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Measurement of Color Constancy by Color Memory Matching

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Degree of color constancy was measured when color memory was involved in color comparison judgment. We used the Optical Society of America (OSA) Uniform Color Scales as stimulus color samples, and chose 20 color samples as test stimuli. Four illuminants of 1700, 3000, 6500, and 30,000 K were tested. The observer, completely adapted to a test illuminant, saw a test color sample and stored its color in his memory. After being readapted to the reference white (6500 K), he started selecting a color sample from among the 424 OSA samples which matched the test sample in his memory. We employed a memory matching method called cascade color matching, in which the number of selected color-samples was gradually reduced in four stages. In the final stage, the observer selected a color sample. The results show that, for most test colors, the distributions of selected colors in stages 1 to 4 were similar among all illuminants, and that the $u'v'$ chromaticity distance between a test color under 6500 K and its matched color was quite short. These indicate that good color constancy was retained in memory color comparison.

Key words : color constancy, color memory, surface color, categorical color perception, color matching, color vision, illumination

1. Introduction

We usually see a colored object under various illuminations with different color temperatures. The object appears, however, to have the same color so that we can recognize it by its color. This phenomenon is called color constancy.[1] Many studies have been done on color constancy,[2,4] but its determining factors and mechanism are not yet fully understood.

When we consider color comparison in everyday situations we notice that our memory is inevitably used in all cases to judge the color of an object under different illuminations. It never happens in an ordinary situation that we see the same object side by side under different illuminations, although this is the standard viewing condition in most color constancy studies. It is necessary to remember the color of an object seen under an illuminant in order to compare it with the color of the same object seen under different illuminants.

Thus, color memory is always involved when we observe the color constancy phenomenon. But we do not know whether or how this memory is related to the color constancy. Color memory may change the color of an object,[5,6] or it may help to keep the color constant. In any case, we should note that color memory is an important factor to understand the color constancy mechanism. The present study investigated how good color constancy held when color memory was involved in comparing colors.

2. Method

2.1 *Stimulus*

We used a set of the Optical Society of America (OSA) Uniform Color Scales[7] as stimuli; this set consists of 424 color samples. They are arranged with isotropic equal color difference in the (L, j, g) three-dimensional color space. L is the lightness, j is the yellow-blue, and g is the green-red axis.

The size of a color sample was 5×5 cm, or 4.8×4.8° of visual angle. All samples were randomly placed on four gray boards. This board was of OSA lightness $L=-2$, and 65×65 cm, or 57×57° size. The viewing distance was 60 cm. All color samples were viewed under the reference D65 white illuminant when the memory matching was performed.

We chose 20 color samples, shown in Table 1, as test color samples. They almost uniformly spread over the color space. The test color sample was presented in a gray envelope with a circular hole of 3 cm or 2.9° diameter when the observer was shown the test color sample in order to memorize its color. The envelope prevented the observer from using the shape characteristics of the test color sample, for example, its chipped edge, when he tried to select the same sample later.

2.2 *Illuminant*

Four illuminants of 1700, 3000, 6500, and 30,000 K were tested in the present experiment. Their CIE1931 (x, y) chromaticity coordinates were (0.556, 0.400), (0.414, 0.427), (0.323, 0.345), and (0.263, 0.269), respectively. All test illuminants except 6500 K were made with colored filters placed in front of the slide projectors. The 6500 K illuminant was produced by D65 fluorescent lamps. This 6500 K illuminant was also used as the reference white illuminant.

2.3 *Procedure*

The observer first adapted to the test illumination in the experimental booth for 10 min. Then he was shown 106 color samples spread on a gray board for 50 s. In the middle of this period the test color sample was presented on the board for 10 s. The observer saw the test color

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Table 1. L, j, g values of test color samples.

No.	L	j	g	No.	L	j	g
1	−6	0	2	11	0	−2	4
2	−5	0	2	12	0	8	−2
3	−4	−4	2	13	1	−3	1
4	−4	4	−2	14	1	3	−7
5	−3	1	−5	15	2	2	4
6	−3	3	5	16	2	10	−2
7	−2	2	−10	17	3	−1	1
8	−2	4	0	18	3	5	3
9	−1	3	−1	19	4	0	−4
10	−1	5	−5	20	4	6	0

among many other colors so that he could utilize the whole pattern of color array. He stored the test color in his memory.

The observer did an arithmetical calculation in a loud voice for 30 s, including the test color presentation period, to prevent him from verbally naming the test color. This calculation was the consecutive subtraction of 9 from an arbitrarily given 3-digit number.

After the 50-s period the gray board was removed from the booth, and the illuminant was changed to the reference white of 6500 K. The observer adapted to the reference white for 5 min. During this adaptation period the experimenter took the test color sample out of the envelope, and put it on one of the four gray boards on which comparison color samples were placed at random positions, with caution that the observer did not notice the test color sample by its position.

After the 5-min adaptation of the reference white the observer began the cascade color matching to select the color sample that matched the test color in his memory. There were 4 stages in the cascade color matching. In stage 1, the observer looked at all 424 color samples and rejected those that appeared definitely different from the test color in his memory. In stage 2, he examined the remaining color samples, and rejected some that appeared probably different. In stage 3, he selected a color sample that matched the test color, or several that all appeared like the test color so that he was unable to decide which one was the test color. In stage 4, he was forced to choose a single color sample that most matched the test color. This was the finally matched color sample.

The observer examined color samples one by one on a board, and all four boards in turn under the reference white. If he had perfect color-constancy ability he would choose the same test color sample no matter what illuminant is used. But if he had no color-constancy ability he would choose a color sample which has the same appearance under the reference white as that of the test color sample under a test illuminant. Therefore, degree of color constancy can be measured by the positions of color samples selected within a color space. Two male observers with normal color vision participated in this experiment.

We performed the categorical color-naming for each observer giving the basic color category regions in the OSA color space. Each observer named all 424 OSA color samples using only the 11 basic color categories: red, green, yellow, blue, brown, purple, pink, orange, white, black, and gray.[8] The observer repeated this categorical color-naming twice for each color sample.

If that the observer used the same color name twice for the same color sample this sample was defined as a consistent sample. The region in the OSA color space that contained only the consistent samples for a certain basic color name was defined as the basic category region of that color name. We measured 11 basic color category color regions in the OSA color space for each observer.

In the present memory procedure, the observer could use only the test color appearance in his memory to try to identify the test color sample among many other samples. He did not use shape characteristics of the test color sample. This experimental situation of selecting a colored object is quite different from our everyday situations since color of an object cannot be separated from its shape in ordinary situations.

In this experiment, however, we studied the factor of color memory among many other factors by which color constancy was retained. We attempted to eliminate shape cues of the test color sample in order to derive only the color memory factor in the color constancy phenomenon. We felt it most important to first involve color memory in doing a color constancy study since this has never been considered in previous investigations.

3. Results and Discussion

3.1 *Examples of Selected Color Distributions*

Figure 1 shows two examples of the distributions of selected color samples in stages 1 to 4 in the OSA color space for observer IK. The illuminants are shown in each panel. The test color samples, No. 6 (−3, 3, 5) and No. 7 (−2, 2, −10), are indicated by an open cross symbol. All selected colors are projected on the (j, g) plane without regard to their lightness values. The 11 basic categorical color regions, except for white, gray, and black, are also shown in each panel.

The distributions of the test (−3, 3, 5) are similar for all illuminants; they are restricted in the green category. The finally matched color samples, indicated by filled circles, are located close to the test sample. The distribution for the 6500 K can be viewed as the control distribution since this test illuminant was the same as the reference white. These results indicate that under the reference white the observer selected the same colors that matched his memory of the test color which was seen under different illuminants. Thus, the observer had good color constancy under these conditions.

For the other test (−2, 2, −10), the control distribution, obtained for the 6500 K, was found to be in the pink region. The 30,000 K distribution is similar to the control, but the 1700 K and 3000 K distributions are somehow different. The selected colors expand to the red and the orange regions. However, all finally matched colors, shown by the closed circles, are located close to the test sample. These results indicate that memory ambiguity increased in the neighbor category under some conditions.

The distributions of other test colors for observer IK, and the distributions of all test colors for observer MK were found similar to those shown in Fig. 1.

The categorical shift in color memory, found in this experiment for some test colors, is similar to that reported in previous experiments.[9] However, the categorical memory ambiguity in the present experiment was found not to be systematic among color samples or test illuminants. Moreover, the finally matched color sample was not far removed from the test color-sample position in the color space. Therefore, good color constancy appeared to be retained in this experiment, but it was not clearly shown whether color constancy might be related to categorical characteristics of color memory.

3.2 *Matched Color Positions in the u′v′ Chromaticity Diagram*

In Fig. 2 we plotted the finally matched colors for the two examples shown in Fig. 1 in the $u'v'$ chromaticity diagram to see how good color constancy was retained in a chromaticity diagram. The closed circles represent the colorimetric positions of the test samples under different illuminants. The open triangles represent the matched samples by memory. Asterisks indicate the positions of test illuminants.

If the matched colors coincide with the circles of 6500 K, perfect color constancy was considered to be observed; but if the matched colors coincide with the circles of the

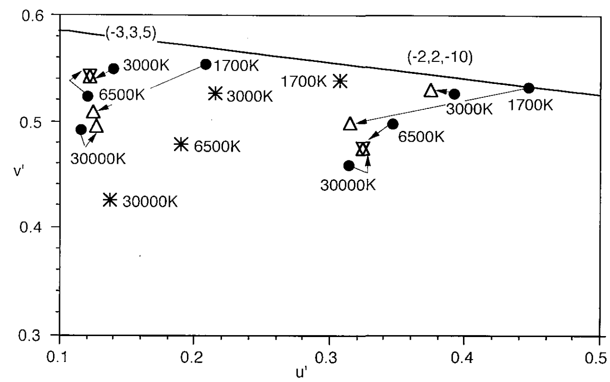

Fig. 2. Two examples of finally matched colors for test color samples of (−3, 3, 5) and (−2, 2, −10) shown in the $u'v'$ chromaticity diagram. Observer: IK. Closed circles (●) represent the colorimetric positions of the test color samples under test illuminants, and triangles(△, ▽) the memory matched samples. Asterisks (*) indicate chromaticity coordinates of test illuminants.

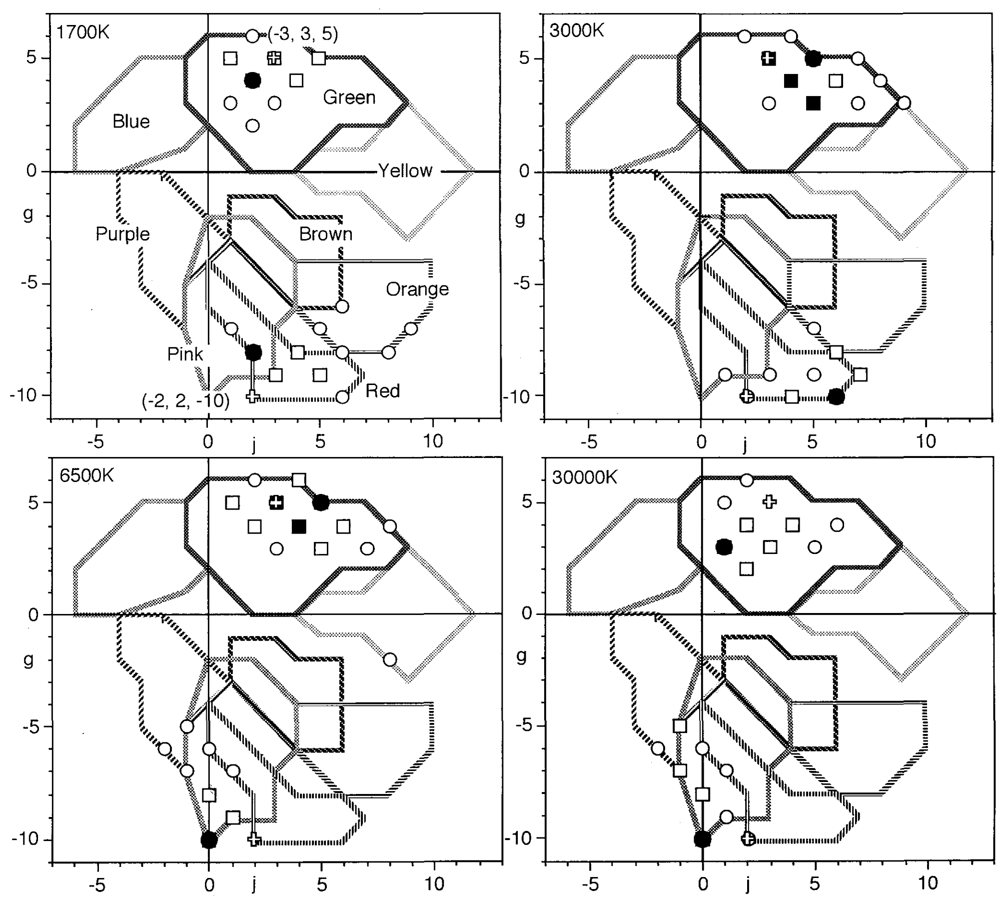

Fig. 1. Two examples of the distributions of selected color samples in stages 1 (○), 2 (□), 3 (■) to 4 (●) of the cascade color matching. Observer: IK. Open crosses (✣) represent test color samples of (−3, 3, 5) and (−2, 2, −10). Test illuminants and basic categorical regions are shown in each panel.

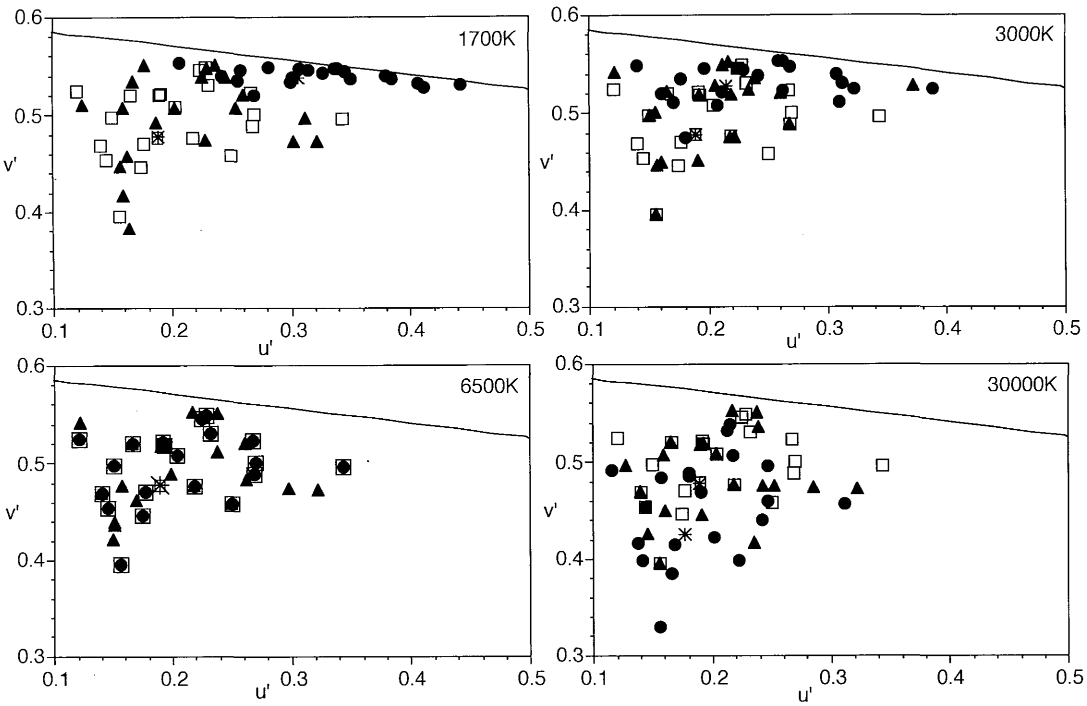

Fig. 3. All matched colors for all 20 test colors seen under four test illuminants. Circles (●) and triangles (▲) represent the colorimetric positions of the test samples and the matched color samples, respectively. Open squares (□) indicate the colorimetric positions of the test samples under the reference white (6500 K) (⊞). Asterisks (*) indicate chromaticity coordinates of test illuminants. Observer: IK.

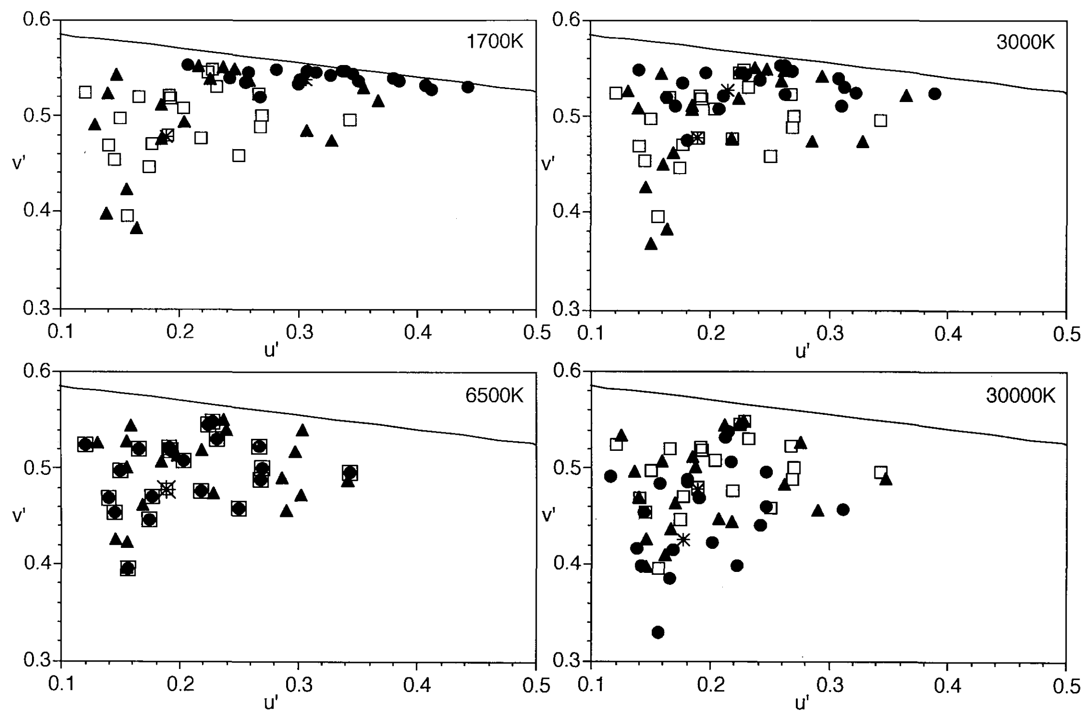

Fig. 4. Same as Fig. 3, but for observer MK.

corresponding illuminants, no color constancy was observed. The triangles in Fig. 2 were found to be spread around the 6500 K circles for both test samples, confirming in these plots that good color constancy existed under these conditions.

Figure 3 shows all matched colors for all 20 test colors seen under the four illuminants. Illuminants are shown in each panel. The circles represent the colorimetric positions of the test samples, and the triangles are the positions of the matched color samples. The squares indicate the color-

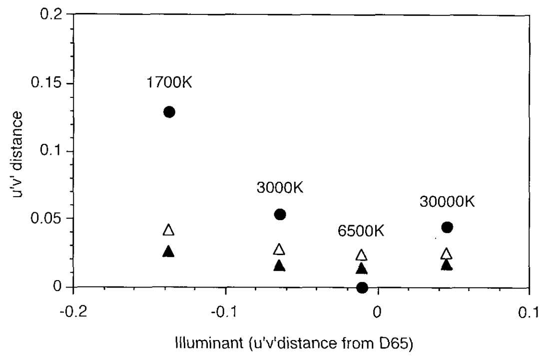

Fig. 5. The mean $u'v'$ distance between the matched colors and the corresponding test colors under the reference white for observer MK (△) and observer IK (▲). Circles (●) indicate the mean distances between the test colors under test illuminants and those under the reference white (6500 K).

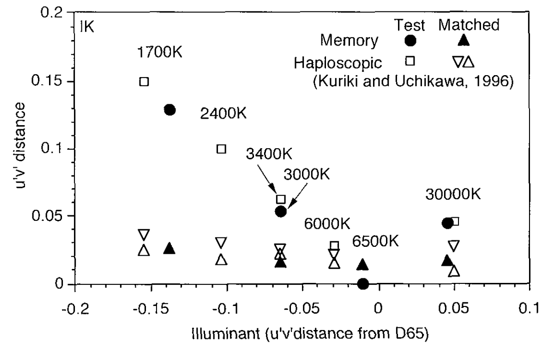

Fig. 6. Comparison in $u'v'$ distance between the present memory experiment and the previous haploscopic experiment[4] for the same observer IK.

imetric positions of the test samples under the reference white. The distribution for 6500 K is the control distribution which should be compared with those for other test illuminants.

The distributions of the matched color samples for 1700, 3000, and 30,000 K are quite similar to the square distribution, and quite different from the circle distribution. We can see that good color constancy exists for all test colors under these illuminants.

Figure 4 shows the results for observer MK, the characteristics of which were very similar to those for observer IK.

3.3 *The u'v' Distance*

It is helpful to have an quantitative index that represents degree of color constancy. We took the $u'v'$ distance between the matched sample, shown by the triangles in Figs. 3 and 4, and their corresponding test sample, shown by the squares. If a triangle fit its corresponding square this would indicate perfect color constancy, and this $u'v'$ distance would be 0. On the other hand, if the triangle fit a corresponding circle there would be no color constancy, and this $u'v'$ distance would be equal to the distance between the circle and the square points.

In Fig. 5 the open and closed triangles show the mean $u'v'$ distances between the matched colors and the corresponding test colors under the reference white for MK and IK, respectively. The circles indicate the colorimetric distances between test colors under test illuminants and those under the reference white.

The colorimetric distance is 0 for the reference white (6500 K), and increases rapidly as the illuminant moves away from the white. But the matched color distance increases only very slightly. This plot is clear evidence that excellent color constancy was obtained in this experiment.

In Fig. 6 for comparison we plotted the results of haploscopic matching obtained by Kuriki and Uchikawa[4] for the same observer IK. They used two matching criteria of matching, surface-color match (open triangles) and apparent-color match (upside-down open triangle). Their haploscopic matching did not involve memory. Their results appeared very similar to the present results for both criteria.

The similarity between the present $u'v'$ distance obtained using memory and the haploscopic data not using memory suggests two possible influences of color memory on the color constancy mechanism. One possibility is that memory has no effect on color constancy. If we could immediately perceive the constant color of a surface, obtained under a white illuminant, when we see the surface color under any illumination, what the color memory does would be just to hold the constant color. In this case it seems reasonable that we would find no difference between memory and haploscopic data.

The other possibility is that when we compare colors of a surface under different illuminations we inevitably use our memory to judge colors. We might have to use memory even under a haploscopic condition. Our visual system cannot measure colors like a colorimetric instrument under different illuminations, but we perceive or recognize colors in a higher level of color vision mechanism. Therefore, we might always use color memory when we see colors even though we are not aware that we do so. In this case, again, we would not find any difference between the present and the haploscopic results.

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