Paper

Perceived Whiteness under Different Lighting Conditions

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Paper originally published in Japanese in J. Illum. Engng. Inst. Jpn., Vol.89, No.11, 2005

ABSTRACT

Many white and nearly white objects are in our living and working areas, such as documents written on white paper, white curtains, white clothes, white walls, and white furniture. The perceived whiteness of these objects is important to the impression of the lighting in these areas. To investigate the perceived whiteness in living areas, a series of experiments were conducted using four different fluorescent lamps in three different environments. It was found that the areas of perceived whiteness in the living area environments were larger than the areas of perceived whiteness under achromatic conditions. Based on these results, a perceived whiteness index is proposed for these experimental conditions.

KEYWORDS: whiteness area, fluorescent lamp, color temperature, achromatic room, living room

1. Introduction

Since the 1930s, many studies have been done regarding the evaluation of white objects such as white paper and white textiles that use fluorescence in order to have them seem more white, the method of quantitatively evaluating the degree of whiteness, and the perceived whiteness, and the CIE Whiteness Index Formulas and JIS Z 8715 (Whiteness Index-Indication Method) have already been established[1)-3)]. The Whiteness Index Indication Method Study Committee (The Color Science Association of Japan) implemented experiments of visual perception evaluation by many experts regarding white paper and white textile objects with D65 fluorescent lamps as the light source, and clarified that the CIE Whiteness Index corresponds closely to the perceptual whiteness regarding the experimental materials within the application limitations of the CIE Whiteness Index Formulas as recommended by the CIE[4)].

Suzuki et al. quantified the whiteness index for the light source color, and proposed whiteness index formulas for the light source color based upon subjective evaluation experiments using several kinds of the daylight fluorescent lamps with an approximate correlated color temperature of 6500K. Suzuki et al. also proposed the quantification of the perceptual whiteness and so on by means of observing photographic colored paper under an illuminating light from high color rendering fluorescent lamps for color evaluation with a correlated color temperature of 5000K[5)-7)].

On the other hand, fluorescent lamps prevail in Japan as the main light source for living spaces. In recent years, many fluorescent lamps have been sold in the market by illumination lamp manufacturers and many kinds of fluorescent lamps with different correlated color temperatures have been used for living spaces. Also, the interior color of the living spaces in contemporary buildings tends to have a higher reflectance ratio for each plane compared to traditional Japanese architecture, and white or colors close to white have been used in many cases for interior materials and objects. The appearance of these colors varies depending upon the spectroscopic characteristics of the light sources, the surrounding environment, and so on.

The appearance of white or colors close to white is also considered to influence the perception of brightness of a space, as, for example, the case in which a room is felt to be dark when a white object in a room is seen as yellowish. Therefore, it is considered important for selecting light sources and interior materials for living spaces to clarify how the perceived whiteness of white and colors close to white used for interior colors varies with the light sources used.

Katayama et al. evaluated the whiteness of white samples under various kinds of illuminating light and clarified the influence of the spectral composition of the illuminating light on the perceived whiteness of the white objects[8)9)]. In the preceding studies by Akatsu et al., an experiment on the whiteness perception was implemented using twelve color sheets of white or colors close to white in a real living space, and it was clarified that the color sheets fall into two categories when the correlated color temperature is reduced: those for which the feeling of whiteness is reduced and those for which it is increased[10)-13)]. Eda et al. studied the perceptual whiteness areas under illumination by fluorescent lamps of incandescent lamp color and daylight color[14)]. However, an evaluation index for white or colors close to white has not been clarified so far.

Therefore, in this study, we have implemented experiments on perceived whiteness using white and close-to-white sheets under various types of illuminating light with the aim of clarifying perceived whiteness in a living space, and we will try to quantify this perceived whiteness based upon the experimental results.

2. Experiments regarding perceived whiteness under various types of illuminating light

84 samples of color sheets consisting of 81 pieces of high brightness (V=9.0~9.25) and low chroma saturation (C=0.5~1.5) covering almost whole hues and three pieces of N9.0, N9.25, and N9.5 were illuminated by fluorescent lamps with different spectroscopic characteristics in order to observe how the perceived whiteness of these color sheets was changed by the spectroscopic characteristics of the light sources under two conditions: an achromatic background (Experiment 1) and a chromatic background (Experiment 2).

2.1 Experiment 1: Experiment regarding perceived whiteness with an achromatic background —Comparison of perceived whiteness with narrow band fluorescent lamps versus broad band fluorescent lamps

Since the three-band fluorescent lamp, which is a narrow band emission type fluorescent lamp, was developed in Japan more than 20 years ago, it has been widely adopted for use, not only in residences, but also in various living spaces. Although the narrow band fluorescent lamp has such features as rendering an impression of transparency, clean color, and accentuated whiteness of paper and china compared to traditional broad band fluorescent lamps, quantitative studies have not been made so far.

2.1.1 Experimental conditions

Four types of fluorescent lamps —narrow band fluorescent lamps with correlated color temperature of 3000 K and 6700 K and broad band fluorescent lamps with correlated color temperature of 3000 K and 6500 K— were used for the experiment. The demonstrated color sheets were 84 pieces in total, or 33 color sheets with Munsell values of 9.25 and C=0.5~1.5 covering almost whole hues, 48 pieces of color sheets with Munsell values 9.0 and C=0.5~1.5 covering almost whole hues, and three color sheets of N9.5, N9.25, and N9.0. The HV/Cs of the color sheets used in the experiment are shown in Figure 1.

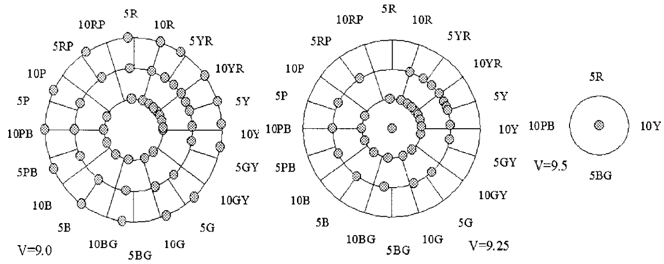


Figure 1 The 84 munsell color sheets used in the experiment

The experimental room was divided into a preparatory adaptation booth and an observation booth, each of which had a width of 1.5 m, a depth of 1.8 m, a ceiling height of 1.8 m, and interior walls covered with cloth of N8. A table covered with a cloth of N5 was set at the center of each booth. The illuminance of the horizontal plane of the tables was set at 500 lx. The afore-mentioned four types of fluorescent lamps were installed in the observation room, and monochromatic fluorescent lamps with R, G, and B phosphors were installed in the preparatory adaptation booth. The whole ceiling surfaces of both booths were made luminous ceilings by using milky white diffusion panels. The subjects were five young people.

2.1.2 Experimental procedure

Before the experiment, each subject was instructed to enter the preparatory adaptation booth, which was illuminated with a colored light set at random, and the subject was put in chromatic adaptation for around 10 minutes so that he or she could not detect the color temperature of the illuminating light in the observation booth. Then the subject was instructed to move into the observation booth and put in preparatory adaptation for around five minutes. After that, a color sheet, which was taken out one at a time at random from the 84 color sheets in a box beside the table, was put on the table and the subject was requested to classify it as either "a color sheet felt to be white" and "a color sheet not felt to be white". Figure 2 shows the experimental setting. Each subject repeated the experiment five times.

2.1.3 Experimental results

Figure 3 shows the experimental results with a narrow band fluorescent lamp and a broad band fluorescent lamp, both with a correlated color temperature of 3000 K. The horizontal axis shows the hue of the presented color sheet and the vertical axis shows the frequency of selection. As shown in Figure 3, the number

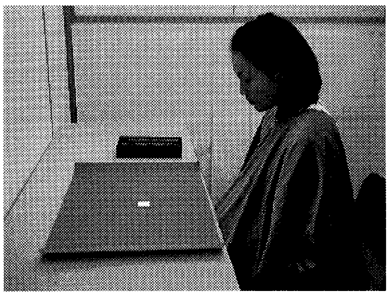


Figure 2 Experimental set-up in which an observer is observing a colour sheet on the table

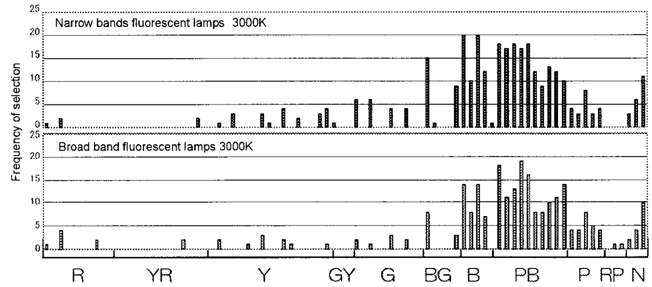


Figure 3 Whiteness evaluation values of the 84 munsell color sheets in the achromatic room under the narrow bands fluorescent lamps, (of which correlated colour temperatures is 3000 K) and the broad band fluorescent lamps

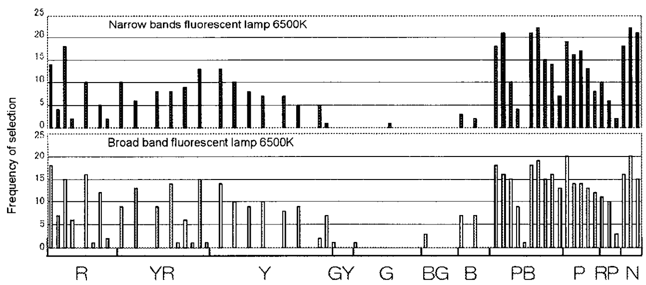


Figure 4 Whiteness evaluation values of the 84 munsell color sheets in the achromatic room under the narrow bands fluorescent lamps, (of which correlated colour temperatures is 6500 K) and the broad band fluorescent lamps

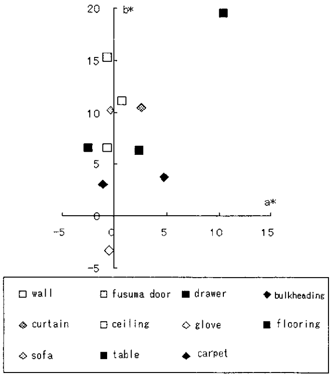
of color sheets evaluated as being white in the light from the narrow band fluorescent lamp was larger compared to the same with the broad band fluorescent lamp, and a t test (5% significance level), which is a test of frequency, was performed to find that the difference is significant. When the results are examined by hue, the number of selected hues was large in the PB series and the B series. Figure 4 shows the experimental results with the narrow band fluorescent lamp and the broad band emission fluorescent lamp, both with a correlated color temperature of 6500 K. As seen in Figure 4, the number of color sheets selected as being white under the illuminating light of the broad band fluorescent lamp was larger than that with the narrow band fluorescent lamp. A t test, a test of frequency, was performed to find that this is a significant difference. Also, among the selected hues, as was the case with 3000 K, the hues of the PB series and the B series were large in number compared to the other hues. Also, hues of the N series were selected in large numbers. When the selected hues are compared by the differences in the correlated color temperatures, the hues of the PB series and the B series were selected heavily in 3000 K, while the R series and the YR series were also selected in 6500 K, and it was clarified that the range of selected hues was expanded in the case of 6500 K.

2.2 Experiment 2: Perceived whiteness with a chromatic background in a real space

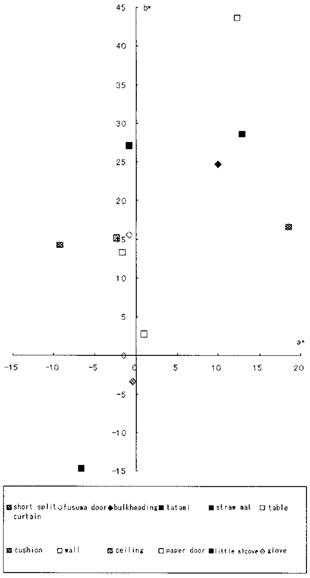
We see white and colors close to white in complicated and uneven chromatic backgrounds in actual living spaces. Hence, we evaluated the perceived whiteness of white or close-to-white color sheets that were illuminated by narrow band fluorescent lamps with different correlated color temperatures in an environment of a living space.

2.2.1 Experimental conditions

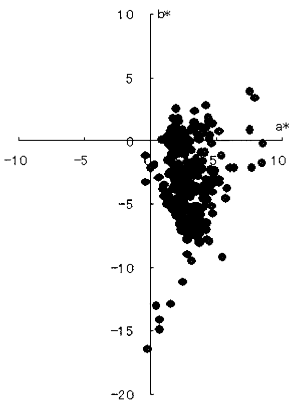
A living room (around 17 m^2), with an interior with white as the basic color, and a Japanese-style living room (around 10 m^2) were used for the experiment. A surface-mount illuminating appliance with a milky white globe was set at the center of the ceiling in each room. The light sources were three-band fluorescent lamps with correlated color temperatures of 3000 K and 6700 K. The horizontal illuminance on the surfaces of the tables was set at 500 lx. A background of N5 was used as a uniform achromatic background in Experiment 1, while a complex and uneven chromatic background was used in Experiment 2. For the chromatic background, a living room and a Japanese-style living room with modern residential interior colors were selected from model house brochures from several house manufacturers, and each photograph was printed in color after a mosaic treatment in to 315 chips. The spectrographic reflectance of each chip was measured, and the chromaticity coordinates of each chromatic background was calculated. Figures 5(a), (b), (c), and (d) show a*b* coordinate values on the CIE 1976 $L^*a^*b^*$ chromaticity diagram of the living room, the Japanese room, and each chip for the two kinds of chromatic backgrounds. Typical experimental settings are shown in Figure 6. The subjects were the same five young persons who participated in Experiment 1.



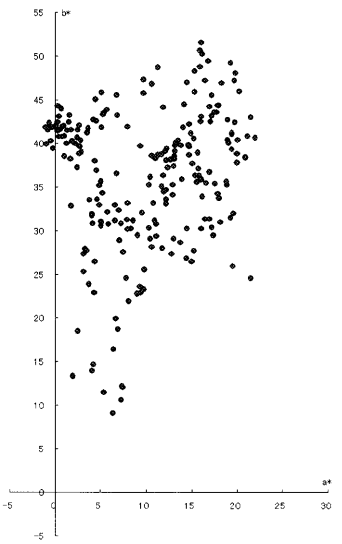
(a) Living room



(b) Japanese room

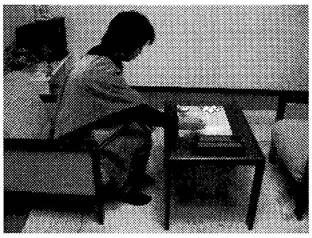


(c) Chromatic background of the Living room

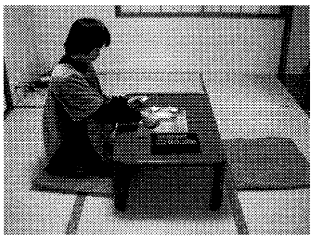


(d) Chromatic background of the Japanese room

Figure 5 Chromaticities of colour chips under different fluorescent lamps in living areas and Japanese style living areas plotted on the CIE 1976 $L^*a^*b^*$ chromaticity diagram



(a) Living room



(b) Japanese room

Figure 6 A typical experimental scene

2.2.2 Experimental procedure

Each subject was instructed to enter the living room or the Japanese room and was put in color adaptation for around 10 minutes. The succeeding experimental procedure was the same as was the case for Experiment 1. The repeat frequency was five sessions.

2.2.3 Experimental results

Figure 7 shows the experimental results for the living room and the Japanese room with an illuminating light from a fluorescent lamp with a correlated color temperature of 3000K. The horizontal axis shows the color sheets by hue and the vertical axis shows the selection frequency. The results of the selection frequency in the living room and the same in the Japanese room were put into a t test (5% significant level), a test of frequency, to clarify that there is a significant difference. From the viewpoint of hues, a large number of selections were made in hues of the PB series, the P series, and the N series. Figure 8 shows the experimental results of the living room and the Japanese room with an illuminating light from a fluorescent lamp with a correlated color temperature of 6700K. Similarly, a t test, a test of frequency, with both results was done and it was clarified that there is a significant difference.

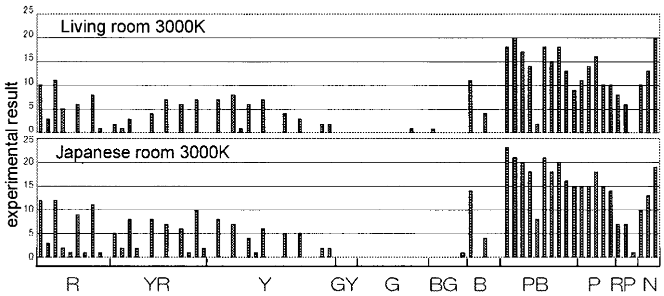


Figure 7 Whiteness evaluation values of the 84 munsell color sheets in the Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 3000K

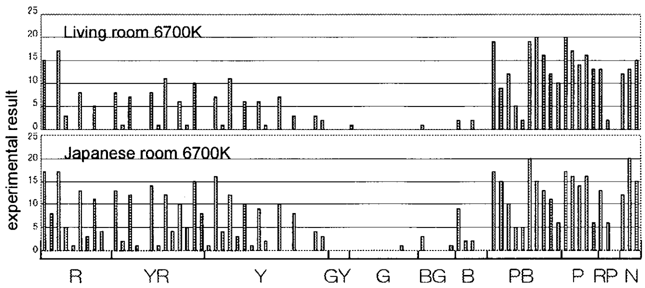


Figure 8 Whiteness evaluation values of the 84 munsell color sheets in the Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 6700K

3. Comparison of experimental results

The results of Experiment 1, which was implemented with an achromatic background, and the results of Experiment 2, which was implemented with chromatic background, were compared. The experimental results are shown in Figure 9 and 10. In case of correlated color temperature of 3000 K, the selected number was large in hues of PB series, P series, and N series in both achromatic background and chromatic background. Number of kinds of selected hues was large in the achromatic background compared to the chromatic background. As a result of the t test, the test of frequency, it was clarified that there is no significant difference between the living room and the achromatic background, but that there are significant differences between the Japanese room and the living room and between the Japanese room and the achromatic background.

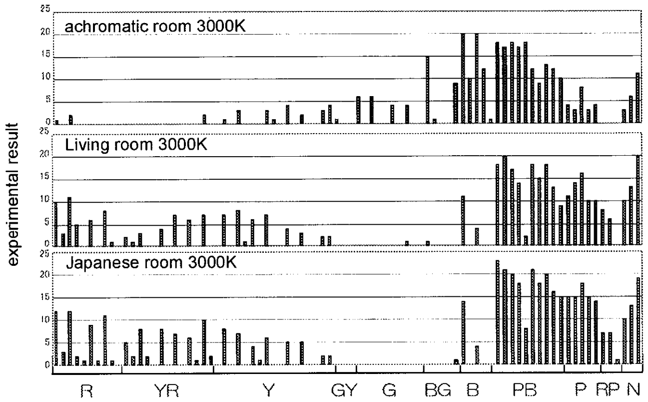


Figure 9 Whiteness evaluation values of the 84 munsell color sheets in the achromatic room and Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 3000 K

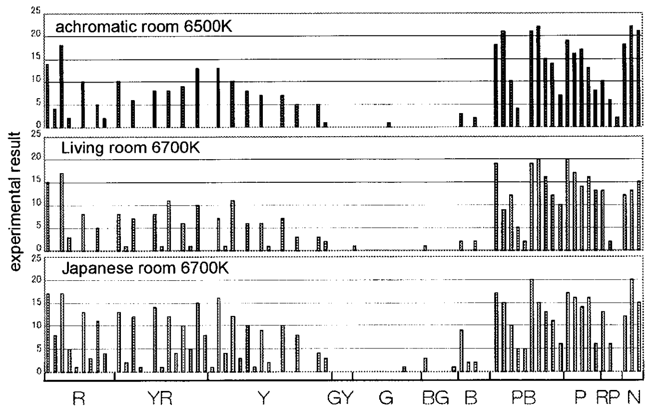


Figure 10 Whiteness evaluation values of the 84 munsell color sheets in the achromaticroom and Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 6700 K

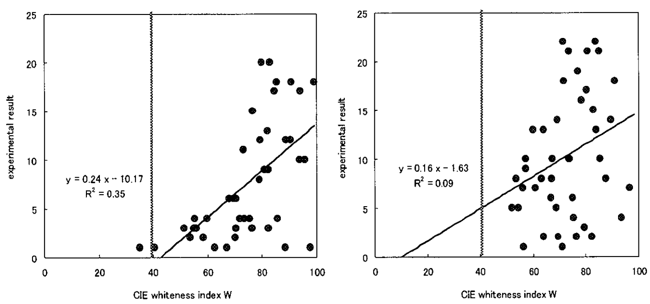
In the case of the correlated color temperature 6700 K, the selected number was large in hues of the PB series, the N series, and the R series with both the achromatic background and the chromatic background. As a result of the t test, the test of frequency, it was clarified that there is no significant difference between the living room and an achromatic background, but that there are significant differences between the Japanese room and the living room and between the Japanese room and the achromatic background.

4. Correspondence between the experimental results and the color perception property values

As mentioned before, the CIE whiteness index was recommended in 1986 and JIS Z 8715 was established based upon it. Also, many studies were implemented on color appearance models to forecast the appearance of material colors under various illuminating lights, and the CIE proposed CIECAM97s in 1997, in which the color perception property value was defined. Hence, the relationship between the experimental results in this study versus the whiteness index and the color perception property values defined by CIECAM97s was examined.

Figure 11(a) shows the relationship between the selection frequency with the 3000 K correlated color temperature in Experiment 1 and the whiteness index, and Figure 11(b) shows the relationship between the selection frequency with the 6500 K correlated color temperature in Experiment 1. As shown in Figures 11(a) and (b), the correlation coefficient between the selection frequency and the whiteness index was 0.60 in the case of 3000 K and 0.30 in the case of 6500 K, and it was found that the correlation was low in either case.

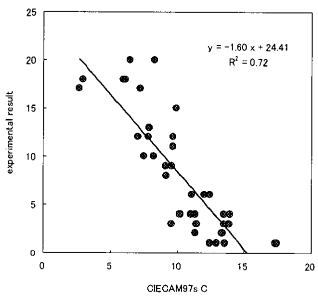
As mentioned before, Mukai et al. studied the relationship between the experimental results of subjective evaluations by Akatsu et al., which was used as basic data, and chroma C, which is one of color perception properties in the CIECAM97s, and found that there is a



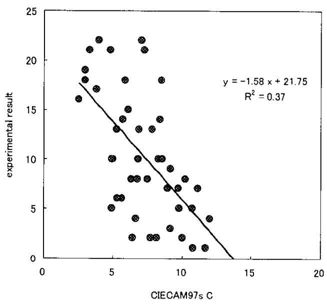
(a) Correlated color temperature 3000 K (b) Correlated color temperature 6500 K

Figure 11 Correction between the experimental result and CIE whiteness index W in the achromatic room highly negative relationship with a correlation coefficient of -0.93 between chroma C and the subjective evaluation results. Although the number of color sheets was limited to seven in the subjective evaluation experiment done by Akatsu et al., 84 color sheets of white or colors close to white covering almost whole hues were used in the experiments of this study. Hence, we have examined the corresponding relationship between the experimental results in this study and chroma C.

Figures 12(a) and (b) shows the relationship between the selection frequency with an achromatic background in correlated color temperatures of 3000K and 6500K, respectively, versus chroma C. As shown in Figures 12(a) and (b), the correlation coefficient was -0.85 in the case of the 3000 K correlated color temperature and -0.60 in case of the 6500 K correlated color temperature. Also, Table 1 shows the correlation coefficients between the selection frequency of white in Experiments 1 and 2 and the color perception property values. As shown in Table 1, it was found that there is a negative correlation between the selected frequency and chroma C, although the correlation coefficient was smaller than what was shown by Mukai et al. Also, it was known that the correlation coefficient between the experimental results and the distance from the center of the coordinates, which is shown by (a, b), was in the range from -0.57 to -0.78.



(a) Correlated color temperature 3000 K



(b) Correlated color temperature 6500 K

Figure 12 Correction between the experimental result and the modified CIECAM97s chroma C in the achromatic room

Table 1 Correction between the experimental result and the CIE whiteness index W, the modified CIECAM97s C, s, a and b in the achromatic room

		achromatic room		Living room		Japanese room	
		3000K	6500K	3000K	6700K	3000K	6700K
whiteness index	W	0.60	0.30	0.54	0.47	0.68	0.35
CIECAM97s	chroma C	−0.85	−0.60	−0.57	−0.68	−0.74	−0.78
	saturation s	−0.84	−0.60	−0.60	−0.66	−0.76	−0.77
	Distance from the Center of the coordinates by ab	−0.78	−0.64	−0.57	−0.76	−0.74	−0.77

5. Trial for quantification of perceptual whiteness

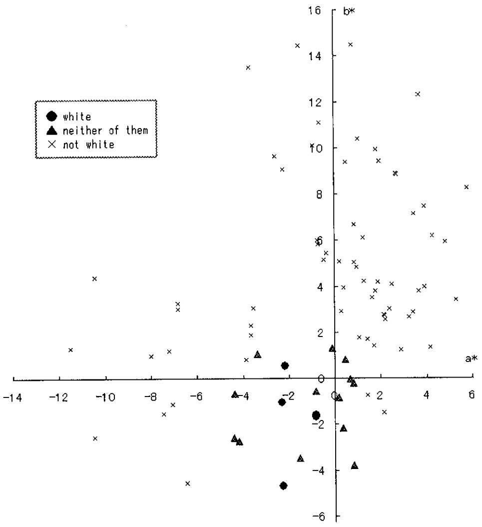
5.1 Permissible rate of whiteness and calculation of the locus of the equal perceptual whiteness rate

In Experiments 1 and 2, the subjects were requested to observe 84 color sheets under each illuminating condition and to classify each sheet as either “a color sheet felt to be white” or “a color sheet not felt to be white”. In other words, we had them judge if the demonstrated color sheet is permissible as white or not.

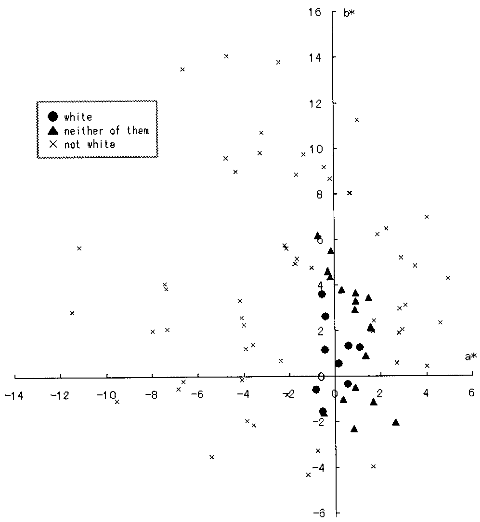
As mentioned before, Suzuki et al. proposed a whiteness formula based upon experiment in which the psychological whiteness of 44 pieces of photographic color paper, for which the a*b* coordinate values were distributed in the third and fourth quadrants on the CIE 1976 $L^*a^*b^*$ chromaticity diagram, while being illuminated by high color rendering fluorescent lamps for color evaluation (5000 K correlated color temperature).

In this study, the purpose of which was to study the perceived whiteness in a residential space, experiments were performed with color sheets of high brightness and low chroma saturation covering almost whole hues and with fluorescent lamps of different correlated color temperatures, which are used for general illumination. Therefore, it is impossible to directly compare the results of this study with the results by Suzuki et al. who used different light sources and color sheets for demonstration, but we have decided to study what difference there is in regard to the white area.

The permissible rate for the experimental results in Experiments 1 and 2, which allows the results to be regarded as being statistically significant, was calculated using a chi-square distribution applying a significance level of 5%. Firstly, the results obtained for each illuminating condition by the chi-square distribution on the results of Experiment 1 were classified into three groups: those with a probability exceeding 72%, which is permitted as being apparently white; those with a probability below 28%, which is judged as apparently not being white; and those with probability in the range from 28% to 72%, which is judged as being neither of them. Figures 13(a) and (b) show the distributions of the permissible rates of whiteness for each color sheet on the a*b* coordinates of the CIE 1976 $L^*a^*b^*$ chromaticity diagram for the correlated color temperatures of 3000 K and 6500 K (both narrow band fluorescent lamps), respectively. Here, the symbol ● indicates color sheets of which the permissible rate of whiteness



(a) Correlated color temperature 3000 K

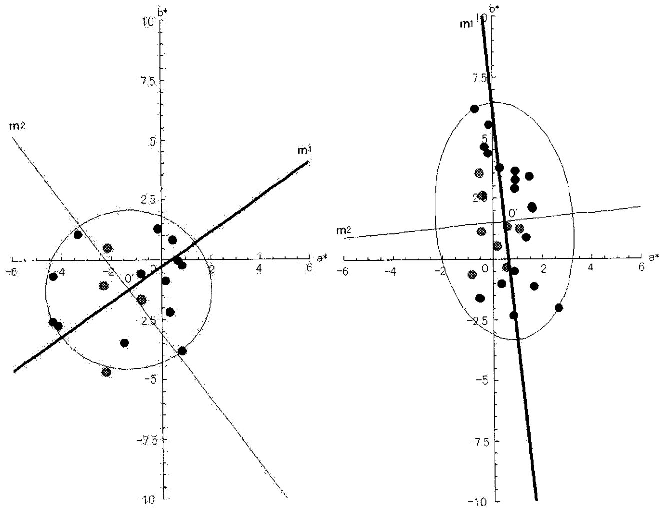


(b) Correlated color temperature 6500 K

Figure 13 The distribution of permissible rate to the perceptual whiteness in the achromatic room under the fluorescent lamp with the correlated color temperature of 3000 K

exceeded 72%, the symbol ▲ indicates those with permissible rate of whiteness in the range from 28% to 72%, and the symbol × indicates those with a permissible rate of whiteness below 28%.

Then, the locus of the equal perceptual whiteness permissible rate was obtained from the permissible rate of whiteness. An average of the color sheets permitted as being “white” and “neither of them” was put at the center of the coordinates. For the long axis, analysis of the main component was made using the measured value of each colored sheet, the *a*b* value, to obtain the eigenvalue and eigenvector for calculating the first main component. From the first main component, the slope and then the straight line passing through the

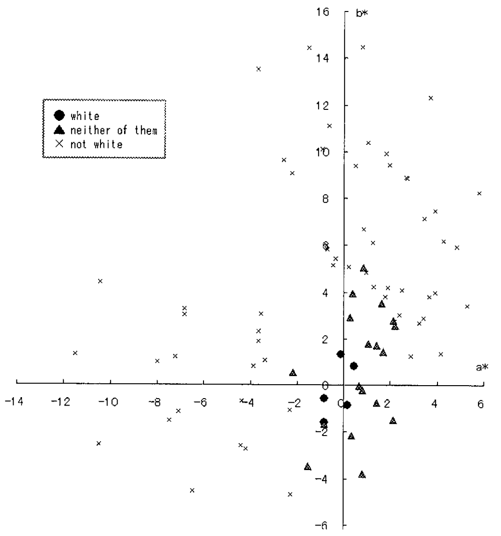


(a) Correlated color temperature 3000 K (b) Correlated color temperature 6500 K

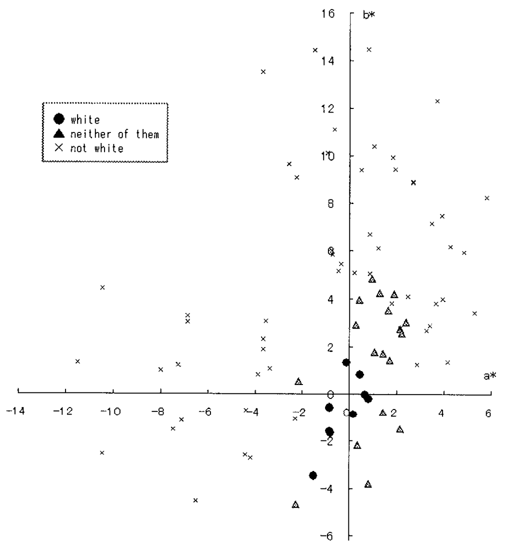
Figure 14 The Locus of the equal perceptual whiteness rate in the achromatic room

center of the coordinates were obtained to define the long axis. The short axis was put as a straight line that crosses the long axis perpendicularly and that passes through the center of the coordinates. The locus of the equal perceptual whiteness permissible rate was calculated based upon the equation for an ellipse (two dimensional curve) as shown below. There are three constants, b, c, and d, in the equation for an ellipse, and three points were set in order to determine these constants. Regarding the three points, a point for which the coordinate on the long axis is a maximum and the coordinate on the short axis is a minimum was selected as one point, and a point at a position symmetrical to that point in relation to the center O', or axisymmetrical in relation to the long axis, was selected as another point. Also a point for which the coordinate on the short axis is a maximum and the coordinate on the long axis is a minimum was selected as the remaining one point. Figures 14(a) and (b) show the loci of the equal perceptual whiteness permissible rates in the cases of the correlated color temperatures of 3000 K and 6500 K (narrow band fluorescent lamps), respectively.

Then, an analysis regarding Experiment 2 was made following a similar procedure. Figures 15(a) and (b) show the permissible rates of whiteness in the living room and the Japanese room, respectively, under an illuminating light of 3000 K correlated color temperature (narrow band fluorescent lamp), and Figures 16(a) and (b) show the permissible rates of whiteness in the living room and the Japanese room, respectively, under the illuminating light of 6700 K correlated color temperature (narrow band fluorescent lamp), both on the

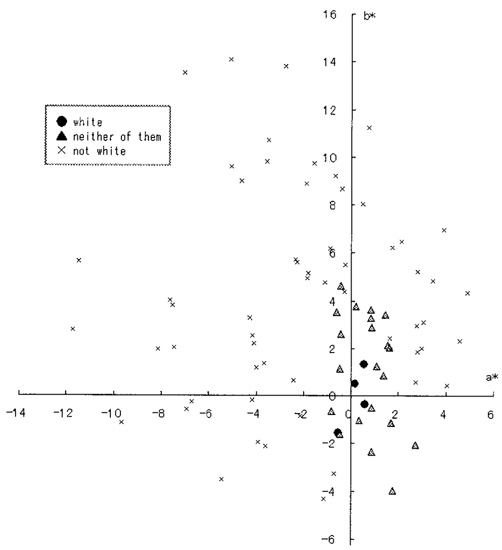


(a) Living room

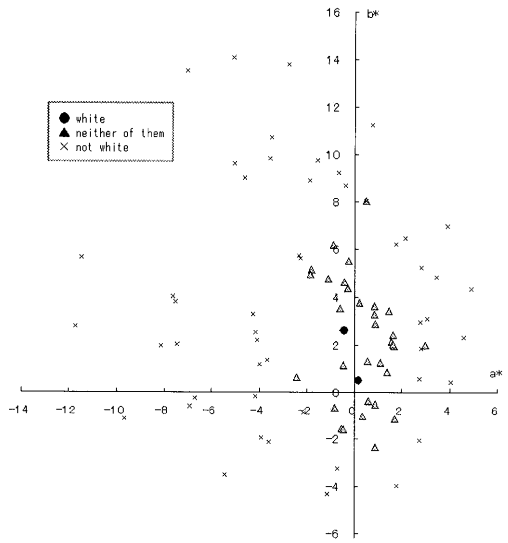


(b) Japanese room

Figure 15 The distribution of rate of permissible rate to the perceptual whiteness in the Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 3000 K



(a) Living room



(b) Japanese room

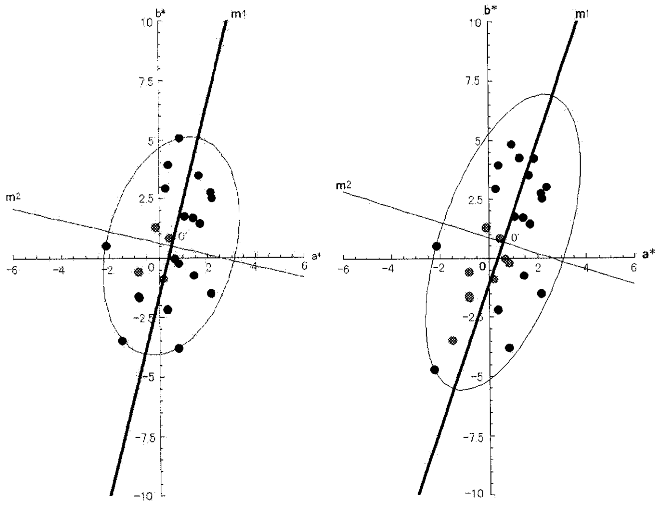
Figure 16 The distribution of rate of permissible rate to the perceptual whiteness in the Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 6700 K

a*b* coordinates of the CIE 1976 $L^*a^*b^*$ color space.

Following a similar procedure as was the case for Experiment 1, the loci of the equal perceptual whiteness permissible rates were obtained from the permissible rates of whiteness as shown in Figures 15(a) and (b), and Figures 16(a) and (b). Figures 17(a) and (b) show the loci of the equal perceptual whiteness permissible rates in the living room and the Japanese room, respectively, under the illuminating light of 3000 K correlated color temperature, and Figures 18(a) and (b) show the loci of the equal perceptual whiteness permissible rates in the living room and the Japanese room, respectively, under the illuminating light of 6700 K correlated color temperature.

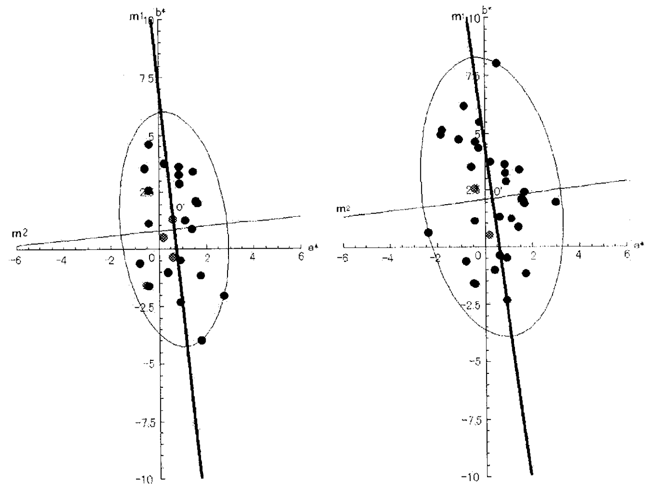
As shown in Figures 14(a) and (b), Figures 17 (a) and (b), and Figures 18 (a) and (b), the loci of the equal perceptual whiteness permissible rates under each illuminating condition of correlated color temperature of 3000 K and the same of 6700 K are nearly elliptical. Also, when the values of coordinates at the center of these loci of the equal perceptual whiteness permissible rates are compared, it is clarified that the centers of the coordinates are located in the range of 1 through 3 in both the a* value and the b* value, both in the first quadrant.

While the range of colors with high permissible rates of whiteness was from -1 to 1 in the a* value and from



(a) Living room (b) Japanese room

Figure 17 The Locus of the equal perceptual whiteness rate in the Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 3000 K



(a) Living room (b) Japanese room

Figure 18 The Locus of the equal perceptual whiteness rate in the Living room and Japanese room under the fluorescent lamp with the correlated color temperature of 6700 K

-4 to -7 in the b* value and shifted toward the direction of blue in the experiment by Suzuki et al., the area of colors with high permissible rates of whiteness in this study is wide in range in the direction of the b* axis from the direction of PB to the direction of Y. It was clarified that the area of the loci of the equal perceptual whiteness permissible rates as shown by the ellipses is large with the illuminating condition with the 6700 K correlated color temperature compared to the 3000 K, and also that the whiteness area is larger with the chromatic background in the real space compared to the achromatic background.

5.2 Trial for quantification of the perceptual whiteness

As described before, it was clarified that the shape of the loci of the equal perceptual whiteness permissible rates, which was established from the chromaticity coordinates of the color sheets that were evaluated as being "white" and "neither of them," is an ellipse. Also it was clarified that the chroma C and the distance from the coordinates' center as expressed by (a, b) correspond to each other as a result of a study of the relationship between the color perception property values and the results of the subjective evaluation. Hence, we have tried to quantify the perceptual whiteness assuming that the perceptual whiteness is related to the chroma corresponding to the color intensity and the direction of the color. As it is clear in the a*b* of coordinates on the CIE 1976 $L^*a^*b^*$ color space, the color intensity increases in parallel with an increase in the distance from the center of the coordinates. It was clarified by the experiment that, when chroma C gets lower, the color intensity is decreased, and the rate of perception of the color as being white gets higher. Also, the direction of the color expresses the perceived hue, and it was clarified in this experiment that the perceptual whiteness varies by differences in hue.

Hence, the correspondence of the distance r between the a*b* value of a color sheet that was evaluated as being "white" or "neither of them" under each experimental condition, as described in Paragraph 5.1, and the center of the coordinates versus chroma C was studied. As a result, it was found that the correlation coefficient between these two items is outstandingly high. Since the correlation between the distance r and chroma C exceeded 0.80 in all of conditions, we have decided to express the color intensity by the distance r from the center of the coordinates. Since an increase in the distance r means an increase in the perceptual whiteness area under a particular illuminating light, the perceptual whiteness area can be estimated by the area of the ellipse surrounding the loci of the equal perceptual whiteness permissible rate. Area S of an ellipse is expressed by equation (1).

$$S = \frac{\alpha}{2} \times \frac{\beta}{2} \times \pi \quad \cdots\cdots (1)$$

Here, α: The long axis of the loci of the equal perceptual whiteness permissible rate

β: The short axis of the loci of the equal perceptual whiteness permissible rate

α (long axis) and β (short axis) in equation (1) are constants obtained through the equation of the loci of the equal perceptual whiteness permissible rate.

When the density of the color sheets that were selected as being white or neither of them in each experimental condition was observed, it was found that, although area S of ellipse in each condition obtained from equation (1) was almost the same, the density of the selected color sheets was different as shown in Figure 19. Hence, the selection rate a of perceived whiteness was derived, and the volume of an ellipsoidal body as show in equation (2) was put as C.

$$C=\frac{1}{2}\times\frac{4}{3}\times\frac{\alpha}{2}\times\frac{\beta}{2}\times a\times\pi \quad \cdots\cdots (2)$$

Here, a: Average of the following fraction:
(numerator) Experimental results (selection frequency)
(denominator) Distance from the center O' of the locus of the equal perceptual whiteness permissible rate for each a^*b^* value

For the selection rate a in equation (2), the distance from the center of coordinates O' in the loci of the equal perceptual whiteness permissible rates under each illuminating condition for correlated color temperatures 3000K and 6700K, as shown in Figures 15(a) and (b), Figures 17(a) and (b), and Figures 18(a) and (b), to the chromaticity coordinates of the color sheets that were selected as being white and neither of them was put as r', the product of the reciprocal of r' and the selection frequency for each color sheet was calculated, and the averages of such products was set as a.

Then, we would like to discuss the direction of color. The direction of the colors that are perceived as being white varies by the experimental conditions. According to the experimental results with the narrow band fluorescent lamps as shown in Figures 3, 4, 7, and 8, many 3PB series hues were perceived as white in any experimental space with a correlated color temperature of 3000K, while many 10PB hues were perceived as white with a correlated color temperature of 6500K. Thus, it was clarified that a shift in the hues perceived as white owing to an increase in the correlated color temperature was observed. Meanwhile, the slope in the direction of long axis of the loci of equal perceived whiteness varies by correlated color temperature and background conditions. Hence, we have decided to have the slope correspond to the direction of the color. In addition, since the density of the selected color sheets varies even if the area of the ellipse surrounding the loci of the equal perceptual whiteness permissible rates is the same as shown in Figure 19, we have decided to take the selection rate into consideration for quantification.

Hence, equation (2) to calculate the volume of the ellipsoidal body was modified to create equation (3) by the addition of a parameter for the slope that expresses the direction of the color, and it was put as the Perceptual Whiteness Index (PWI).

Perceptual Whiteness Index (PWI)

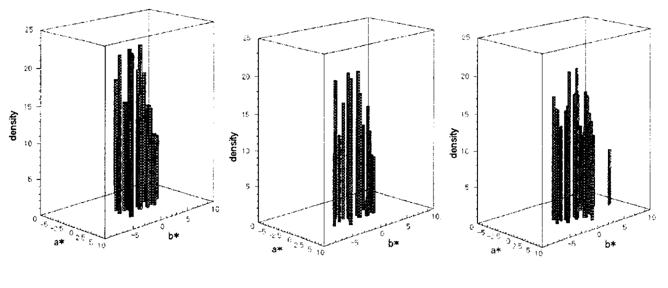
$$=\frac{1}{2}\times\frac{4}{3}\times\frac{\alpha}{2}\times\frac{\beta}{2}\times\sin\theta\times a\times\pi \quad \cdots\cdots (3)$$

Here, 1/2 is for upper half of ellipsoidal body.

θ in equation (3) expresses the slope of the long axis of the loci of the equal perceptual whiteness permissible rates, and it was set using the metric hue angle.

$$\theta = H_{ab}^{\circ} = \tan^{-1}\left(\frac{b^*}{a^*}\right)\times\frac{180}{\pi}$$

As shown in equation (3), the Perceptual Whiteness Index (PWI) is composed of the volume of ellipsoidal body S, which was derived from the perceptual whiteness area, the slope θ to express the direction of the color, and the selection rate a. Table 2 shows the Perceptual Whiteness Index under each experimental condition, and Figure 20 shows the correspondence between the subjective evaluation values and the Perceptual Whiteness Indices. As seen in Figure 20, the correlation coefficient was 0.80 and a high correlation could be obtained. By the way, the selection frequency in the



(a) Achromatic room (b) Living room (c) Japanese room

Figure 19 The distribution of density of Perceptual whiteness in the different environmental condition under the fluorescent lamp with the correlated color temperature of 6700K

Table 2 Correction of the experimental result and Perceptual Whiteness Index

experimental room		correlated color temperature	α (long axis)	β (short axis)	a (selection rate)	θ (metric hue angle)	PWI
achromatic room		3000K	3.33	3.36	9.29	0.40	87.09
		6500K	4.90	2.77	10.75	0.96	293.63
chromatic room	Living room	3000K	4.67	2.64	9.84	0.92	233.44
		6700K	5.14	2.25	10.33	0.94	235.76
	Japanese room	3000K	6.52	2.59	11.22	0.89	353.43
		6700K	6.15	2.93	7.47	0.96	270.13
Correlation frequency							0.80

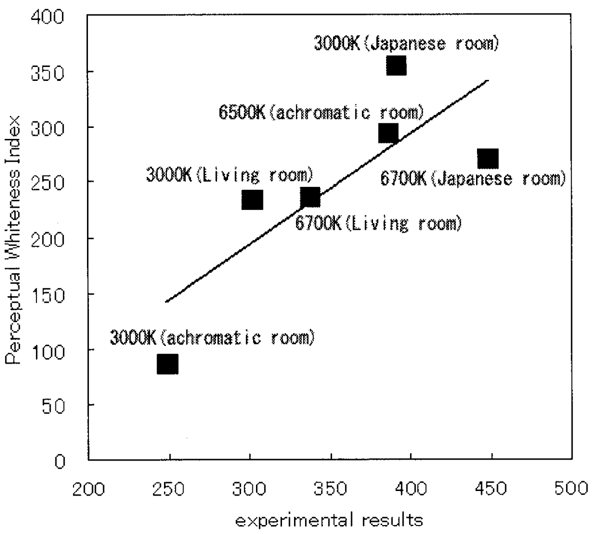


Figure 20 Relationship between the experimental results and the Perceptual Whiteness Index

case of the 3000K correlated color temperature with an achromatic background was small compared to the other experimental conditions. Especially, the selection frequency of color sheets of the R, YR, and Y series was small, and as a result a small Perceptual Whiteness Index was obtained, as shown in Figure 20. In view of the above, the appropriateness of the quantification equation for the perceptual whiteness within the scope of experimental conditions for this study could be found.

6. Closing remarks

The perceptual whiteness of white and colors close to white with fluorescent lamps of different correlated color temperatures was studied under the conditions of an achromatic background and chromatic backgrounds that simulated real spaces.

The results are summarized as follows:

1) In the achromatic background condition with a correlated color temperature of 3000K, the narrow band fluorescent lamps show a higher selection rate of color sheets judged as being white compared to the broad band fluorescent lamps.
2) In the achromatic background condition with a correlated color temperature of 6500K, the broad band fluorescent lamps show a higher selection rate of color sheets judged as being white compared to the narrow band fluorescent lamps.
3) The number of color sheets being judged as white is larger in the chromatic background condition in the real spaces compared to that in the achromatic background condition.
4) The permissible rate of whiteness was calculated based upon the experimental results, and the loci of the equal perceptual whiteness permissible rates, which have the shape of an ellipse, was derived.
5) The Perceptual Whiteness Index (PWI) was derived from the volume of the ellipsoidal body S that was derived from the perceptual whiteness area as obtained from experiment in this study, the slope θ to express the direction of color, and the selection rate a.
6) A high correlation was obtained between the Perceptual Whiteness Index (PWI) and the subjective evaluation values obtained through experiment in this study.

In the experiments of this study, as shown in Table 2, the influence of the illuminating light and the influence of the background are included in each coefficient, but each influence has not been segregated. It is necessary to study further the influence of the color contrast effect by background in the future. Also, we would like to confront themes such as the relationship between the perceptual whiteness and the perceptual brightness and the influence of aging on the perceptual whiteness.

References

(1) JIS Z 8715(1991): Whiteness Index —Indication Method.
(2) Uchida, Y.: A Consideration on CIE Whiteness Index Formula, J. Color Sci. Assoc. Jpn., 14-12, pp.106-113 (1990).
(3) Uchida, Y.: Study on Visual Judgment of Fluorescent Whitening Samples and Whiteness Evaluation, pp.97-119 (1994).
(4) Baba, B.: Quantitative Evaluation of Whiteness, Jpn. J. Optics, 10-1, pp.11-17 (1981).
(5) Suzuki, T.: Whiteness Index Based Upon Permissible Level of Perceptual Whiteness, J. of Color Sci. Assoc., 14-2, pp.11-121 (1990).
(6) Suzuki, T., Fuchida, T., Komatsubara, H. and Sakata, K.: Study of Whiteness Index by Light Source Color, J. Illum. Engng. Inst. Jpn., 77-2, pp.9-12 (1993).
(7) Suzuki, T.: A Trial Regarding the Quantification of Perceptual Whiteness, J. Color Sci. Assoc. Jpn., 23-3, pp.168-175 (1999).
(8) Katayama, I., Iiyama, M. and Masumi, K.: Influence of Spectral Composition of Illuminating Light on Perceived Whiteness, J. Illum. Engng. Inst. Jpn., 85-5, pp.338-345 (2001).
(9) Katayama, I., Masumi, K. and Aoki, T.: Relationship between Chromatic Strength and Perceptual Whiteness, J. Illum. Engng. Inst. Jpn., 86-5, pp.286-291 (2002).
(10) Ayama, M., Akatsu, T., Toriumi, E., Mukai, K. and Kanaya, S.: Whiteness Perception under Different Types of Fluorescent Lamps, Color Res. Appl.28,

pp.96-102 (2003).

(11) Tate, Y., Kanaya, S., Ayama, M. and Mukai, K.: Study of Whiteness Area under Various Illuminating Light, Proc. the 32nd Annual Conf. IEIJ (1999).

(12) Tate, Y., Kanaya, S., Ayama, M. and Mukai, K.: Study on Perceived White under Chromatic Background, Proc. the 34th Annual Conf., IEIJ (2001).

(13) Kanaya, S., Ayama, M., Halonen, L., Eloholma, M. and Mukai, K.: A Comparative Study of Whiteness Perception in Japan and Finland, International Lighting Congress 2001 Proceeding, pp.427-432 (2001).

(14) Eda, T., Ayama, M., Kanaya, S. and Mukai, K.: Perceptual White Area under Illumination by Fluorescent Lamps of Incandescent Lamp Color and Daylight Color, J. Illum. Engng. Inst. Jpn., 89-2, pp.91-99 (2005).