Paper

Quantitative Evaluation of Perceived Whiteness under Different Illuminations

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ABSTRACT

The perceived whiteness of 12 approximate white-color samples was evaluated under four different fluorescent lamps (EXD, EXN, EXWW, and EXL) using a paired comparison method, and then an interval scale was configured. Under all illuminations, the perceived whiteness of purple and red hue samples was highly evaluated while green and blue-green hue samples were poorly evaluated. The C/V index, a perceived whiteness evaluation index, which focused on the brightness-enhancement effect of color components that were included in the approximate white objects or illuminations, showed a high correlation with the interval scale value under each illumination. Furthermore, compared to various color appearance models, the index showed a superior predicting performance. The above findings confirmed that the C/V index was effective in evaluating the perceived whiteness of approximate white objects under different illuminations, and the brightness-enhancement effect of color components was an important factor in determining the perceived whiteness.

KEYWORDS: perceived whiteness, G_0 function, chromatic strength, C/V index, color appearance model

1. Introduction

There are a number of white objects around us —paper, textiles, photographs, and painted objects to name a few. And being perceived as white often plays an important role in raising their value as commercial products. For this reason, many studies have been conducted on methods to enhance perceived whiteness and its quantitative evaluation¹⁾⁻¹¹⁾. These studies have clarified that perceived whiteness is a psychological phenomenon that is connected with brightness and colorlessness. However, the perceived-whiteness evaluation formulas proposed in the past were experimental formulas based on results of visual evaluation; without consideration of the visual mechanism that regulates perceived whiteness, the basis of the evaluation formulas was not clear.

Meanwhile, there was a fascinating report on the appearance of chromatic stimuli. Evans *et al.*¹²⁾⁻¹³⁾ made a 1° opening in the center of a 10° white background (approx. 7000 K, 320 cd/m²) and then displayed spectral colors and colors on the purple boundary. When the luminance of a colored stimulus is 0, the opening is perceived as black in the object color mode; as the luminance is gradually increased, the blackness decreases and color and grayness begin to be perceived. Furthermore, as the luminance of the central stimulus is increased, the color begins to increase while the grayness decreases, eventually reaching a point of luminance where

grayness is not perceived. Evans *et al.* named that point the zero-gray point and defined it in Equation (1):

$$G_0 = \log(L_s / L_b) \dots \dots \dots (1)$$

where G_0 is the zero-gray point, L_s the background luminance, and L_b the luminance of the central stimulus. The G_0 that is obtained as the function of the wavelength of the central stimulus is the G_0 function that expresses the perceived blackness cancellation capability of a spectral color stimulus; Evans *et al.* called this chromatic strength. Chromatic strength emerges as the capability to enhance the brightness perception of spectral color stimuli in the Helmholtz-Kohlrausch effect¹⁴⁾. All color perception phenomena are attributed to their inherently common mechanism¹⁵⁾; the chromatic strength increases in the short-wavelength region, becomes minimum near 570 nm and increases again in the long-wavelength region.

The authors of this paper focused on chromatic strength and its effect to enhance perceived brightness as a perceived whiteness evaluation method based on the visual mechanism. The perceived whiteness evaluation index, the C/V index, was then deductively extracted and its effectiveness and the validity of its hypothesis¹⁶⁾⁻¹⁸⁾ were examined. However, since we had the subject externally peek at the observation box in a half-dark room and made evaluations, the subject was not included in the test

illumination.

In this paper, an evaluation experiment of perceived whiteness was conducted under conditions closer to the actual environment by using an experimental booth that included a subject, and the relationship between the experimental results and the *CV* index, a perceived whiteness evaluation index, was examined. For illuminants, four types of fluorescent lamps of different chromaticities were used. Furthermore, the above was compared with when the chroma values of color appearance models were used as a perceived whiteness prediction index.

2. Perceived whiteness evaluation

2.1 Experimental setup

The experimental booth used was 1.8m-wide, 1.8m-deep, and 2.2m-tall with N5.5 achromatic-color inner walls. The outline of the experimental booth is given in Figure 1.

The illuminants used were the four types of three-band type daylight fluorescent lamp (EXD), neutral-white (EXN), warm-white (EXWW), and incandescent lamp color (EXL). The illuminants were covered with white acrylic boards and installed on the ceiling of the booth. Table 1 shows *xy* chromaticity coordinates of the four illuminants used for the experiment, and values of the correlated color temperature. Those values were calculated from the spectral distribution of an illumination penetrated through the white acrylic cover inside the booth, which had been measured using the compact-type spectrometer EPP2000 (StellarNet, Inc.).

The Munsell hues of approximate white samples used in the experiment were 4R, 4YR, 5Y, 3GY, 3G, 9G, 7BG,

Figure 1 Schematic of the experimental booth

5B, 3PB, 10PB, 7P, and N; the Munsell value was 9.25 for all and the Munsell chroma 0.5 except for N. Each sample was a 5 cm-by-5 cm square; we prepared the combination of 66 patterns necessary for the paired comparison of 12 different samples. The color paper materials were specially manufactured by JAPAN COLOR ENTERPRISE CO. LTD., which did not include fluorescent whitening agent. The same firm was also commissioned to measure the spectral reflectance distribution. Table 2 shows the Munsell hues, chromaticity coordinates under the standard illuminant D_{65} , and *Y* values. Figure 2 shows the chromaticity distribution of samples in the *xy* chromaticity diagram. The symbol $\times$ represents the chromaticity coordinates of the standard illuminant D_{65} . The two diagonal lines denote the JIS tint index, $T_w = 3$ and $T_w = -3$; inside those diagonal lines is the applicable range for the JIS whiteness index. Of the approximate white samples used in this experiment, 3G, 9G, 7BG, 5B, and 4YR were beyond this applicable range.

Approximate white sample pairs displayed on the desk at the center of the experimental booth were presented. The sample presentation background was N5 achromatic, and the surface illuminance of the desk was 1000 lx. The subjects observed samples from a direction of approxi-

Table 1 *xy* chromaticity coordinates of the four illuminants used for the experiment, and values of the correlated color temperature

Lamp	<i>x</i>	<i>y</i>	T_c (K)
EXD	0.318	0.345	6160
EXN	0.349	0.375	4920
EXWW	0.411	0.404	3480
EXL	0.420	0.407	3330

Table 2 Munsell hues, chromaticity coordinates under the standard illuminant D_{65} , and *Y* values of samples used for the experiment

No.	Munsell Hue	<i>x</i>	<i>y</i>	<i>Y</i>
1	N	0.3145	0.3316	84.40
2	4R	0.3165	0.3307	84.36
3	4YR	0.3195	0.3339	84.31
4	5Y	0.3200	0.3387	84.49
5	3GY	0.3185	0.3398	84.74
6	3G	0.3118	0.3362	84.60
7	9G	0.3098	0.3342	84.82
8	7BG	0.3085	0.3314	84.32
9	5B	0.3087	0.3291	84.60
10	3PB	0.3098	0.3278	84.42
11	10PB	0.3117	0.3277	84.68
12	7P	0.3133	0.3283	84.36

Figure 2 Chromaticity distribution of samples in the xy chromaticity diagram

The two diagonal lines denote the JIS tint index, $T_w = 3$ and $T_w = -3$; inside those diagonal lines is the applicable range for the JIS whiteness index. The symbol $\times$ represents the chromaticity coordinates of the standard illuminant D_{65} .

mately 45° with the natural vision of both eyes; the visual angle for sample pairs was approximately $4^\circ \times 11^\circ$.

2.2 Experimental procedure

After the subject adapted to the illumination inside the experimental booth for five minutes, he or she evaluated which of the left or right sample looked whiter than the other. The judgment of whiteness was dependent on the internal criteria of each subject. Repeat count of the judgment was once per one illuminant.

The subjects consisted of 10 people with normal color vision (average age 19.1; four males and six females). Of them, one male and three female subjects had experienced a visual psychological experiment.

3. Experimental results and discussion

Figure 3 shows average values of the experimental results. The error bars show standard deviations. The abscissa denotes the hue of approximate white color samples; with the exception of N, they were all placed along with the Munsell hue circle. The ordinate denotes the number of selection. As a result of judging their sensory evaluation by the number of circular-triads, the consistency¹⁹⁾ of the evaluation by each subject was significant at the 1% level of χ^2 test under all four illuminations. The agreement¹⁹⁾ between the subjects was also significant at the 1% level under all four illuminations.

Figure 3 Average values of the experimental results

The error bars show standard deviations. The abscissa denotes the hue of approximate white color samples; with the exception of N, they were all placed along with the Munsell hue circle. The ordinate denotes the number of selection.

Figure 4 Interval scales of perceived whiteness

The abscissa denotes the hue of approximate white color samples; with the exception of N, they were all placed along with the Munsell hue circle. The ordinate denotes the interval scale value, which is composed of the evaluation values of the 10 subjects.

Figure 4 shows the interval scale value of perceived whiteness, which is composed of the evaluation values of the 10 subjects by application of Thurston's case V²⁰. For further details the reader should refer to Appendix A.

Under all four illuminations, the perceived whiteness of purple and red samples such as 4R, 10PB, and 7P was highly evaluated while that of green-hue samples such as 3G and 9G was poorly evaluated. The sample N was not corresponding to the highest perceived whiteness. Those findings were consistent with the results of our previous study¹⁷.

3.1 Perceived whiteness evaluation index: the *CV* index

Attention was focused on chromatic strength and its effect to enhance perceived brightness as a perceived whiteness evaluation method based on the visual mechanism.

Regarding the relationship between chromatic strength and perceived whiteness, the perceived whiteness evaluation index was defined using Equation (2) based on the following hypothesis and called the *CV* index.

The hypothesis was as follows: "a white object under a white illumination whose spectral distribution includes many wavelength components of great chromatic strength, or a whitish object whose spectral reflectance includes many wavelength components of great chromatic strength is perceived as brighter and its perceived whiteness becomes greater."

$$C/Vindex = \frac{\int_{380}^{780} P(\lambda)R(\lambda)C(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)R(\lambda)V(\lambda)d\lambda} \times Y \times a \dots \dots \dots (2)$$

where $P(\lambda)$ is the spectral distribution of the illumination,

Figure 5 Results of calculating the perceived whiteness evaluation index, the *CV* index, from the spectral distribution of illuminations and the spectral reflectance distribution of approximate white color samples

$R(\lambda)$ is the spectral reflectance distribution of the white object, $C(\lambda)$ is the wavelength function of the vector luminance obtained using Guth's color perception model²¹, $V(\lambda)$ is the CIE standard spectral luminous efficiency, Y is the luminous reflectance, and a is the adjustment factor.

In Equation (2), Y can be expressed by the definition of tristimulus values of the object color as Equation (3):

$$Y = \frac{\int_{380}^{780} P(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)\bar{y}(\lambda)d\lambda} \times 100 \dots \dots \dots (3)$$

where $\bar{y}(\lambda)$ is one of the CIE1931 color matching functions. From Equation (3) and $\bar{y}(\lambda) = V(\lambda)$, Equation (2) becomes Equation (4).

$$\begin{aligned} C/Vindex &= \frac{\int_{380}^{780} P(\lambda)R(\lambda)C(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)V(\lambda)d\lambda} \times 100 \times a \\ &= \frac{\int_{380}^{780} P(\lambda)R(\lambda)C(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)V(\lambda)d\lambda} \times a' \dots \dots \dots (4) \end{aligned}$$

The *CV* index increases when many wavelength components of great chromatic strength are included in the spectral reflectance distribution of the whitish object or in the spectral distribution of the illumination. Readers should note that the numerator of Equation (4) does not represent luminous efficiency for compound spectra, differing from the CIE $V(\lambda)$ function, because of the failure of additivity for different spectra. The *CV* index does not evaluate brightness for compound spectra but correspond to the amount of chromatic strength contained in the compound spectra per unit luminance. For details of the calculation procedure of the *CV* index see Appendix B.

Figure 5 shows the results of calculating the perceived whiteness evaluation index, the CV index, from the spectral distribution of illuminations and the spectral reflectance distribution of approximate white color samples. Figure 5 shows that the higher the correlated color temperature of the illumination becomes, the greater the CV index becomes; thus, an increase in perceived whiteness is predicted.

Figure 6 shows the results of a simple regression analysis on interval scale values and the CV index of perceived whiteness. Strong correlations were observed under all illuminations, and were all significant at the 1% level.

The above findings confirmed that the CV index is effective for a perceived whiteness evaluation of approximate white objects under different illuminations.

3.2 Relationship between chromatic strength and perceived whiteness

Chromatic strength has two aspects. One is the capability to cancel achromatic components or to induce color perception, and the other is a brightness-enhancement capability. When discussing perceived whiteness, there are very few percentages in which color-perception inducing components are included in the

spectral reflectance distribution of approximate white objects or the spectral distribution of illuminations. When the chromatic strength of those few color components is great, the brightness-enhancement effect becomes superior to color-perception, and perceived whiteness increases. When the chromatic strength of color components is small, there is no stimulus region for the brightness-enhancement effect to be superior to color-perception, thus perceived whiteness declines as color-perception increases. For details, refer to Appendix C.

3.3 Relationship between perceived whiteness and the chroma of color appearance models

The psychological determinants of whiteness are appearing bright and not appreciating color. For this reason, from a broad perspective, perceived whiteness has a negative correlation with the chroma value. Here, the chroma values were calculated under different illuminations using color appearance models, and their relationship with the results of a perceived whiteness evaluation examined. Seven color appearance models were used: CIELAB, CIECAT94LAB²²⁾ (CIELAB, which applied CIECAT94²³⁾ to predicting chromatic adaptation), CIECAM97s²⁴⁾, CIECAM02²⁵⁾, NLCAM (the non-linear color appearance model by Nayatani *et al.*²⁶⁾), NC-IIIIC by

Figure 6 Results of a simple regression analysis on interval scale values and the C/V index of perceived whiteness

Ikeda *et al.*²⁷⁾, and CIECAT94NC-III C (NC-III C, which applied CIECAT94 to predicting chromatic adaptation).

The simple correlation coefficients were obtained with the experimental results of the perceived whiteness evaluation in this study, which are given in Table 3 and Figure 7 along with the C/V index results. In Table 3, the maximum absolute value of simple correlation coefficients under each illumination is shown in boldface. As a general tendency, a negative correlation is observed between perceived whiteness and the chroma values that color appearance models predict. While the chroma values of CIECAM97s and CIECAM02 show a strong negative correlation with perceived whiteness under EXD and EXN illuminations, under an illumination at a low correlated color temperature, the correlation between the chroma value and perceived whiteness is weak. The chroma values of CIECAT94LAB, CIECAM97s, CIECAM02 and NLCAM show the tendency that as the correlated color temperature of an illumination increases, the simple correlation coefficient to the values of a perceived whiteness evaluation decreases. Concerning CIELAB, NC-III C, and CIECAT94NC-III C, there is little change in the simple correlation coefficient due to the correlated color temperature of an illumination. Examining Table 3 and Figure 7, one can see that the

predicting performance of C/V index is superior to that of the chroma values of color appearance models as the predicting index of perceived whiteness under different illuminations. Chroma values of NC-III C using CIECAT94 for chromatic adaptation prediction showed the second-highest correlation with the perceived whiteness evaluation value, next to the C/V index.

4. Conclusion

The perceived whiteness evaluation index: C/V index was defined with a focus on the brightness-enhancement effect of color components that are included in approximate white objects and illuminations. A perceived-whiteness evaluation of approximate white objects under different illuminations was then conducted. The conclusions obtained are as follows:

- (1) The C/V index is effective for a perceived-whiteness evaluation of approximate white objects under different illuminations.
- (2) The perceived-whiteness predicting performance of the C/V index is superior to that of color appearance models.
- (3) The brightness-enhancement effect of color components that are included in approximate white objects and illuminations is an important determinant of perceived whiteness.

Table 3 Simple correlation coefficients between the experimental results of the perceived whiteness evaluation and chroma values calculated using color appearance models along with the C/V index results

The maximum absolute value of simple correlation coefficients under each illumination is shown in boldface.

Illuminant	Predictive Index							
	C/V index	Chroma predicted by Color Appearance Model						
		CIELAB	CIECAT94LAB	CIECAM97s	CIECAM02	NLCAM	NC-III C	CIECAT94NC-III C
EXD	0.839	-0.697	-0.571	-0.881	-0.928	-0.609	-0.673	-0.705
EXN	0.879	-0.591	-0.410	-0.793	-0.718	-0.243	-0.700	-0.705
EXWW	0.925	-0.606	-0.266	-0.493	-0.280	0.097	-0.741	-0.875
EXL	0.902	-0.596	-0.230	-0.442	-0.194	0.141	-0.745	-0.896

Figure 7 Simple correlation coefficients between the experimental results of the perceived whiteness evaluation and chroma values calculated using color appearance models along with the C/V index results

Appendix A Derivation of interval scales using a paired comparison method⁽²⁸⁾⁽²⁹⁾

Assume n stimuli and paired stimuli (j, k) of them, where $j, k=1, 2, \dots, n$. N independent comparative judgments are conducted on each pair (j, k) and p_{jk} 's, probability that j is judged higher order than k , are derived on each pair (j, k) . x_{jk} 's, probability variables, are derived from p_{jk} 's. x_{jk} 's compose an $n \times n$ matrix $\mathbf{X}$. $S_D(j)$, interval scale value, is derived from the average of column of matrix $\mathbf{X}$. In case that n is large, however, some p_{jk} 's become 1 or 0 because of clear difference between stimuli j and k . In this case, x_{jk} 's corresponding to the p_{jk} 's become indefiniteness. In consequence $\mathbf{X}$ becomes an incomplete matrix including empty elements.

Derivation method of the interval scale from the incomplete matrix of probability variables is given by H. Gulliksen²⁹⁾. Steps of the procedure are as follows.

- (1) Sum up the number of elements in column k of the incomplete matrix $\mathbf{X}$ and express the value in n_k . Note that the n_k counts out the principal diagonal element x_{jj} .
- (2) Form an $n \times n$ matrix $\mathbf{M}$ following the rules as below.
Enter n_k in the principal diagonal cell in $\mathbf{M}$. Enter -1 in $\mathbf{M}$ for each cell entry in $\mathbf{X}$ where data exist. Enter 0 in all other off-diagonal cells. Note that $\mathbf{M}$ is a symmetric matrix and that the sum of each row (and column) is zero, and hence $\mathbf{M}^{-1}$ does not exist.
- (3) Assuming that column vectors $\mathbf{Z}$ and $\mathbf{S}$ are as follows, equation (A-1) is obtained.

$$\mathbf{Z} = \begin{bmatrix} \sum_j^n x_{j1} \\ \vdots \\ \sum_j^n x_{jn} \end{bmatrix}, \mathbf{S} = \begin{bmatrix} S_D(1) \\ \vdots \\ S_D(n) \end{bmatrix}.$$

$$\mathbf{Z} = \mathbf{MS} \dots\dots\dots (A-1)$$

Equation (A-1) is not solved for column vector $\mathbf{S}$ because $\mathbf{M}$ has no inverse matrix $\mathbf{M}^{-1}$.

- (4) Form an $n-1 \times n-1$ matrix $\mathbf{M}_{11}$ eliminating the first row and column from matrix $\mathbf{M}$.
- (5) Form column vectors $\mathbf{S}_1$ and $\mathbf{Z}_1$ eliminating the first rows from column vectors $\mathbf{S}$ and $\mathbf{Z}$, respectively.
- (6) Equation (A-2) is obtained.

$$\mathbf{Z}_1 = \mathbf{M}_{11} \mathbf{S}_1 \dots\dots\dots (A-2)$$

- (7) Equation (A-2) is rewritten as follows because $\mathbf{M}_{11}$ has the inverse matrix $\mathbf{M}_{11}^{-1}$.

$$\mathbf{S}_1 = \mathbf{M}_{11}^{-1} \mathbf{Z}_1 \dots\dots\dots (A-3)$$

- (8) Column vector $\mathbf{S}_1$ is the interval scale with the starting point at $S_D(1)$.

Appendix B The calculation procedure of the CV index¹⁷⁾

The calculation procedure of the CV index is given in the following:

- (1) Using the tristimulus values X_n', Y_n', Z_n' of the perfect reflecting diffuser under an arbitrary adapting illumination, they are converted to the responses R_n', G_n', B_n' of three types of cones:

$$\begin{bmatrix} R_n' \\ G_n' \\ B_n' \end{bmatrix} = \mathbf{M} \begin{bmatrix} X_n' \\ Y_n' \\ Z_n' \end{bmatrix} = \begin{bmatrix} 0.2435 & 0.8524 & -0.0516 \\ -0.3954 & 1.1642 & 0.0837 \\ 0 & 0 & 0.6225 \end{bmatrix} \begin{bmatrix} X_n' \\ Y_n' \\ Z_n' \end{bmatrix} \dots\dots\dots (A-4)$$

- (2) The correction factor of chromatic adaptation effect $\mathbf{d}$ is obtained by the von Kries' law from (A-5):

$$\mathbf{d} = \begin{bmatrix} 107.60 / R_n' & 0 & 0 \\ 0 & 80.11 / G_n' & 0 \\ 0 & 0 & 55.38 / B_n' \end{bmatrix} \dots\dots\dots (A-5)$$

- (3) We obtain the luminance response $A'(\lambda)$, and the color responses $T'(\lambda)$ and $D'(\lambda)$ after a chromatic adaptation from the CIE1931 color matching functions $x(\lambda)$, $y(\lambda)$, $z(\lambda)$.

$$\begin{bmatrix} A'(\lambda) \\ T'(\lambda) \\ D'(\lambda) \end{bmatrix} = \mathbf{m} \mathbf{H} \mathbf{d} \mathbf{M} \begin{bmatrix} x(\lambda) \\ y(\lambda) \\ z(\lambda) \end{bmatrix} = \begin{bmatrix} 0.4 & 0 & 0 \\ 0 & 1.0 & 0 \\ 0 & 0 & 4.0 \end{bmatrix} \begin{bmatrix} 0.5967 & 0.3654 & 0 \\ 0.9553 & -1.2836 & 0 \\ -0.0248 & 0 & 0.0483 \end{bmatrix} \mathbf{d} \mathbf{M} \begin{bmatrix} x(\lambda) \\ y(\lambda) \\ z(\lambda) \end{bmatrix} \dots\dots\dots (A-6)$$

- (4) The wavelength function $C'(\lambda)$ of vector luminance is obtained after a chromatic adaptation from Equation (A-7):

$$C'(\lambda) = \{A'(\lambda)^2 + T'(\lambda)^2 + D'(\lambda)^2\}^{1/2} \dots\dots\dots (A-7)$$

- (5) The adjustment factor b is obtained from Equation (A-8):

$$b = \frac{\int_{380}^{780} C(\lambda) d\lambda}{\int_{380}^{780} C'(\lambda) d\lambda} \dots\dots\dots (A-8)$$

where $C(\lambda)$ is the wavelength function of vector luminance under an illumination that can give an achromatic point in the ATD color space. When chromatically adapting illuminant is the standard illuminant D_{65} , $b = 1.072$, and when the standard illuminant A, $b = 0.803$.

(6) The CV index is obtained from Equation (A-9):

$$C/Vindex = \frac{\int_{380}^{780} P(\lambda)R(\lambda)C'(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)V(\lambda)d\lambda} \times b \times a' \dots (A-9)$$

where $P(\lambda)$ is the spectral distribution of the adapting illumination, $R(\lambda)$ is the spectral reflectance distribution of whitish object, $V(\lambda)$ is the CIE standard spectral luminous efficiency, and a is the coefficient ($a' = 133.044$) to adjust the CV index to 100 when $R(\lambda) = 1.0$ under the standard illuminant D_{65} .

Appendix C The relationship between chromatic strength and perceived whiteness¹⁸⁾

Chromatic strength has two aspects; one is the capability to cancel achromatic components or to induce chromatic perception, and the other is a brightness-enhancement effect capability. Here, those two aspects and their relationship with perceived whiteness are outlined.

Since one important psychological determinant for perceived whiteness is to perceive as bright and not to perceive any color, the perceived whiteness W_p can be defined by Equation (A-10):

$$W_p = f(AC, B, L) \dots \dots \dots (A-10)$$

where AC is the achromatic perception, B is the brightness-enhancement effect, and L is lightness.

Now, if chromatic perception is C , a decrease in achromatic perception means an increase in color, and the relationship between achromatic perception AC and chromatic perception C can be expressed as Equation (A-11):

$$AC + C = \alpha \dots \dots \dots (A-11)$$

where α is a constant value. To simplify, if $\alpha = 0$, $AC = -C$, Equation (A-11) can be expressed as Equation (A-12):

$$W_p = f(-C, B, L) \dots \dots \dots (A-12)$$

In Equation (A-12), B and C can both be attributed to the visual chromatic channel response; they increase as the increase in luminous stimuli rise. With chromatic strength as the common factor for the brightness-enhancement effect and chromatic perception, B and C are defined by Equations (A-13) and (A-14):

$$B = kr(x - x_{0b}) + a \dots \dots \dots (A-13)$$

$$C = l\{r(x - x_{0c})\}^r + b \dots \dots \dots (A-14)$$

where x is the log luminance, x_{0b} and x_{0c} are the

Figure A-1 Characteristics of brightness-enhancement effect B and chromatic perception C near their thresholds

thresholds for B and C respectively, and a, b, k, l are constants. r is the log value for chromatic strength and can be defined by Equation (A-15):

$$r = \log S(\lambda) + 1 \dots \dots \dots (A-15)$$

where $S(\lambda)$ is the chromatic strength value at the wavelength λ .

Figure A-1 shows the characteristics of B and C near their thresholds. Here, they show $r = 1.1$ and $r = 3$ as when chromatic strength is small and large, respectively. To simplify, $k = l = 1$, and $a = b = 0$. In Figure A-1, $r = 1$ corresponds to achromatic components.

When the reflectance of a wavelength with great chromatic strength is relatively large in the spectral reflectance distribution of whitish object, or when relatively many wavelength components with great chromatic strength are included in the spectral composition of an illumination, the brightness-enhancement effect B becomes superior to chromatic perception C (both arrows in Figure A-1), thus enhancing perceived whiteness. In contrast, in the case of wavelength components with small chromatic strength, there is no stimulus region where the brightness-enhancement effect B can be superior to chromatic perception C , and thus, perceived whiteness is believed to decline as chromatic perception increases. However, as Figure A-1 clearly shows, even in the case of wavelength components with great chromatic strength, if they are excessively included in the spectral distribution of an illumination or the spectral reflectance distribution, it will not be perceived, even as white, as chromatic perception C increases.

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