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Color Appearance Determined by Recognition of Space

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The color appearance was measured for a test patch which was placed in a test room illuminated by daylight lamps and was looked at from a subject room illuminated by one of four colored illuminations, red, yellow, green and blue, through windows of various sizes. When the window was small 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 was seen within the window of a larger size the color returned to the original color of the test patch. To recognize the test room as a space was essential to perceive the real color of the test patch. The results were explained by the concept of the recognized visual space of illumination.

Key words: color appearance, color mode, color constancy, chromatic adaptation, apparent lightness, space recognition, recognized visual space of illumination, 3D space

1. Introduction

The central point of the concept of recognized visual space of illumination RVSI is the claim that the color appearance of any objects or surfaces is determined based on recognition of illumination in the space where they are placed. In other words the recognition about the illumination takes place first and then the color perception follows. The recognition of the illumination in the space takes place when people recognize the existence of the space. This claim was affirmatively shown by an experiment where the color of an achromatic test patch was judged when seen through a red, yellow, green or blue filter in a room illuminated by a daylight type of lamp.[1)] When the filter was close to the patch so that the subject saw only the patch inside the filter, the color appeared the same as that of the filter. The appearance changed to the original color of the test patch, namely achromatic, as soon as the subject saw something inside the filter besides the test patch surface as the filter was moved from the patch toward the subject. In other words the color of the test patch returned to its original color whenever the subject recognized another space through the filter besides the space where the subject stayed. In the experiment, however, it was not physically another space that the subject saw but a space seen through a filter. The subject saw the same space as he stayed but only a portion of it through the filter.

In this experiment we will actually present a subject a physically different space where a test patch is placed and which is differently illuminated from the subject room. The subject will see the space through a window opened between the two rooms. The size of the window will be varied so that the information the subject can get for the test room is varied. We can expect that the appearance of the test patch will return to its original color whenever he can construct a new RVSI for the test room. The method of using two real rooms and of changing the window size was used before,[2,3)] but the color appearance change of the test patch demonstrated was very small. We can now see the reasons for the small change. Even with the smallest window in that arrangement some other portions of the test room were already visible besides the test patch, though only a little piece of them. Binocular observation was used and it helped to recognize the existence of the test room even with the smallest window. The difference in color of the illumination between the two rooms was not large enough to exaggerate the color appearance of the test patch. These three settings in the previous experiment will be improved in the present experiment.

2. Apparatus

An experimental booth was built at Chulalongkorn University and was composed of two rooms as in the previous experiment,[1)] the subject room and the test room, separated by a wall with a window of variable size. Both rooms were furnished with the same achromatic wallpaper of about N9.3 which had some texture. The subject room was 1.3 m long, 1 m wide and 2.4 m high and various objects were put on the shelf attached to the front wall. Pictures were also hung on the wall. The objects were books, wooden blocks, artificial flowers, dolls, a real green plant, a table cross, and others as shown in Fig. 1. A window indicated by a small square W was opened on the front wall at the eye level of the subject sitting on a stool and she could see the test room through it. The size of the window was changed by replacing plywood P on which apertures 19×19, 33×33, 60×60, 120×120, and $270 \times 320\,\text{mm}^2$ in size were opened, respectively. They were denoted as windows 1, 2, 3, 4 and 5, or W1, W2, W3, W4 and W5, respectively. Figure 1 illustrates window 1.

A small standing plate denoted as N was a holder for an achromatic patch of N5 which was pasted on the plate facing the window. A subject could see the surface through window 1 from the side of the test room. The arrangement was for one of the control experiments where the color appearance of the illumination in the subject room was measured.

The test room was also decorated by various objects such as dolls, wooden blocks, a sculpture, living plants, books, a

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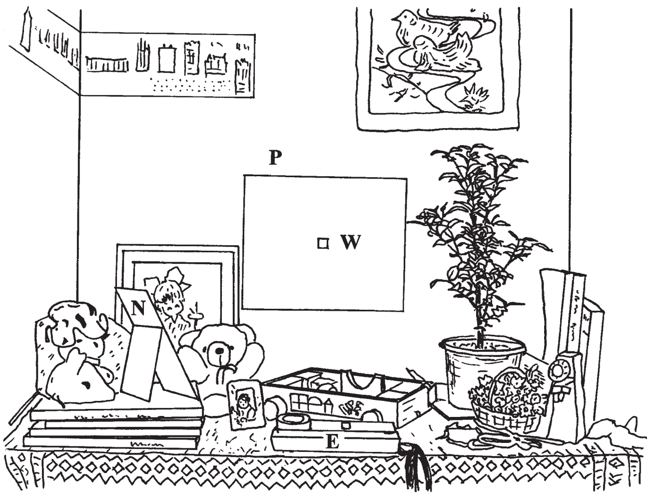

Fig. 1. Subject's front view. W, window for the test room; P, frame for the window; E, illuminometer; N, achromatic patch for the control experiment. The patch is pasted facing to the window W.

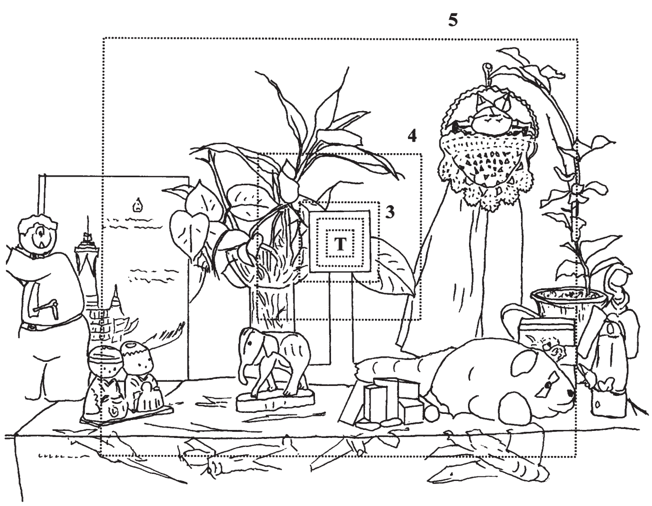

Fig. 2. View of the test room. A square drawn by solid lines and denoted as T indicates the test patch. Four squares and a rectangle drawn by dotted lines indicate the visual fields seen through windows 1 through 5.

table cross and others as shown in Fig. 2. The central square T drawn by solid lines is the test patch $8 \times 8\,\mathrm{cm}^2$ in size. It was attached at the top of a supporting arm which was temporally fixed on a shelf. The arm was easily changed to another arm when the test patch was to be changed. The depth of the shelf on which the above objects were placed was 35 cm and the test patch was separated from the back wall by 14 cm. These arrangements helped the subjects to perceive a three dimensional space for the test room. Four squares and one rectangle drawn by dotted lines show the extent of the visual field viewed monocularly by the subject through different windows. The visual fields of the windows 3, 4 and 5 are indicated by the corresponding numbers. Figure 3 shows only the inside scenes of windows. With the small two windows, W1 and W2 they were filled only with the test patch. In these cases the surface of the test patch

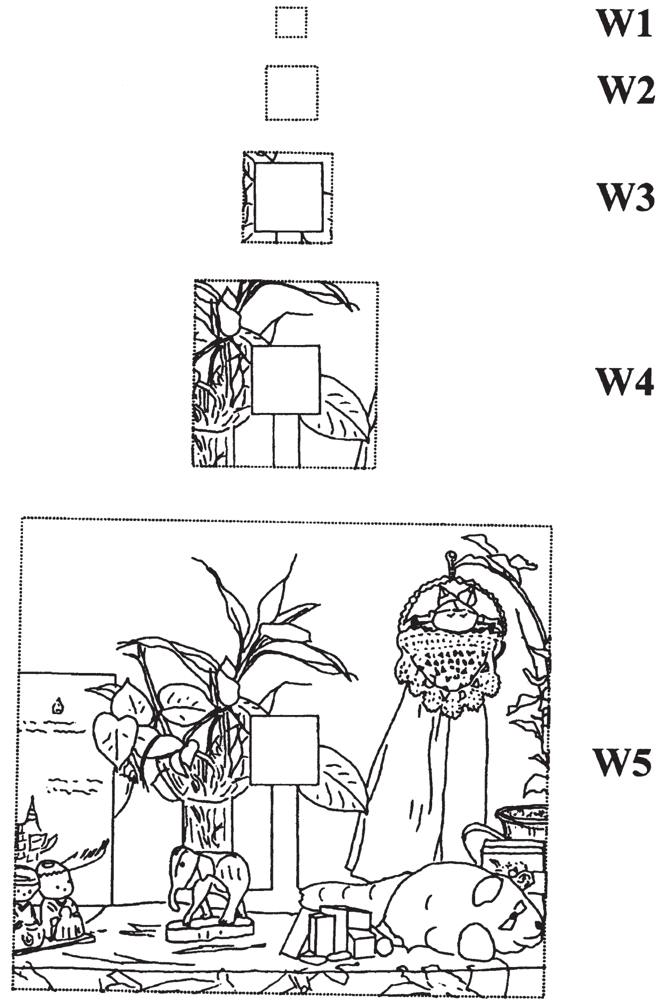

Fig. 3. View of the test room with different windows.

appeared to the subject as if it was pasted on and just a part of the front wall. The distance from the subject's eye to the window was 90 cm and that from the window to the test patch was 87 cm.

Two fluorescent lamps of daylight type served as the ceiling light of the subject room. They were covered by one of four colored films, red, yellow, green or blue to provide colored illumination for this room. Their chromaticities are shown in Fig. 4 by filled circles denoted by R, Y, G and B, respectively. The open circle W represents the color without any film. The solid curve represents the black body locus. The test room was always illuminated by the lamps without films and its chromaticity coordinates coincide with W in Fig. 4. Both illuminance of the subject and the test room were controlled by the respective light controllers. In the present experiment the 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 E placed on the shelf as shown in Fig. 1. The illuminance of the test room was also 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 did not appear light source color because of high luminance but appeared object color in most cases.

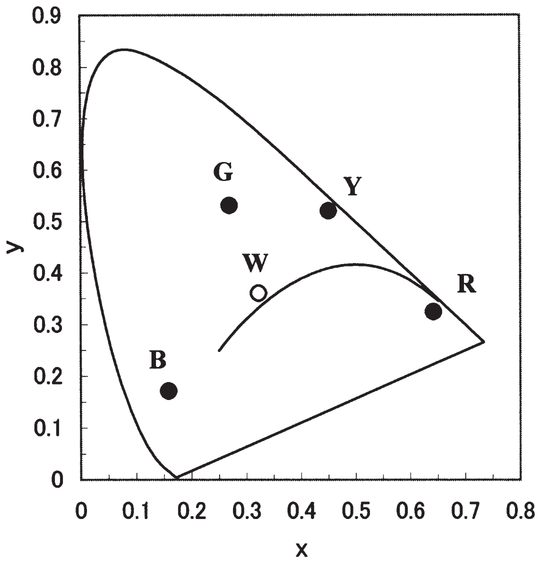

Fig. 4. Chromaticities of colored illumination of the subject room.

Five different colors were employed for the test patch, 5R5/3, 5Y5/3, 5G5/3, 5B5/3 and N5.

3. Procedure

After a few minutes of adaptation time in the subject room which was lit with one of the four colored illuminations the subject looked monocularly at the test patch through the window and judged the color by the elementary color naming method, the amounts of chromaticness, whiteness and blackness first and the amounts of unique hues next, both in percentage. The subject was instructed not to fix her eyes on the test patch alone but to look around the rooms except when she was to judge the test patch color. This was to construct and keep stable the RVSI for the subject room. For the same reason no chinrest or mouthpiece was used, so that the subject could move his/her head freely. Each was asked, however, not to move his/her body to peep around the test room through the window. Five test patches were randomly presented and five windows were also randomly employed. When all 25 combinations had been investigated one session was over. Five such sessions were carried out for each illumination color.

Besides the above experiments two control experiments were carried out. One was to measure the color appearance of the illumination in the subject room as exhibited on the achromatic color patch N5 placed in that room, shown by N in Fig. 1. Its color was judged as seen from the test room through window 1. Patch N5 was large enough so that window 1 was filled only with the patch and no other objects could be seen by the subject in the test room. The color of the illumination without any color film was also measured. The other was to measure the original color appearance of the test patches. This was done by observing the test patches through window 5 when both rooms were lit with the daylight type of lamps. Measurement was repeated five times in both experiments.

Four subjects, all with normal color vision, participated in the experiment: MI (male, 70 years old, Japanese), PP (female, 52, Thai), PK (female, 32, Thai) and AK (female, 23, Japanese). Both eyes of the subject MI had been operated for cataracts and intraocular lenses inserted about one year earlier. Except for subject PK, they had had prior experience being a subject for this kind of experiment. The subjects MI and AK used their right eye, and PP and PK their left eye.

4. Results

The color of the test patch appeared natural in most cases, but with a few exceptions. With the red and blue illumination and with windows 1 and 2 all the test patches appeared unnatural. With the green illumination only the red test patch, 5R5/3 appeared a little bit unnatural. With the yellow illumination such unnatural appearance was not experienced at all. According to the concept of RVSI an object appears natural if it has the luminance to locate inside the RVSI and appears unnatural if it has the luminance to locate outside the RVSI.[4)] The border luminance between natural and unnatural appearance was denoted as nBu by Thiangthangtum *et al.*[5–7)] In the present experiment the luminance of the test patches was kept constant with a constant vertical plane illuminance 25 lx and with a constant Munsell Value 5. Different color appearance modes indicate the test patches were judged based on different RVSIs: on the RVSI for the subject room with W3 to W5 and on the RVSI for the test room with W1 and W2.

The results of the control experiment are shown in Fig. 5 on a usual polar diagram of hue and chromaticness elements, on the left the color of the illumination of the subject room and on the right the original color of the test patches. Different symbols represent subjects and the filled circles their average. The chromaticness is given by the distance from the center and the outer circle corresponds to chromaticness of 100%. The angle gives the hue in terms of the percentage of the unique hues, R, Y, G and B. Individual variation is small in judging the color of illumination, but larger in judging the color of test patches. In the case of illumination the color was exhibited on the achromatic patch of N5 and seen from the test room through or rather at the aperture of the smallest window. The subject

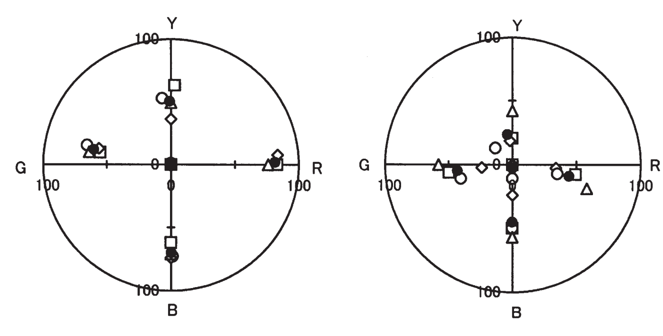

Fig. 5. Left, colors of illumination of the subject room as judged from the test room. Right, original colors as judged for the test patches. ○, the subject MI; ◇, PP; △, PK; □, AK; ●, the mean.

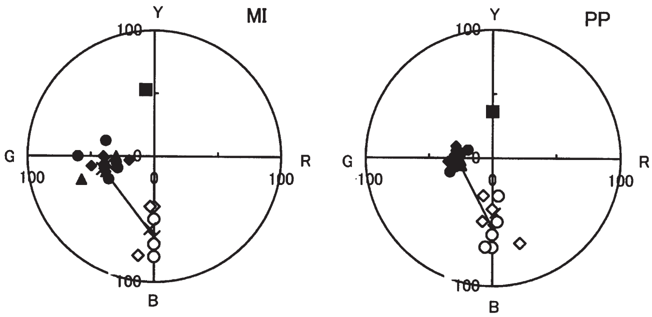

Fig. 6. Data from the yellow illumination and the green test patch combination. Left, the subject MI; right, PP. Symbols indicate the window size: ◇, W1; ○, W2; ▲, W3; ●, W4; ■, W5; ×, the average of five sessions. A large filled square shows the color appearance of the illumination judged by respective subjects.

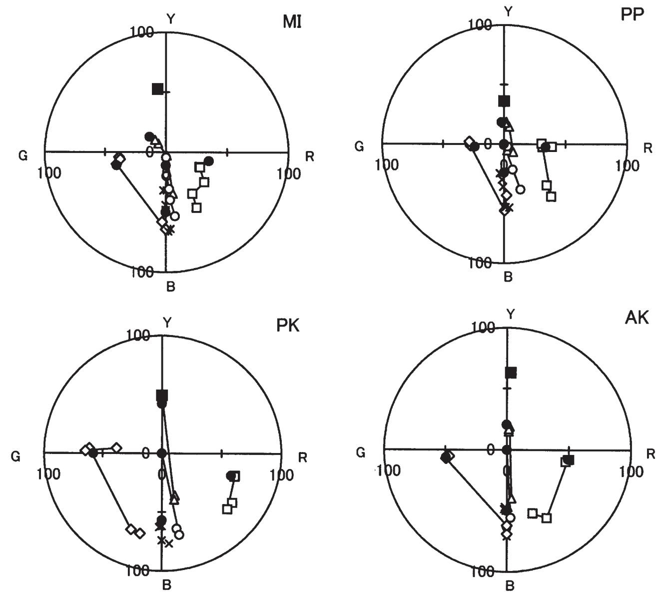

Fig. 7. Results for the yellow illumination and five test patches. Each section corresponds to a subject. □, the test patch 5R; △, 5Y; ◇, 5G; ×, 5B; ○, N5. Filled circles denote the original color of the test patches and a large filled square the color appearance of the yellow illumination.

perceived only color there and did not need to imagine anything about its property as an object. In the case of test patches the color was seen as an attribute of an object. It was possible that the judgement about the color was influenced by the judgement about the object, thus causing large individual variation. All the colors of illumination happened to be almost unique hues except the green illumination which deviated a little bit from the unique green toward yellow. The colors of the test patches were also very close to the unique hues.

Figure 6 shows the results of the color judgement by the subject MI on the left and PP on the right for the test patch 5G5/3 with the yellow illumination of the subject room. Symbols correspond to the window size, open diamonds, open circles, filled triangles, filled circles, and filled squares to windows 1, 2, 3, 4 and 5 respectively. There are five data points for each symbol corresponding to the five sessions. A large filled square gives the color appearance of the room illumination as judged by the respective subject. Five data points of each window size scatter to some extent to indicate the variance in judging the color appearance of the test patch, but data points are clearly grouped into two, open symbols at blue color and filled symbols at green color. By referring to Fig. 5 we notice that all the filled symbols are near the original color of the test patch and we can know that the color of the test patch was judged based on the recognition of the illumination of the test room. The open symbols, on the other hands, are far from the original color and locate at the opposite side of the illumination color. They were obtained with W1 and W2, where the windows were filled only with the test patch and no other objects of the test room were seen through the windows. The color of the test patch was judged based on the recognition of illumination for the subject room.

Data from five sessions were averaged for all the test patches and the results are shown in Fig. 7 for the four subjects and for the case of yellow illumination. Different symbols represent test patches, squares for 5R5/3, triangles for 5Y5/3, diamonds for 5G5/3, exes for 5B5/3 and circles for N5. There should be five points for each symbol, but those from W1 and W2 overlapped sometimes and those from W3, W4, and W5 also overlapped sometimes so that in some cases there appeared fewer points than 5. Filled circles show the original color of the test patches and large filled squares the color of the yellow illumination. When the window was small as true of W1 and W2 the colors of all the test patches appeared very bluish and the corresponding two data points locate at the bottom in the polar diagram; when it was enlarged as W3, W4 and W5 they all shifted upward to return to their original colors, which differed among subjects as we saw in Fig. 5.

As all the subjects showed similar effects of the window size for all four illuminations we took the average of the four subjects. The results are shown in Fig. 8. Different symbols represent test patches as before and filled squares the colors of illumination in the subject room. Colors of test patches appeared roughly but not exactly opposite the color appearance of the illumination when the window size was 1 or 2, or when the subjects could see only the test patches through the windows. In these situations the color of the patches must be judged based on the RVSI for the subject room. Ikeda *et al.* obtained the color appearance of a physically achromatic patch for different colors of illumination.[8,9] The present results for the test patch N5 agree quite well with their results when the window was of a small size like 1 or 2. We would like to point out that the color appearance of N5 did not become exactly opponent to the color appearance of the illumination in the subject room shown by the filled squares in the cases of red, green and blue illumination. Chromatic adaptation that takes place in the brain does not follow simple color opponency.

An interesting finding here is that the color appearance of other test patches also came close to that of N5 with these small windows. Thus with the yellow illumination, for

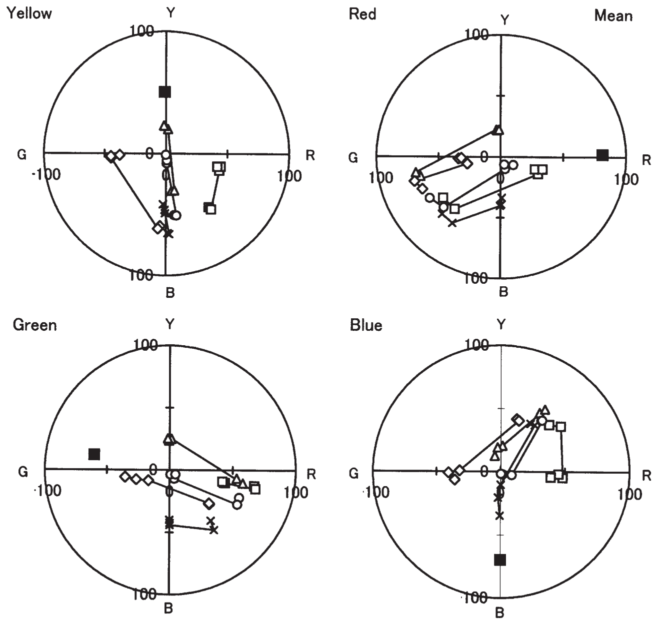

Fig. 8. Color appearance change of test patches for different window size. Mean results of four subjects. Sections correspond to four different illumination colors of the subject room. Symbols indicate the test patches as in Fig. 7.

example, all the test patches appeared very bluish, the same as N5. This can be expected from the opponent colors theory as the yellow illumination desensitizes the yellow valence of the yellow-blue pair and consequently sensitizes the blue valence. We will also explain the finding by the concept of RVSI. In Fig. 9 a RVSI is illustrated by a sphere rather than the simplified circle customarily used because four hues are

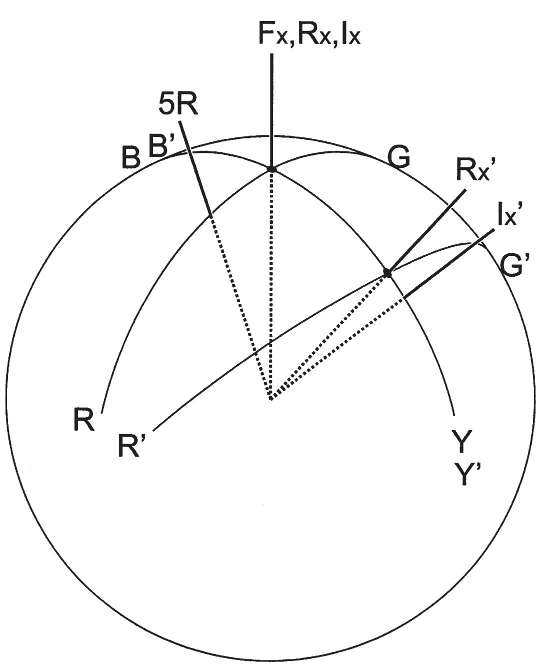

Fig. 9. Illustration to explain the color appearance change of the test patch 5R by RVSI shown by a sphere when the illumination of the subject room is yellow.

involved in the present experiment. F_X represents the fundamental axis. The recognition axis R_X coincides with F_X when the room illumination is neutral. The red, yellow, green and blue color start from R_X toward four directions as indicated by R, Y, G and B, respectively. In the case of yellow illumination of the present experiment the illumination axis I'_X will locate at a certain point on the yellow color and the original recognition axis R_X is drawn by I'_X to locate near it as shown by R'_X. The R'_X defines the axis of achromatic color appearance in this space of yellow illumination and red, yellow, green and blue color directions shift accordingly to new directions as shown by R′, Y′, G′ and B′. The loci of Y′ and B′ coincide with those of Y and B. The color appearance of objects in this room is now determined in relation to R'_X. In the case of test patch 5R4/3 the original color was almost unique red as seen in Fig. 4 and it locates in the original RVSI on a line intersecting with the red color arc R such as shown by 5R. With the recognition axis R'_X the color on the line 5R will appear reddish blue. Similarly, the test patch 5G4/3 will appear greenish blue, the 5B4/3 more saturated and the 5Y4/3 desaturated without changing their hues. The results shown in Fig. 8 suggest that a more complicated shift of the recognition axis takes place under illumination of other colors. In the case of the red illumination, for example, the R_X seems not simply to shift along the red color arc R but goes off toward the yellow color.

The most important point of the present experiment was to see whether the color appearance of the test patch would return to its original color when the window size was increased and the subject could recognize the test room as a different space from the subject room. As seen in Fig. 2 and more clearly in Fig. 3, the smallest window through which the subject could see any objects in the test room beside the test patch is W3. By investigating Fig. 8 we can indeed see it is the third point in the data that suddenly moved its position from those of W1 and W2. The color appearance changed to come close to the original color of the test patch.

To see more clearly the effect of the window size on the color change we calculated in Fig. 8 the distance between each data point and its original color point. The absolute value of the distance cannot be directly compared among curves as they differ in location and direction in the polar diagram of two elements, hue and chromaticness, but the change in the distance within one curve can show the change of color appearance as most of the curves are relatively straight in shape. The results are shown in Fig. 10, where the distance is taken along the ordinate and the window size along the abscissa. Symbols represent the test patches as in Fig. 8. A sudden drop is clearly seen in each curve from W2 to W3 and the recovery to the original color or the completion of the color constancy for the test room almost took place with W3. The sudden change cannot be explained by the change of chromatic adaptation at the retina. There was a change in the color distribution on the retina when the window was changed from 1 to 2, 2 to 3, and so on, but the largest change took place from W4 to W5 and not from W2 to W3, if we assume the change is expressed by the change in area of the window. The ratio of the area increase was 3.4

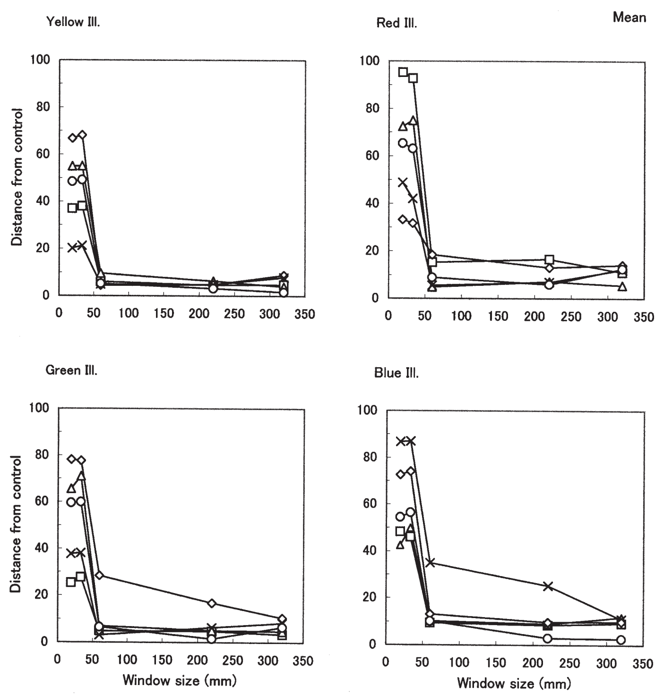

Fig. 10. Change of the color appearance of test patches exhibited by the distance from the data point to the original color in Fig. 8.

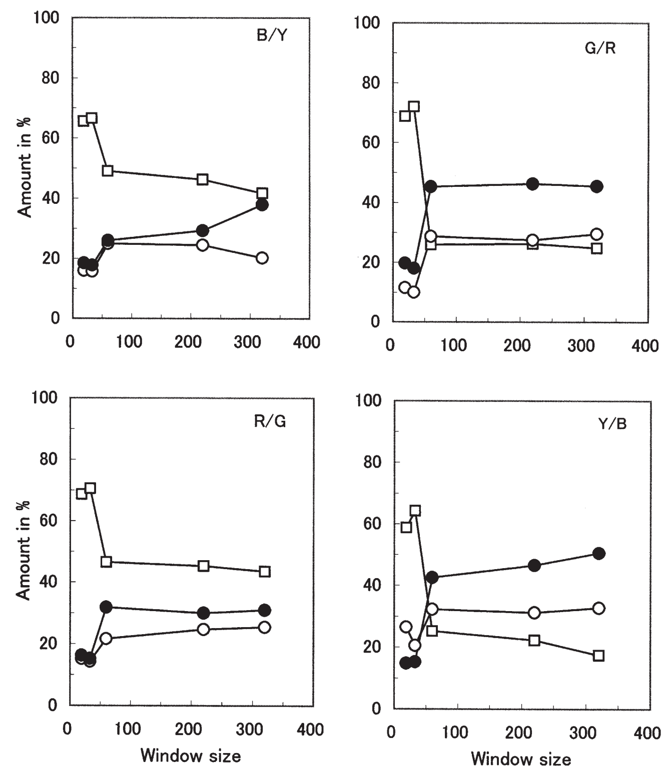

Fig. 11. Change of color elements for different window size. □, chromaticness; ○, whiteness; ●, blackness. The test patch-illumination combination is shown at the upper right corner of each section. Average of four subjects.

at the window change from W2 to W3, but it was 4 at the window change from W3 to W4, and 6 from W4 to W5. On the other hand, there was a big change in the space recognition from W2 to W3. With the former window the subject recognized only the subject room and the test patch was a mere object belonging to that room. With the latter window the subject could see portions of plant leaves beside the test patch and could clearly recognize the test room. Once she recognized the test room she constructed a RVSI for that room and the color of the test patch was judged in relation to the RVSI. It is most reasonable to understand the present results in terms of the recognition of the test room.

The last point of the results is about the amounts of chromaticness, whiteness and blackness for different windows. The results from four combinations of test patch and illumination are shown in Fig. 11. The combination is indicated at the upper right corner in each section and G/R, for example, denotes the green test patch 5G5/3 observed with the red illumination. Symbols represent elements: open squares for chromaticness, open circles for whiteness and filled circles for blackness. The ordinate gives the amount of each element in percentage and the abscissa the window size. The chromaticness is large with W1 and W2 and dropps suddenly with W3 as we saw before. The drop is replaced both by whiteness and blackness. This property was observed for other combinations as well.

5. Discussion

The present experiment together with the previous one[1] showed that the color appearance of a test patch is determined based on the recognition of the space and illumination to which the test patch was recognized to belong. If a subject constructed in his brain only one RVSI for the subject room as in the cases of windows 1 and 2, the appearance of a test patch was determined based on the RVSI. But if he constructed another RVSI for the test room as the cases of windows 3, 4 and 5 the appearance was determined based on the newly constructed RVSI.

The reason the subjects were able to construct the RVSI for the test room with so little initial visual information as green leaves and the back wall is still to be investigated. The wall appeared uniform to the subjects and the leaves located just behind and very close to the test patch with some even touching the test patch. The distance from a subject's eye to the patch was around 180 cm and the depth perception among these objects was not provided by the head motion even if there was such movement. The movement altered the parts of the test room that could be seen and this might have helped the recognition of another room behind the window. But the most likely reason for the recognition of the test room with only a little initial visual information through window 3 would lie on the fact that the subjects knew beforehand that there was a test room beyond that window, and that it was arranged with the test patch, green leaves and the white wall at the region through window 3. This reason was supported by all the subjects participating in the experiment based on their subjective impression.

Many experimental results reported in the past can be reinterpreted in the same way by using RVSI.[10] A good example is the Gelb effect about apparent lightness. A black disc appeared white to a subject when it was presented in the dark alone and illuminated by a hidden light without being noticed by the subject. But it immediately returned to black when a white paper was placed on the disc. In our interpretation the subject constructed only a RVSI for the dark in the former situation. The brightness size of the RVSI was small and the black disc was near the edge of the RVSI or even went outside the RVSI, giving a white appearance or an unnaturally bright appearance as an object in the space. By being presented with plural objects, the black patch and the white paper, as in the latter situation, the subject was able to construct a new RVSI for the hidden illumination. He naturally perceived the original colors of the black disc and the white paper. A similar experiment was done by Uchikawa *et al.*[11] who measured the color appearance of color samples, each with and without a narrow grey surrounding of 20% reflection. They were presented one by one in the dark but illuminated by hidden illumination. The color samples appeared as the aperture colors without the surround but as the surface colors with the surround. Our interpretation is that the presence of the surround together with the color sample helped to construct another RVSI for the hidden illumination and the color sample was perceived based on RVSI. We express for these two experiments that the increase of the initial visual information helped to construct a new RVSI for the hidden illumination. The color terminologies, unrelated color and related color, defined by CIE, the International Commission on Illumination, can be understood in the same context. The effect of amount of the initial visual information for constructing RVSI was also investigated by Kanitani and Ikeda[12] by the border nBu. The apparatus was very similar to the present experiment and the border was measured by illuminating a test patch locally and hiddenly. The nBu suddenly changed from that of the subject room to that of the test room when the window was increased so that the back wall of the test room and the tips of grass leaves were seen within the window. Only a small amount of information was enough to recognize the test room and to construct the RVSI for the room.

Recently many researchers have investigated color perception using a real 3D space rather than a 2D display and obtained results relevant to ours. Kraft *et al.*[13] investigated the efffect of complexity in a scene on the color constancy. In one situation only a test patch was placed in a space of which side and back walls were visible, and in another situation a Macbeth Color Checker Chart and two rectangular solid objects were added in the space to increase the complexity. They found no effect of the complexity and the color constancy was there in both situations to the same degree. From our results and thouse from Uchikawa *et al.* the low-complexity situation already had enough initial visual information to construct the RVSI for the scene and the color constancy took place. Another example is an experiment done by Cataliotti and Bonato.[14] They placed in a room two adjacent square patches and illuminated them by a hidden means. The left patch was a black paper with L^* of 20 to serve as a test stimulus and the right patch was either a uniform white paper or a Mondrian pattern to serve as an inducing field according to their terminology. The illuminance of the hidden illumination was adjusted so that the luminance of the test stimulus was the same as that of a white surface placed in the room. The subject's task was to measure the apparent lightness of the test stimulus by comparing it with a grey scale. The result showed that the apparent lightness was equivalent to 78 of L^* in the case of the uniform white paper while it was 60 in the case of the Mondrian pattern. In our interpretation the initial visual information for the hidden illumination was not enough to construct a complete RVSI for the area illuminated by the illumination in the former case and subjects judged the lightness of the test stimulus mainly based on the RVSI for the room of which illumination was much lower than that which was hidden. With more initial visual information in the latter case of Mondrian pattern the subjects could construct a more complete RVSI for the hidden illumination and the apparent lightness of the test stimulus approached more to the original lightness. Yamauchi *et al.* investigated the effect of the amount of the initial visual information for constructing a new RVSI by gradually inserting objects into a hidden illumination where a test patch was located[15] or by gradually constructing a miniature room within the hidden illumination around the test patch.[16,17] Both the apparent lightness and the chromaticness of the test patch changed gradually from those based on the RVSI for the main room to those based on the RVSI for the hidden illumination. This shows that a RVSI for the hidden illumination may take intermediate sizes between the RVSI for the main room and that for the hidden illumination. The fact that the apparent lightness 60 is far from the original lightness 20 in the above quoted experiment indicates that the Mondrian pattern placed beside the test stimulus was not enough to construct a complete RVSI for the hidden illumination. A similar experiment to that of Cataliotti and Bonato was carried out by Yamauchi and Uchikawa[18] but using the border method. A subject observed a stimulus pattern displayed on a CRT monitor through a window made on the front wall of a room. Local illumination was simulated on the stimulus pattern by increasing or decreasing the lightness of a limited area of the pattern. The interpretation for this result is that the border nBu is determined by the space illumination of the local area.

It is our belief that our visual system was developed to recognize the 3D space that surrounds us. One of the most important properties of space is its illumination, how brightly it is illuminated. It is natural to suppose that the color appearance is determined based on the recognition of the 3D space and its illumination. The concept of RVSI was developed from that belief. We believe that the visual system can be revealed rightly and properly by investigating it in relation to the 3D understanding and hope more experiments will be done where three dimensional spaces are actually employed.

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