrian pattern on a monitor showed poor color constancy [16]. The degree of color constancy is less in 2D images than in real scenes [17,18]. It has been shown that the color constancy in a photograph is improved when it is viewed monocularly and exclusively through a hole, eliminating the information in the surroundings. However, it decreases again if the photograph is jumbled [19]. These results lead us to the assumption that color constancy is not only a low-level mechanism, but also a much higher-level one, i.e., one influenced by the naturalness of the environment. In other words, a natural environment is necessary for high color constancy.

The recognition of spatial structure is important for stable color appearance, as we cannot identify the color of an object under different illuminations without knowing which space the object is placed in and how that space is illuminated [20–22]. In natural and 3D environments, observers have no difficulty in recognizing an object's color, as one can recognize the space and its illumination. What happens, on the other hand, if we are in an unnatural environment? We might not be able to recognize the colors correctly and thus fail to have good color constancy.

In this study, we examine the manner in which color constancy is affected by unnatural viewing conditions in which the spatial structure is distorted. In this situation, it would be difficult to obtain the spatial information, such as the depth, the position, and the arrangement of objects. We predict that color constancy will decrease under unnatural viewing conditions, especially if the distortion of spatial structure affects color constancy in the same manner as a jumbled photograph [19].

We used a kaleidoscope-type viewing box for scrambling the spatial structure of the view. We measured the neutral color perception of a paper patch in rooms lit with white and reddish incandescent illuminations that are typical for normal indoor lighting.

2. EXPERIMENT

A. Apparatus

We built an experimental booth (150 cm wide, 300 cm deep, and 210 cm high), as shown in Fig. 1. The booth consisted of

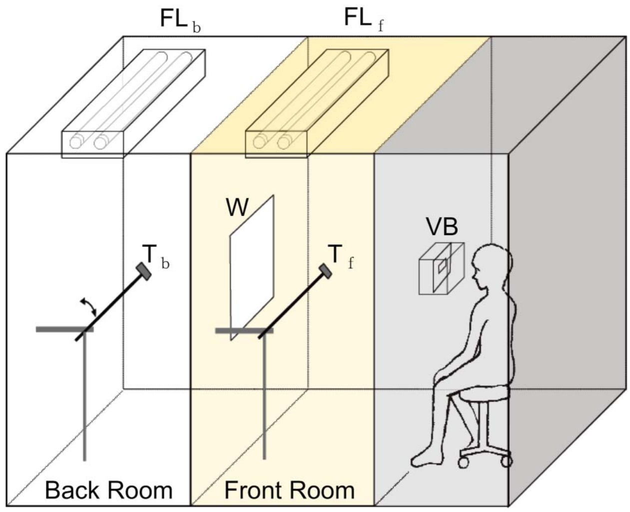

Fig. 1. Scheme of the experimental booth. FL_b, FL_f, lamps in back and front rooms (e.g., white and reddish); T_b, T_f, test patches; VB, viewing box; W, window between back and front rooms.

two rooms arranged adjacent to each other and connected by a window (the "back" and the "front" room) and a dark space where an observer viewed the rooms through a viewing box installed on a wall in the front room. Many objects of various colors were placed in both rooms to simulate a natural indoor environment. The back and front rooms were illuminated by fluorescent lamps (FL_b, FL_f) with correlated color temperatures of approximately 5000 K (Toshiba FLR40S•N-SDL/M•A•NU, Ra 90) and approximately 3000 K (FLR40S•L-EDL/M•A•NU, Ra 95). For simplicity, we call the illuminant with 5000 and 3000 K as "white" and "reddish" illuminant, respectively.

All combinations of illumination color and room were tested: front(reddish)/back(white) and front(white)/back (reddish). The illuminance was set at 500 lx. Note that we measured the horizontal illuminance on a 70 cm high desk immediately below the test patches for color judgments (T_b, T_f) in both rooms.

An observer looked at the inside of the rooms through a viewing box and judged the color of a test patch supported by a black pole and placed in the center of either the back room or the front room at a height of 115 cm. A viewing box with a rectangular aperture was used in the natural viewing condition. Black paper covered the inside of the box. Observers viewed the room(s) binocularly. The field of view was $35° \times 35°$ and limited to the front/back room (otherwise completely dark surrounding). In the unnatural viewing condition, this box was replaced by a box with a kaleidoscope made of three rectangular mirrors of dimensions 25×60 mm arranged in an equilateral triangle. Observers viewed the room(s) monocularly in this condition. The spatial structure of the observer's view, including the edge of window between front and back room, was scrambled due to reflections from the mirrors. Only the view of the test patch and its immediate surroundings were the same as in the natural viewing condition since the aperture of the kaleidoscope was aligned with the patch. The field of view and, thus, the averaged color of the view were approximately the same in both viewing conditions. The difference in viewing conditions was only in the arrangement of the scene, and both rooms were visible. Therefore the chromatic information of the total view can be considered as approximately the same in both natural and unnatural viewing conditions. Moreover, for each of the two-room conditions, front(reddish)/back(white) and front (white)/back(reddish), adaptation state was the same when the test patch was placed in either the front or back room. However, we still provide a comparison of both two-room conditions. We expected that observers were not able to recognize how the two rooms were illuminated correctly, due to the lack of the spatial information, such as the depth, the position, and the arrangement of objects. In that situation, the probability that they could estimate the color of objects correctly was lower, even if color information had been provided.

Figure 2 shows examples from the point of view of the observer. In the one-room condition (1), the window between the back and the front rooms (W in Fig. 1) was covered by a board with the same wallpaper as that used on the other walls, so that the observer only saw the front room. In the two-room condition (2, 3), the window was open, and the observer saw both rooms at the same time. We tested the natural and unnatural viewing conditions (4–6) for the one- and two-room conditions.

Test patches for color judgment covered a range from (in Munsell notation) 7.5YR5/3 to 5PB5/8 via N5 at 0.25 chroma steps. Their chromaticity coordinates, measured using a

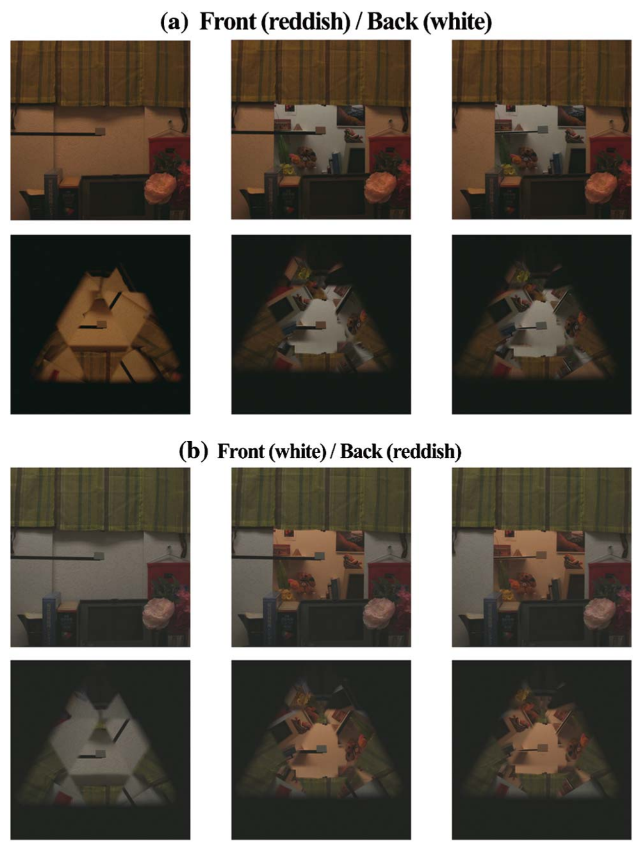

Fig. 2. Examples from view of an observer. (a) shows the condition with reddish illumination in front room (FR) and white illumination in back room (BR). The combination of illumination color was flipped in (b). (1) 1-room condition (natural viewing condition). (2) 2-room condition (natural) with test patch in FR. (3) 2-room condition (natural) with test patch in BR. (4) 1-room condition (unnatural viewing condition). (5) 2-room condition (unnatural) with test patch in FR. (6) 2-room condition (unnatural) with test patch in BR.

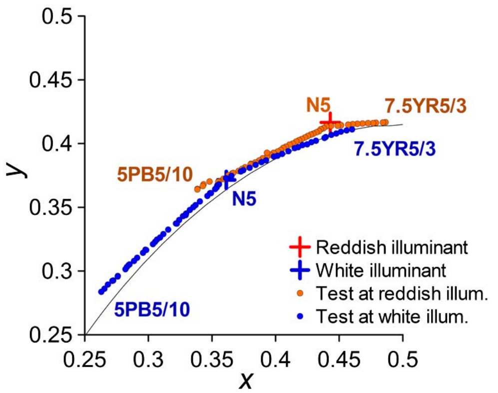

Fig. 3. CIE 1931 chromaticity coordinates of test patches with a range of 7.5YR5/0.25–3, N5, 5PB5/0.25–8 (circles) in front room (FR, reddish) and back room (BR, white). Red and Blue crosses show the illuminant of reddish (3000 K) and white (5000 K) room, respectively. Thin curve indicates the black body locus.

spectroradiometer (Minolta CS-1000) from the position of an observer, are shown in Fig. 3. The test patches vary along (approximately) the black body locus. The luminance of all test patches was roughly the same at approximately $55\ \mathrm{cd/m^2}$. To make the visual angle of test patches 2°, 7×7 cm and 3×3 cm square patches were used in the back and the front rooms, respectively.

B. Procedures

An experimenter changed the test patches one by one. The observer judged the color of each test patch by answering one or two hues out of red, green, blue, and yellow. We tested a series of test patches; the color for which the judgment changed from yellow-red (Y, R or YR) to blue-green (B, G or BG) was considered a neutral perception point. We considered this simplified color-naming method reasonable, as the series of test patches changed along the black body locus, shifting the color from YR to B. In fact, we rarely received responses of G during the experiment.

One session consisted of judgments for test patches in the front room in the one-room condition and in the back room or the front room in the two-room condition. The natural and the unnatural viewing conditions were tested for these three room conditions. The order of conditions tested was randomized in each session and for each observer. Experiments were conducted by a method of adjustment for 12 observers for the front(reddish)/back(white) conditions and 10 observers for the front(white)/back(reddish) conditions. All observers had normal color vision. Each observer made one judgment for each condition.

Detailed data was also obtained from three observers by a method of constant stimuli in the front(reddish)/back(white) conditions. In this case, five test patches were judged five times each in each condition during one session; five sessions were conducted for each observer.

3. RESULTS

Figure 4 shows the results obtained from three observers in the front(reddish)/back(white) conditions on the CIE 1931 xy diagram. The mean of five sessions is shown for each condition. Each symbol has error bars indicating standard deviation, most of which are smaller than the symbols, thus showing the high reliability of the judgments.

In the results for the one-room condition shown by circles, neutral points for the natural and unnatural conditions overlap. They are close to the chromaticity of illuminant in the front room (red cross), which means color constancy was high in both viewing conditions. This suggests that the color of illumination can be recognized even if the spatial structure is jumbled in the case of an environment with a single illumination. Natural spatial structure may not be necessary for color constancy, and good color constancy can be obtained in the case where natural illumination itself and belongingness are intact.

The results for the front room in the two-room condition shown by triangles differed in their viewing conditions. The mean neutral point in the unnatural viewing condition (open orange triangle) is further from the chromaticity of illuminant in the front room (red cross) than that of the natural viewing condition (filled orange triangle). This means that the degree of color constancy for the front room decreased in the unnatural viewing condition. However, those differences are smaller than expected, mainly because the neutral perception point in the front room is shifted, even in the natural viewing condition, suggesting the large influence of the chromaticity of illuminant in the back room or the immediate background (i.e., the wall of the back room). We discuss this issue below.

In the case of the back room shown by squares, the mean neutral points for both viewing conditions overlap and remain

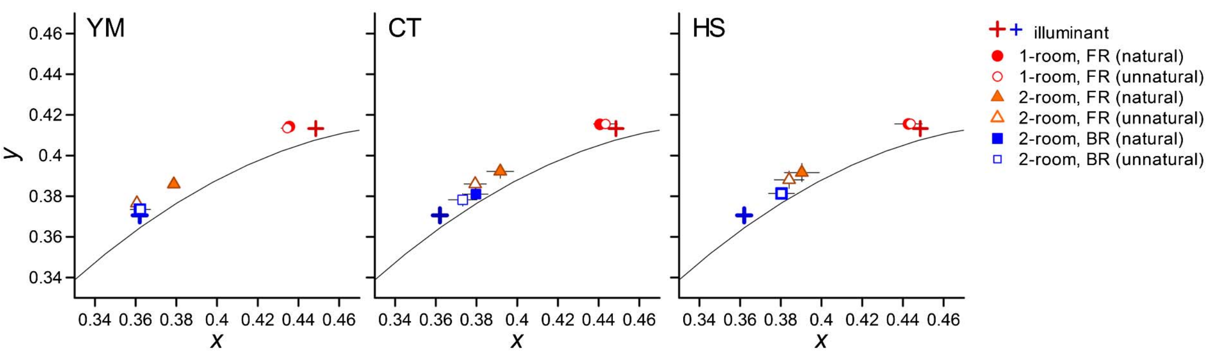

Fig. 4. Results from observer YM, CT, and HS on the xy chromaticity diagram in the front(reddish)/back(white) condition. Filled and open symbols indicate natural and unnatural viewing conditions, respectively. Standard deviations are shown by error bars. Circles, front room in 1-room condition; triangles, front room in 2-room condition; squares, back room in 2-room condition. Note that filled squares for YM and HS are not visible since open and filled squares are superimposed almost perfectly.

close to the chromaticity of illuminant in the back room (blue cross), which means the degree of color constancy is high in both viewing conditions.

It is interesting to note that the difference between observers is particularly large regarding the neutral points of the front room in the two-room condition. The neutral point of YM under the unnatural condition is close to the chromaticity of illuminant in the back room (blue cross), or there is no color constancy, and it is also close to the observer's neutral point in the back room (blue squares). This suggests that it was difficult to locate the position of the test patches in either the back or the front room, and that those colors were judged primarily based on the immediate background. In the case of CT, the observer's neutral point in the front room is closer to that of the back room (blue squares), but the shift is smaller than that for YM. The large individual difference in this particular condition implies that the color appearance under unnaturally scrambled environments tends to become unstable.

Figure 5(a) shows the results obtained from 12 observers in the front(reddish)/back(white) condition. Each symbol shows the mean of 12 observers for each condition, with error bars indicating standard deviation. These results show a similar trend to the results obtained from three observers shown in Fig. 4. Although the individual difference of neutral points is large, the overall trend is the same for most observers. The mean neutral point in the unnatural viewing condition (open orange triangle) is further from the chromaticity of illuminant in the front room (red cross) than that of the natural viewing condition (filled orange triangle). In other words, the neutral perception of the back room becomes closer to that of the front room in the unnatural viewing condition (open orange triangle and blue square), suggesting that the appearance of test patches became similar regardless of its position.

The results obtained from 10 observers in the front(white)/back(reddish) condition in Fig. 5(b) also show a similar trend. The mean point in the unnatural viewing condition (open blue triangle) is further from the chromaticity of white illuminant in the front room (blue cross) than that of the natural viewing condition (filled blue triangle), suggesting a decrease in color constancy in the front room. However, contrary to the neutral perception in the front room shifted even in the natural viewing condition under the front(reddish)/back(white) condition [filled orange triangle in Fig. 5(a)], the shift from the chromaticity of illuminant in the natural viewing condition (filled blue triangle) is small. It is also interesting to note that the shift of the neutral point for the test patch in the back room [orange squares in Fig. 5(b)] is larger than that in the front(reddish)/back(white) condition [blue squares in Fig. 5(a)]. This asymmetry suggests that the influence of the chromaticity of illuminant in the back room is not the same in the front (reddish)/back(white) and the front(white)/back(reddish) combinations.

To evaluate the effect on color constancy, the color constancy index (CI) was calculated based on the Euclidean distance on the CIE1976 $u'v'$ chromaticity diagram as the same method used by Arend *et al.* [23]: CI = 1–(distance between neutral perception point and the chromaticity of illuminant where the test patch was placed)/(distance between the chromaticity of white and reddish illuminant). Perfect constancy is indicated by CI = 1, and no constancy is indicated by CI = 0. Note that there are no pre- and post-adaptation conditions since observers viewed both rooms simultaneously in our experiment. Although the meaning of CI we calculated may not be equivalent to that of Arend *et al.*, we used the CI for evaluating how the neutral perception point was close to the chromaticity of illuminant where the test patch was actually placed. The means of 12 (or 10) observers with error bars indicating standard deviation are shown in Fig. 6 [(a), the front(reddish)/back(white) condition; (b), the front(white)/back(reddish) condition)]. Generally, the CI is high in the one-room condition and in the room with white illuminant and lower in the room with reddish illuminant under the two-room condition. The trend that the CIs of the front room decrease under the unnatural viewing condition more than under the natural viewing condition is consistent in both the front (reddish)/back(white) and the front(white)/back(reddish) conditions. Both showed significant differences ($p < 0.01$ by Student's *t*-test). This suggests a stronger influence of the immediate background on the color appearance of a test patch when it is difficult to locate the position of a test patch.

The results obtained from observers are also evaluated based on the shift of their Munsell chroma; the mean of 12 (or 10) observers is shown in Fig. 7. Here no chroma shift

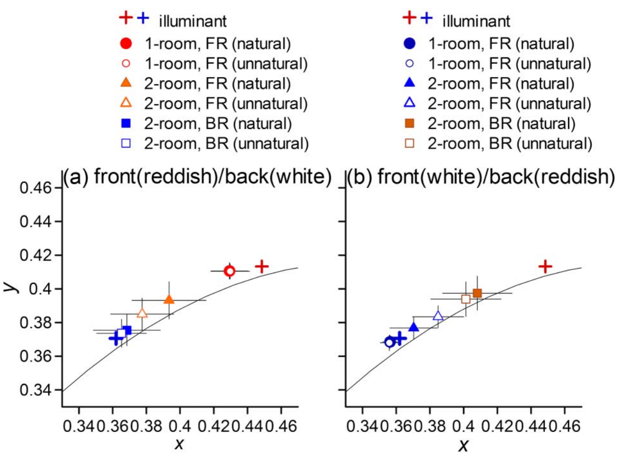

Fig. 5. Mean results obtained from all observers. Standard deviations are shown by error bars. (a) Front(reddish)/back(white). (b) Front (white)/back (reddish). Filled and open symbols indicate natural and unnatural viewing conditions, respectively. Circles, front room in 1-room condition; triangles, front room in 2-room condition; squares, back room in 2-room condition. Orange and blue symbols indicate reddish and white illumination, respectively.

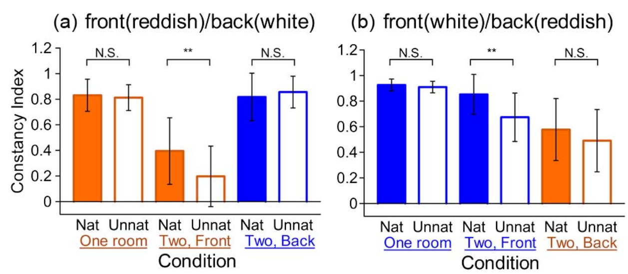

Fig. 6. Color constancy index. Error bars indicate standard deviation of observers. Significant differences between viewing conditions are shown by the symbols above the bars [**($p < 0.01$)]. "One room," "Two, Front," and "Two, Back" indicate "1-room condition," "2-room condition with the test patches in the front room" and "2-room condition with the test patches in the back room," respectively.

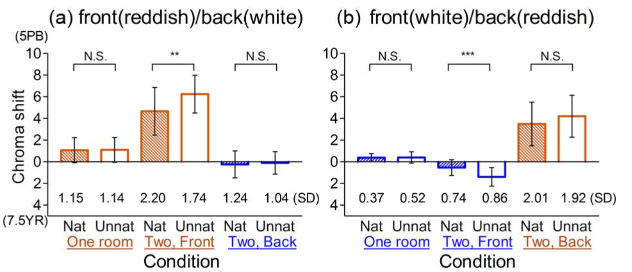

Fig. 7. Shift of color appearances in Munsell chroma. Error bars indicate standard deviation of observers. Significant differences between viewing conditions are shown by the symbols above the bars [**(p < 0.01), ***(p < 0.001)]. "One room," "Two, Front," and "Two, Back" indicate "1-room condition," "2-room condition with the test patches in the front room," and "2-room condition with the test patches in the back room," respectively.

indicates perfect color constancy, and a larger shift indicates decrease of color constancy. For the front(reddish)/back (white) condition [Fig. 7(a)], the one-room condition and the white back room, there is little shift for the natural and unnatural viewing conditions, again suggesting good color constancy. For the case of the reddish front room in the two-room condition, the natural viewing condition induces a shift in the bluish direction, indicating the neutral perception shifted in the direction of the white illuminant in the back room. The unnatural viewing condition shows further shift.

In the front(white)/back(reddish) condition [Fig. 7(b)], the one-room condition again shows little shift for the natural and unnatural viewing conditions. In the case of the white front room in the two-room condition, the natural viewing condition shows little shift (contrary to front(reddish)/back(white) condition). However, the unnatural viewing condition shows a shift in the orangish direction, indicating that the neutral perception shifted toward the reddish illumination of the back room. However, the shift is much smaller than that in the reddish front room for the front(reddish)/back(white) condition. Significant differences between viewing conditions ($p < 0.01$ by Student's t-test) were shown only for the test patch in the front room for the two-room condition.

4. DISCUSSION

We showed that the color constancy was weaker under an unnatural viewing condition when a test patch is in the front room. This suggests that the appearance of the test patch is influenced more by the illumination color of back room when the natural spatial structure was collapsed. This could be interpreted that the simultaneous contrast effect becomes stronger in unnatural viewing conditions since the appearance of test patches in the back room did not show significant difference.

The color appearance did not change in the one-room condition, even for the unnatural viewing condition. This suggests that the distortion of spatial structure by a kaleidoscope does not affect the recognition of illumination color. As a matter of fact, observers reported the impression that illumination color did not change. This would be due to the fact that some parts of the objects were still recognizable through the kaleidoscope or that the statistics of color distribution were kept constant, as in a natural scene [9]. This trend differed from the previous result that color constancy decreased when a photograph was jumbled [19]. It is likely that a real environment includes richer clues sufficient to compensate for the distortion of spatial structure under single illumination. However, many objects in the scene were still recognizable in our distortion, and the possibility remains that a much stronger distortion of a scene could lead to the effects of unnatural viewing conditions on color constancy.

In the natural and unnatural viewing conditions, not only the spatial structure, but also the number of eyes was different (binocular in the natural and monocular in the unnatural). The potential influence of binocular cues versus monocular cues is not clear in our experimental conditions. Some researches (Yang and Shevell [24], for example) showed the increase of color constancy in the monocular compared to the binocular view, but some other researches did not show the difference [25,26]. Probably, the difference of the monocular and binocular views affects color constancy when it changes the recognition of 3D spatial configuration (for examples of extreme cases, see [6,27]). Although we did not examine the difference in color perception of the monocular and binocular views in a natural viewing condition, the position of test patches were recognizable even in the monocular view, and we did not find the difference in color appearance in our preliminary observation. In addition, the result showing good color constancy in one-room condition suggests that the difference of color appearance in the monocular and binocular views is negligible.

The distortion of view by a kaleidoscope-type viewing box also changes low-level stimulus attributes such as spatial frequency components and the spatial distribution of chromaticities across the stimulus. However, it should have changed the color constancy in the one-room condition if those factors had an influence. Additionally, if only the change in low-level stimulus attributes affected the color appearance, then the results of the one-room condition would agree with that of our previous research, since both investigations used essentially the same manipulation [19]. Although we cannot distinguish those factors directly, our results are not likely to be explained solely by a low-level stimulus change.

It should be noted that the neutral perception point in the room is shifted, even in the natural viewing condition in the case of the front(reddish)/back(white) condition. This shows that the back room had an influence on the neutral perception in the front room. Although the reason for the large influence is not clear at present, there are several likely possibilities. One is the simultaneous color contrast effect. It has been reported that a local effect exists, even if a target and its surroundings are separated in depth [28]. However, it has also been shown that the color appearance was not determined solely by local contrast [15]. In the present research, the local contrast may have influenced color judgment. It is possible that the separation of the two rooms was insufficient, as there was a large window and a bright background. Yang and Shevell [29] examined surface color perception under two illuminants and showed that the second illuminant reduced color constancy. In the case of the front(white)/back(reddish) condition, on the other hand, the neutral perception point in the front room is not shifted in the natural viewing condition. This suggests that the test patch under reddish illumination was more influenced by an immediate background. The shift of neutral perception for the test patch in the back room cannot be explained by simultaneous contrast since the background was the wall illuminated by reddish light in this case. The results of test patch under white light, on the other hand, show little shift. The appearance under white illumination would be more stable than those under chromatic illumination.

Kuriki *et al.* showed that a patient with simultaneous agnosia exhibited an extreme simultaneous contrast effect [30]. The patient made achromatic adjustments so that the center color patch had almost the same chromaticity as its surroundings, suggesting that his color constancy could have been realized by the use of local chromatic-contrast signals between the edge of the target and its surroundings with higher priority than that used by normal observers. This would be consistent with the strong influence of the surrounding background under unnatural viewing conditions shown in our results. This suggests that when a spatial structure is destroyed and the overall spatial clue cannot be used, observers use a strategy in which contrast information is a clue for color recognition. It was also shown that a cerebral achromatopsic exhibited a large variation in color-naming as background luminance was varied [31]. Although the judgments of color and lightness depend little on an immediate background under normal circumstances, they might do largely under unnatural circumstances.

Gilchrist proposed an anchoring theory in lightness perception [32,33]. Lightness perception in a scene would be derived from relative luminance values based on a combination of local and global anchoring of lightness values. In the theory, it is assumed that each surface belongs to a framework or frameworks of reference in a scene and is anchored within each framework. The results showing lower color constancy in unnatural viewing conditions could be interpreted using the framework of space and illumination recognition. In natural viewing conditions, the framework of two illuminations is distinct, but not in the unnatural viewing condition.

5. CONCLUSION

Our results showed that color constancy is not influenced by unnatural viewing conditions with a distortion of spatial structure under a single illumination color. However, the degree of color constancy decreased in unnatural viewing conditions in multiple rooms and illumination colors, suggesting that naturalness and spatial factors play an important role in color constancy in a complex environment. Color appearance under white illumination is more stable across different viewing and background conditions. Color appearance under colored (reddish) illumination shows less color constancy in complex environments and has an unstable appearance under different viewing and background conditions. The presence of white illumination would influence the perception of object color. The decrease in color constancy under unnatural environments suggests that the effect of local contrast is stronger in the unnatural viewing condition.

To conclude, our results suggest that spatial factors play important roles in color constancy, at least in a complex illumination environment, and should be considered when the color appearance of an object is to be predicted.

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