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The Brain Adaptation to the Color of Illumination and not the Retinal Adaptation to the Color of Objects that Determines the Color Appearance of an Object in the Space

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Color appearance was measured for a test patch which was placed in a test room illuminated by the daylight type of illumination and was looked at from the subject room illuminated by one of the four colored illuminations, red, yellow, green, and blue, through a window of three different sizes. When the window was the smallest so that only the test patch was seen within the window the color of the test patch appeared almost opponent to the illumination color, but as soon as something is seen within the window of larger size the color returned to the original color of the test patch to indicate the color constancy. To recognize the test room as a space was essential to perceive the real color of the test patch. This returning to the original colors was not influenced by green color of objects densely placed in the test room or by red color of objects again densely placed in the test room. The results imply that the color appearance of the test patch is not determined by the retinal chromatic adaptation, but by the brain adaptation to color of the illumination in the space.

Key words: color appearance, color constancy, chromatic adaptation, space recognition, illumination, recognized visual space of illumination

1. Introduction

The visual system is very sensitive to adapt to the color of illumination in a space, but not so sensitive to the color of objects. We can confirm these properties by some experimental arrangement. Illuminate a room with a colored ceiling light such as a red lamp and open a small hole on the front wall for the next room which is illuminated by the daylight type of illumination. The front wall may be finished by white wallpaper. Beyond the hole put an achromatic paper of a size large enough to fill the hole entirely when a subject looks at the hole. The achromatic paper appears to him as if it is pasted on the hole, which we call the pasting phenomenon. When the subject looks at the subject room from outside the inside appears very reddish, but once he enters into the room the red appearance quickly disappears and the white wall appears white. This demonstrates the property of the visual system called the color constancy. It is often difficult for him to know what color is used for the illumination of the subject room unless he directly looks at the ceiling lamp. Then what color does he see on the hole? He sees a very vivid green or bluish green color.[1,2] The psychophysically achromatic paper turns to the vivid green color. In the next arrangement illuminate the subject room by the daylight type of illumination, but change the front wall to a reddish wall paper so that the reflected light has a similar red color as the first arrangement. Dose the hole appear vivid green color? Answer is no, and unless the entire room is finished with the red wall paper and no objects are left inside the subject room, the hole remains almost achromatic.[3,4] These experiments show that the visual system adapts to the color of illumination but not to the color of objects. In the present paper we will confirm this fact more systematically and precisely.

Let us first explain about the concept of the recognized visual space of illumination RVSI that can explain the above phenomenon. The RVSI is the brain state about the recognition of illumination in a space and illustrated by a circle R as in Fig. 1.[5,6] FX is the fundamental axis to indicate the direction of the absolute achromatic perception and psychophysical achromatic color. IX is the illumination axis to indicate the direction of the color of illumination, the clockwise direction showing red. RX is the recognition axis to indicate the perceptually achromatic color. The direction of the RX is determined by IX in a way it is drawn by IX to come close to IX from the direction FX. This is nothing but the brain adaptation to the color of illumination. Color appearance of any object in this room is determined by the

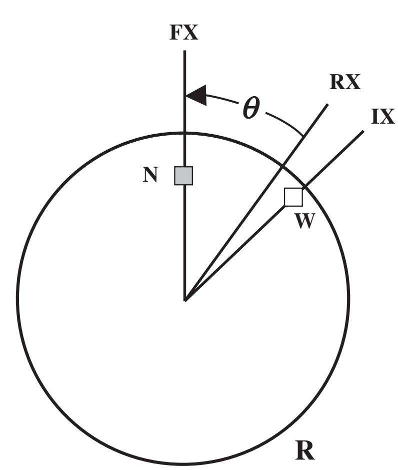

Fig. 1. Scheme to explain color appearance by RVSI.

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angle from the RX to the location of the object in the RVSI. The psychophysical color of the white wall in the above arrangement coincides with the color of illumination and it locates on the IX. The angle from RX to IX is very small in the clockwise direction and the color appearance of the wall should appear slightly reddish, but almost white. This is nothing but the color constancy. The psychophysical color of the aperture is achromatic and an achromatic paper is illuminated by the daylight type of illumination in the next room and it locates on the FX in the RVSI as indicated by N. The angle from RX to N is large in the anticlockwise direction. Its color should appear very vivid green as experienced by the above first arrangement.

In the second arrangement the subject room was illuminated by the daylight type of illumination. The direction of IX coincides with FX and the recognition axis RX remains at the same direction as FX and IX. The achromatic patch in the hole also locates on FX, the angle from RX is zero, and it should appear achromatic.

The strongest and most important assertion in the concept of RVSI is that the recognition axis RX is drawn by IX to come near to it. In other words the chromatic adaptation is achieved by recognizing a space and its illumination. The action of recognizing a space and the illumination is the brain action. So the color constancy is a consequence of the brain adaptation to the illumination. The brain first recognizes the existence of a space, understands about the illumination by looking at objects in the space which are called the initial visual information, and adapts to the illumination. This assertion was proved in a previous experiment where we showed that the color appearance of a test patch changed radically at an instance when a subject recognized the existence of a space.[2] The assertion implies that the brain does not adapt to the color of objects in a space. The present experiment was designed to prove it.

Most of the recent researchers conducted experiments on the color constancy by using a two-dimensional display controlled by computer. In these cases it is not clearly defined to what space the subjects adapted and it is difficult to interpret the results by the concept of RVSI. We are encouraged to see some researchers, not many, used a natural viewing condition by putting subjects in a three-dimensional real room.[4,7–9] It is laborious to construct a real room of which illumination is adjustable and to set up a test stimulus of which color is adjustable independent of the room illumination. But we believe it is vitally important to conduct the experiment in that way so that the subject can recognize a space and its illumination.

2. Experimental Rational and Apparatus

A subject stays in a subject's room illuminated by a colored ceiling light and sees a test room next to the subject's room through a small window. The test room is illuminated by the light of daylight type. He judges the color appearance of a test patch placed in the test room by the elementary color naming method. There exist different methods to assess color appearance of a test patch; the asymmetrical color matching,[10,11] the null method to adjust the test patch to a neutral color appearance,[4,7,12] the elementary color naming method,[1,2,8] and others. We employ the elementary color naming method as it can assess most directly the color appearance of a test patch.

Now when the window to the test room is small so that the subject can only see the test patch filling the window the patch is recognized as an object in the subject room. The color appearance is determined by the principle given in Fig. 1. That is, if the subject's room is illuminated reddishly, the appearance shifts toward green side. This prediction was already confirmed by the previous experiment. When the window is enlarged so that the subject can see objects in the test room beside the test patch, he will immediately recognize the existence of the test room and its illumination, and he will perceive the original color of the test patch to show the color constancy. This prediction was also confirmed by the previous experiment.

In the present experiment the test room is decorated in one of two ways, mostly by red objects, or mostly by green objects. The retinal color distribution of the subject is quite oriented between the two conditions. If the brain adapts to the color of illumination and not to the retinal color distribution, the subject's judgment for the color appearance of the test patch should not differ among the two conditions when the window is large enough to see objects in the test room and to recognize the existence of the test room. On the other hand if the brain adapts to the color of objects the color appearance of the test patch should differ among the two conditions.

The apparatus is same as before but with a slight modification about the test room. The subject's room is a normal room with the size, 1.3 m long, 1 m wide, and 2.4 m high. The walls were furnished with an achromatic wall paper of about N9.3. Objects of various colors were decorated on the front shelf and on the front wall as seen in Fig. 2. The picture shown as Fig. 2 was taken when the room was illuminated with a red light. On the front wall at the subject's eye level a window was opened through which the subject could see the test room. Only one eye was used to

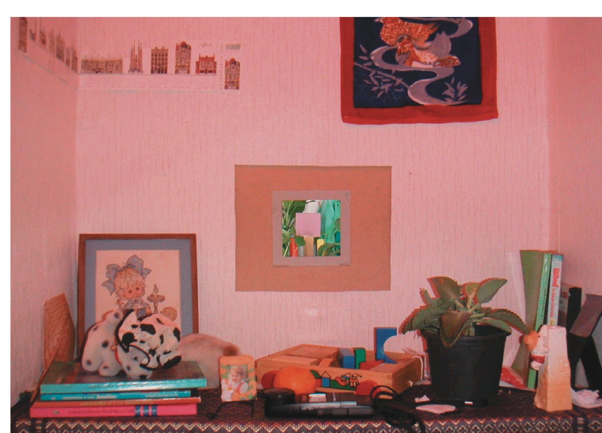

Fig. 2. Front view of the subject room. The window for the test room is W_3 in this case.

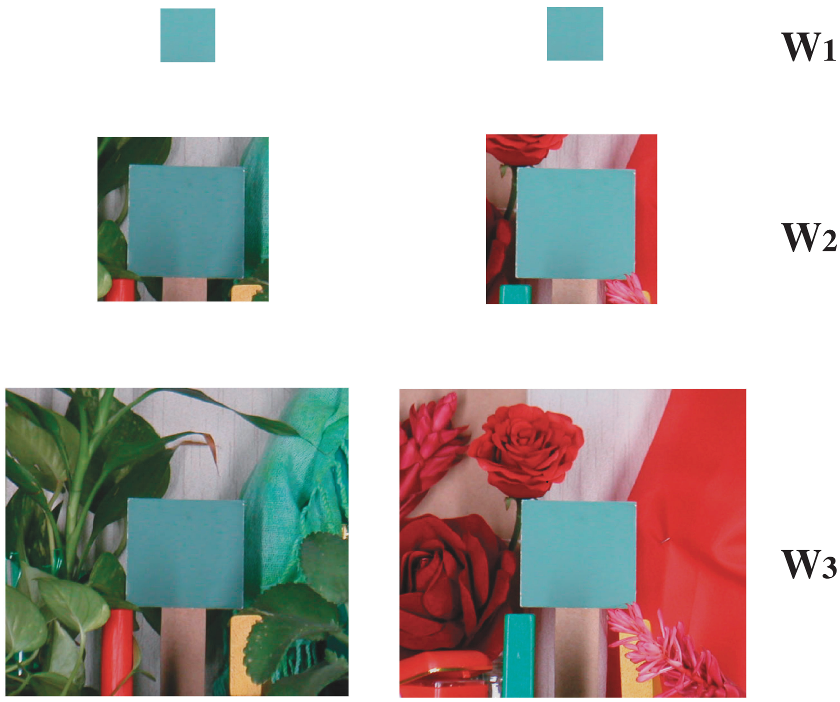

Fig. 3. Test room viewed through different window, W_1, W_2, and W_3. Left column, green condition; right, red condition.

observe the test room. The subject did not use a chinrest or other tool to fix his head. He could move his head horizontally, though he was not particularly encouraged to do so. Three different sizes of window were employed in the present experiment; 19×19, 60×60, and $120 \times 120\,\text{mm}^2$, which turn out 1.2×1.2, 3.8×3.8, and 7.6×7.6 degrees^2 of visual angle, respectively. They are specified as W_1, W_2, and W_3. Figure 2 shows the case of W_3.

The test room behind the subject room had the depth slightly longer than 90 cm. At the center of the room a test patch of the size $8 \times 8\,\text{cm}^2$ was placed by a supporting plywood. The distance from the window to the test patch was 87 cm. The distance from the subject's eye to the window was 90 cm. The test room was illuminated by fluorescent lamps of the daylight type. In the green condition the test room was mostly decorated by green objects as shown at the bottom left of Fig. 3 and in the red condition mostly by red objects as shown at the bottom right. These pictures indicate the visual extent seen through the window W_3. The square at the center is the test patch. Green objects in the green condition were a green cloth and a green real plant on the right, and green real plants on the left. There were placed a red and a yellow block at the bottom. The supporting plywood of the test patch was light brown. The back wall was a white wall paper of N9.3, same as the subject room. These green objects occupied 70% of the entire area of the window W_3 excepting the area of the test patch. In the case of the window W_2 the green objects occupied 68% of the entire area again excepting the test patch area. Red objects in the red condition were a red cloth and a real red flower at the right, artificial two red roses, a real red flower, and a red box on the left. There were placed a green and a yellow block at the bottom. These red objects occupied 70% of the entire area of the window W_3

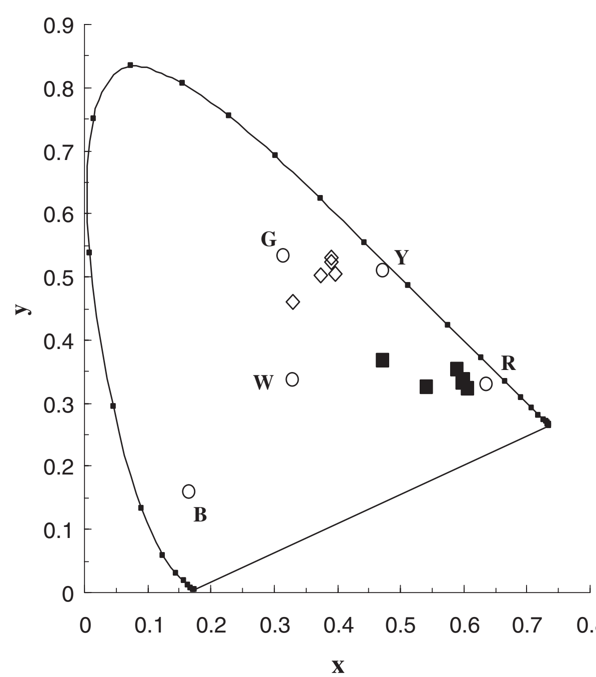

Fig. 4. Chromaticities of illuminations and objects. ○, the subject room illumination, R for red, Y for yellow, G for green, and B for blue. W indicates the test room illumination. ■, red objects in the red condition; ◇, green objects in the green condition.

excepting the test patch area. In the case of the window W_2 the red objects occupied 53%. Chromaticity coordinates x and y of some objects are shown by filled squares for red objects and open diamonds for green objects in Fig. 4. If our hypothesis is correct, that is the brain adapts to the color of the room illumination and not to the color of the objects, the color appearance of the test patch should return to its original color when the window is enlarged from W_1 to W_2, when the subject can recognize the existence of the test room, regardless the conditions.

Four different colors of illumination were employed for the subject room, red, yellow, green, and blue, and their chromaticity coordinates are shown by open circles indicated by R, Y, G, and B in Fig. 4. Note that the object colors of the red condition are close to the red illumination and those of the green condition to the green illumination. The chromaticity point of the test room is shown by W. The horizontal illuminance of the subject room was kept constant at 30 lx on the front shelf regardless of the color of the illumination. It was measured by an illuminometer placed on the shelf as seen in Fig. 2. The illuminance of the test room was kept constant at 25 lx when measured on a vertical plane just in front of the test patch. The illuminance was chosen so that the test patches appeared object color in most cases with the window W_1.

Five different test patches were employed, 5R5/3, 5Y5/3, 5G5/3, 5B5/3, and N5 as before.

3. Procedure

Subjects' task was to judge the color appearance of test patches by the elementary color naming method, namely the judgment of the amounts of chromaticness, whiteness and blackness in percentage, and the amounts of unique hues in percentage. No time limitation was set for the judgment. An experimenter set up the color of the ceiling light to one of the four colors, red, yellow, green or blue, and a subject adapted to the subject room for a few minutes. For this illumination the experimenter presented the subject 15 combinations of all five test patches and three windows arranged in a random order to complete one session. Five such sessions were conducted for each illumination.

Three subjects, all with normal color vision, participated in the experiment: MI (male, 71 years old, Japanese), PP (female, 53, Thai), and PK (female, 33, Thai). All of them participated in the previous experiment.[2] Both eyes of the subject MI had been operated for cataracts and inserted with intraocular lenses. MI used his right eye, PP and PK their left eye to observe the test patch. No chin rest was used and the subjects were free to move their heads, but they were instructed to locate their heads at position so that the test patch came at the center of the window at the time of their judgment. The subjects were advised to look around the subject room and not to gaze at the test patch except the instance when they made the color appearance judgment of the patch.

4. Results and Discussion

Results are shown on the polar diagram used normally in the elementary color naming experiment as shown in Fig. 5. In each figure the distance from the center gives the amount of the chromaticness, the maximum being 100 on the circle, and the angle the hue appearance. R, Y, G, and B represent unique red, yellow, green, and blue hue, respectively. The amounts of whiteness and blackness are not shown here. Four figures correspond to different illumination of the subject room, red, yellow, green, and blue. The color appearance of the illumination is given by a large open square for red illumination, a large open triangle for yellow, a large open diamond for green, and a large x for blue. Each data point in the figures is the average of three subjects. Different test patches are represented by symbols, 5R by squares, 5Y by triangles, 5G by diamonds, and 5B by cross and its modification with a vertical line. The results from the green condition of the test room are shown by open symbols and those from the red condition by filled symbols. For the 5B test patch they are shown by cross and cross with a vertical bar, respectively. Four open circles in each figure give the color appearance of the four test patches obtained under the control condition, when both subject room and test room were illuminated by the daylight type of illumination. These values and those of color appearance of the illumination are borrowed from the previous experiment.[2] To avoid the complication of the figures the results of the test patch 5N are separately plotted in the next figure.

There are always three data points for every test patch corresponding to windows W_1, W_2, and W_3 as connected by lines. But in many conditions two points from W_2 and W_3 overlapped with each other coming near to the appearance under the control condition. The data point from W_1 always separates from other two points and it locates opposite to the color appearance of the illumination. This is quite understandable from the RVSI theory. When the illumination was red, for example, of which color appearance was given by the control condition, the color appearance of any object in the subject room should be determined based on the recognition axis RX of the RVSI for the subject room located close to the illumination axis IX as illustrated in Fig. 1. The window W_1 was small and any test patch was judged as an object placed in the subject room and the appearance was made based on that axis of RX and not on the neutral axis represented by FX. The color appearance of any test patch should come opposite to the color appearance of the illumination. Color appearances of all patches shifted leftward opposite to a large open square with W_1 in the case of red illumination. Those shifted downward opposite to a large open triangle in the yellow illumination, rightward opposite to a large open diamond in the green illumination, and upward opposite to a large cross in the blue illumination, all as predicted by the RVSI theory.

There is observed some variance in the data points between the green and red conditions with the window W_1. For examples in the red illumination, the filled square locates a little bit toward red side compared with the open square, and similarly the filled triangle locates toward red side compared with the open triangle. One reason for this would be that the test patches had influence from colored objects placed in the test room such that colored light was reflected from the objects to fall on the test patches. However, the colorimetric measurement did not show the influence and the test patches gave same chromaticity coordinates, x and y, regardless the test room conditions. The variance is observed in other illumination, but the direction is sometime opposite from the red illumination case. In the

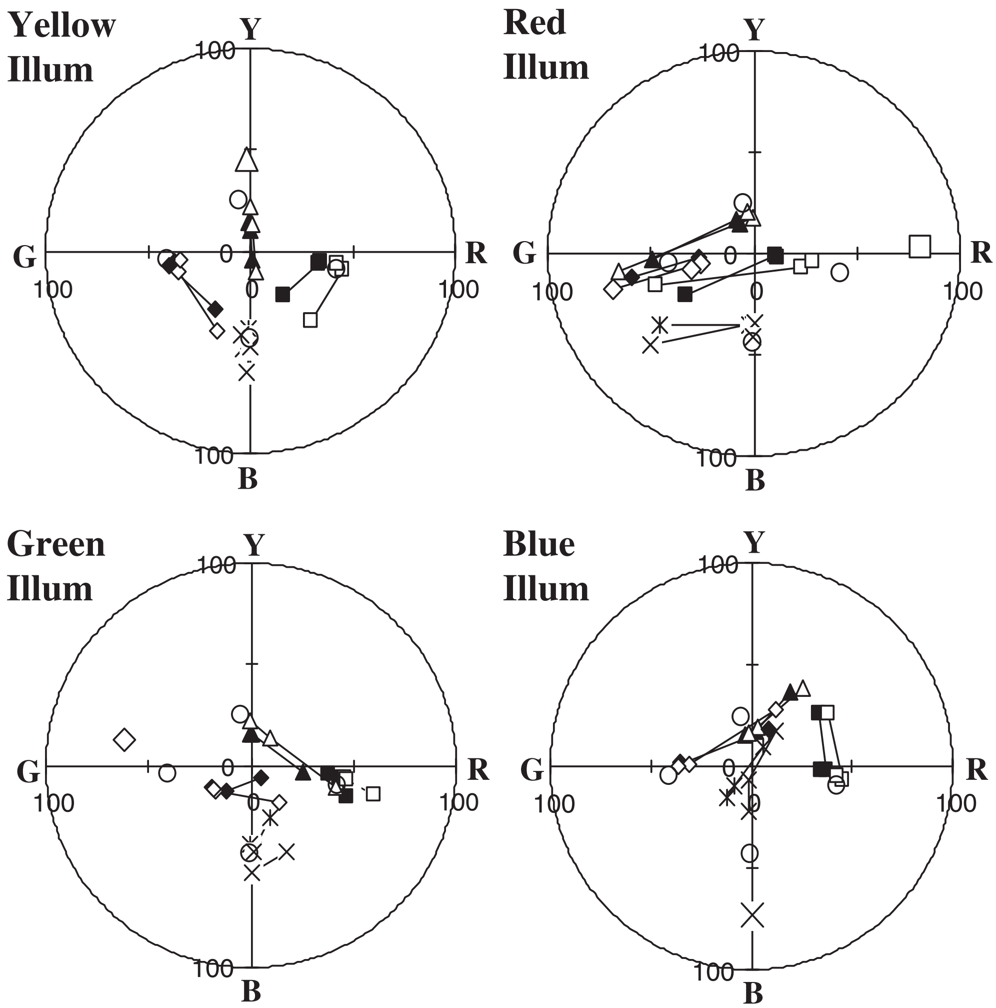

Fig. 5. Color appearance change of test patches for windows W_1, W_2, and W_3. Mean results of three subjects. Sections correspond to four different illumination colors of the subject room. Symbols indicate test patches. □ and ■, 5R; △ and ▲, 5Y; ◇ and ◆, 5G; × and × with a vertical bar, 5B. Open symbols and cross are from the green condition, and filled symbols and cross with a vertical bar are from the red condition. Four open circles indicated the original color of test patches. A large open square, a large open triangle, a large open diamond, and a large cross indicate color appearance of red, yellow, green, and blue illumination of the subject room.

yellow illumination the data point of the red test patch locates toward green with the red condition, for example. We interpret the variance as simple variance of subjects' observation.

The color appearance of test patches suddenly changed to return toward their original colors when the window was changed from W_1 to W_2. This was predicted by the RVSI theory and had been shown by the previous experiment.[2] Subjects could see only few of objects in the test room with W_2 as understood from Fig. 3 but they could already recognize the existence of the test room and could construct a new RVSI for the test room and judged the color of test patches by the RVSI constructed for the daylight type of illumination. The recognition of the test room is nothing but the action of the brain.

Figure 6 shows the results of the test patch N5 for all four illuminations. Symbols here indicate the illumination; squares for red, triangles for yellow, diamonds for green, and cross and cross with a vertical bar for blue illumination, respectively. Large symbols show the color appearance of those illuminations. All points obtained with W_1 locate far from the center or the neutral color appearance and their locations are opposite to respective illumination color. They return to the center when the window was enlarged to W_2. The color constancy took place already with W_2.

Our main aim of the present investigation was to show that the color appearance of test patches are determined by the recognized illumination of a space to which the test patches belong, and not by the retinal chromatic distribution. To see this point, only the data points from W_3 are plotted together for all the five test patches in Fig. 7. Ways of plotting are same as in Fig. 4. All the points came close to the original color shown by open circles to show the color constancy. But there is observed a large deviation from the color constancy in cases when the color of test patch is of the same category as illumination of the subject room. In the

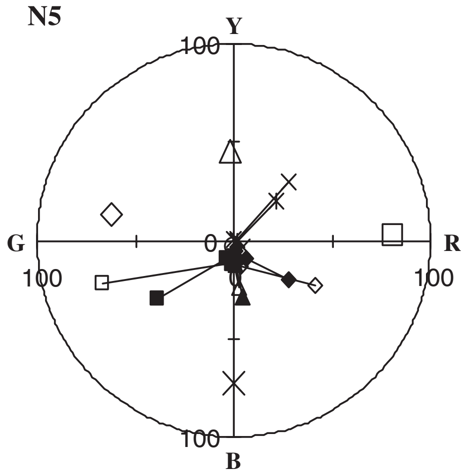

Fig. 6. Color appearance change of the test patch N5 for windows W_1, W_2, and W_3. Symbols indicate the illumination color; squares for red illumination of the subject room, triangles for yellow illumination, diamonds for green illumination, and cross and cross with a vertical bar for blue illumination. Color appearance of illumination of the subject room is indicated by large symbols of □, △, ◇, and ×.

case of red illumination points of 5R5/3 shown by squares deviate from the original color to the opposite direction from the red illumination color shown by a large open square. In the green illumination the points of 5G5/3 shown by diamonds deviate the original color in the direction opposite to the illumination color shown by large open diamond. Similarly in the blue illumination the points of 5B5/3 shown by cross deviated from the original color to the direction opposite to the illumination color shown by a large cross. These show that the color appearance of a test patch is still influenced by the RVSI of the subject room, but only when the color of the test patch is same as the illumination color of the subject room.

The most important point in the present experiment is whether the color appearance of test patches does not differ between the red and green conditions of the test room. Subjects repeated judgment for color appearance for five times for any experimental condition. We calculated the standard deviations of the five data points along the R–G axis and the Y–B axis respectively and plotted them for color appearance points of both red and green conditions of four test patches, 5R, 5Y, 5G, and 5B in Fig. 8. The upper two figures are from the subject PP and the lower two are

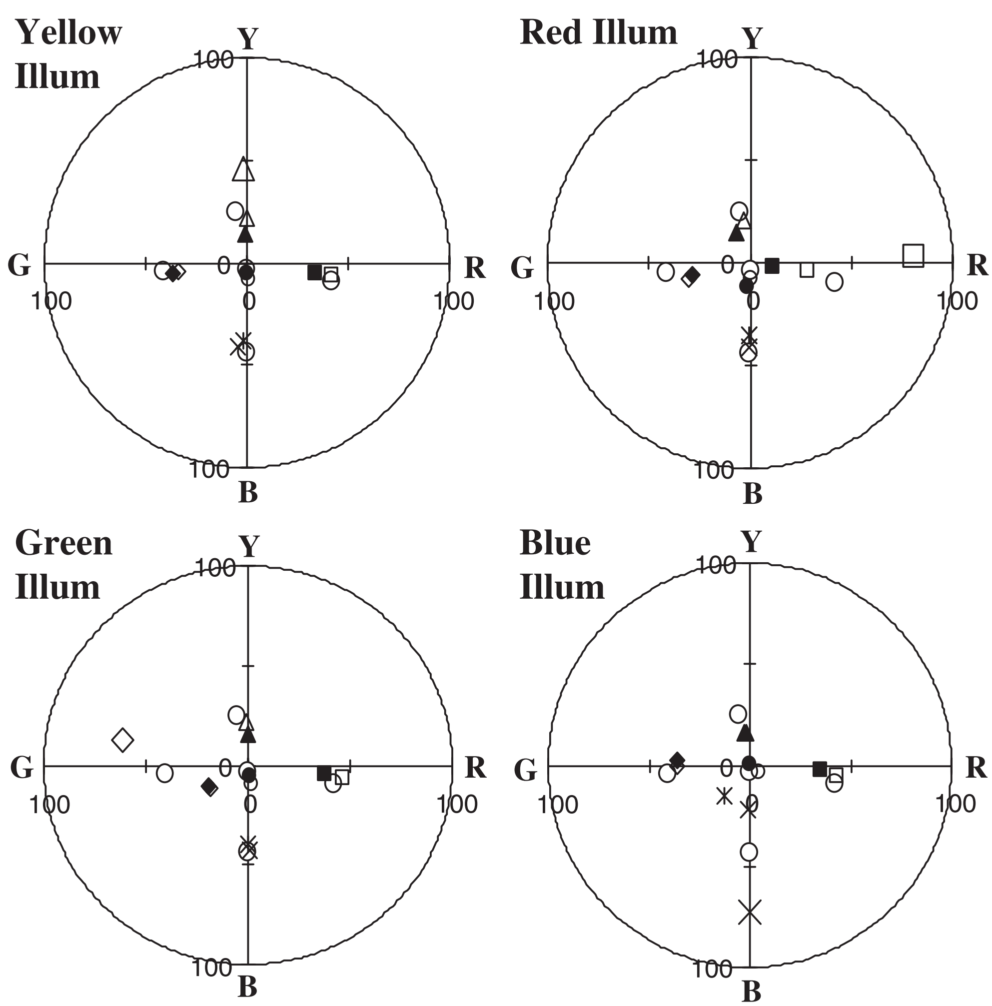

Fig. 7. Color appearance of all the test patches with the window W_3. Symbols for the test patches are same as in Fig. 5.

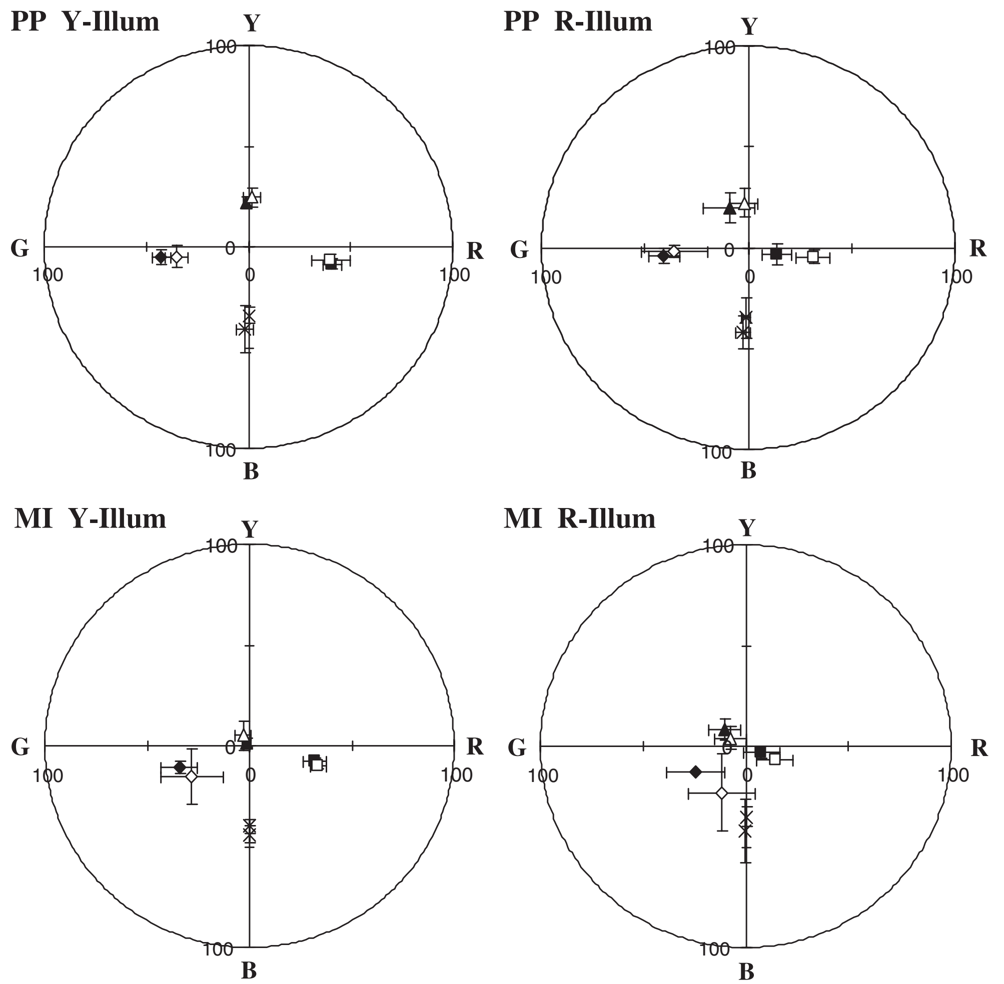

Fig. 8. Standard deviation of five judgments plotted for each test patch with window W_3. Those for the test patch N5 are not shown. Upper two figures are from the subject PP and the lower from MI.

from MI. Only data of red and yellow illumination are shown, which roughly represent cases of large deviation and small deviation, respectively. Except few points the ranges of standard deviation overlap with each other between the red and green conditions. We can conclude that the color appearance of test patches are almost same regardless of the color of their immediate background.

Returning to Fig. 7 we can say that many pairs of data points of red and green condition come very close with each other and they almost overlap. Only exception is for the red test patch of 5R5/3 shown by squares in the case of red illumination. To see overall difference between the red and green condition we took average of the four figures of Fig. 7 and plotted in Fig. 9. We see the difference is small between filled and open symbols and can conclude that the color of objects in the test room does not influence the color appearance of test patches.

Put it in a different expression, the color appearance is not determined by the retinal chromatic distribution, that is, not by the retinal chromatic adaptation. In Fig. 4 we see that the colors of red objects in the test room are close to the red illumination of the subject room and so the colors of green

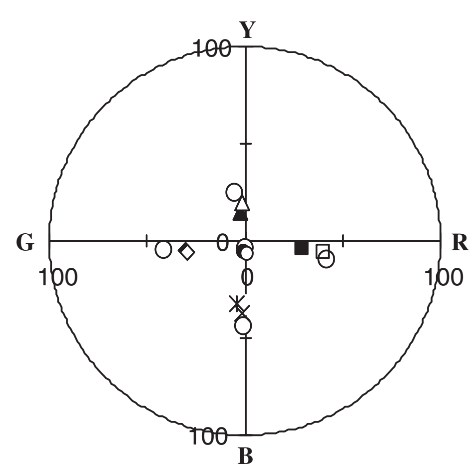

Fig. 9. Color appearance of all the five test patches with the window W_3. Each point is the average of four illuminations. Symbols are same as in Fig. 5.

objects to the green illumination. There is not much difference in chromatic distribution on the retina of a subject whether he looked around the subject room with the window W_1 or looked around the test room through W_3 in respective conditions. But the color appearance of test patches differed greatly as shown in Figs. 5 and 6. It is quite clear now that the color appearance of test patches is determined by the brain adaptation to the illumination of the space that he recognizes. With W_1 he adapted to the colored illumination of the subject room and the recognition axis RX shifted from the fundamental axis FX. Consequently the color appearance of test patches changed according to the amount and the direction of the shift. With W_3 he adapted to the white illumination of the test room and the recognition axis remained at the direction of FX. The color appearance of test patches also remained as their original colors regardless of the red condition or the green condition. In general the color appearance of objects in a space is determined by the brain which adapt to the illumination and not by the retina which might adapt to the color of objects to some extent.

With windows W_2 and W_3 subjects recognized the test room as a new space. The entire visual field of the new space is the size of W_2 and W_3. That entire field excepting the test patch is occupied by either green or red objects. Yet, the color of the objects did not affect the perception of the color of test patch. No wonder Brainard did not get any influence of the background color upon the color of a test patch.[4] In his case the size of the background was small compared to the size of the room and it constituted only a small part of front wall of the room. The RVSI of his subjects must be solidly constructed for the ceiling light and the test patch appeared same color no matter what background he placed behind the test patch.

Gilchrist showed elegantly that the lightness of a test patch was determined in relation to the space to which the subject thought the patch belonged.[13] But he limited his interpretation to plane, not space, as to the position of the test patch, thus he used the word coplanar. We expanded the word coplanar to cospatial as the most important point is whether a test patch belongs to this and that space, not only at this plane and that plane.[14]

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