研 究

B/L Ratios of Surface Colors at Various Illuminance Levels

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To investigate the changes of senses and their meanings, 39 test color chips were used as stimuli to measure the *B/L* values and colorfulness in the range of illuminance levels from 0.01 lx to 3,000 lx. The *B/L* value was measured by matching the test stimulus to the corresponding gray scale in brightness and the chromatic components were measured with its absolute evaluation. As a result, rods and cones responded to mesopic levels having illuminance levels of less than about 3 lx, but only cones responded to photopic levels. The *B/L* value components of larger than 1.0 at illuminance levels higher than 3 lx are caused by the contribution of chromatic responses to the brightness, and had a strong correlation with the colorfulness. In the CIE 1931 (x, y) chromaticity diagram, equal *B/L* values extend to the yellow-blue region. When the illuminance level decreases, the red-green region extends over a greater area in comparison with that of the yellow-blue region. In particular, the illuminance levels of red-type stimuli with high chroma vary greatly.

1. Introduction

The variation of brightness from the photopic to scotopic levels occurs due to the change from cone to rod vision. Various authors have already investigated the brightness perception of spectral lights from the photopic to scotopic levels.[1-5] The method used in the measurement was direct brightness matching between white reference light and spectral lights. Also, it has been found that the measurement value of the brightness of colored lights at the photopic level does not match their luminance.[6-8] These data were used to derive luminous efficiency functions $V_b(\lambda)$ at the photopic level.

Also, in the experiment using object colors, equivalent lightness from the photopic to scotopic levels is obtained by matching the brightness to the gray scale using colored cloth or color chips.[9-11] However, the data on the change in the brightness(B)/luminance(L) of surface colors from the photopic to scotopic levels were insufficiently studied. This article covers the investigation of the *B/L* ratio, varying the hue, value, and chroma of stimuli at various illuminance levels including scotopic, mesopic, and photopic levels.

2. Apparatus

To investigate the change of the stimulus brightness due to different hues, values and chromas, 39 test color chips having different hues and chromas, that is, the Munsell color notation system, 5 R, 5 Y, 5 G, 10 B, and 5 P, were used. **Table 1** shows the photometric characteristics of the data. **Figure 1** shows the CIE 1931 (x, y) chromaticity coodinates of color chips. The stimulus size is fixed over a foveal 10° field with Munsell value N 6 background mask.

The apparatus used consisted of a darkroom (2.6 (H)×2.5(W)×5(D)m) with a board (2.3(H)×2.3(W)m) painted in Munsell value N 6 for non gloss placed on one of its walls. The Munsell value N 6 mask was placed on the board to display a test color chip and a gray scale. Then, the light source was placed to illuminate the wall.

A fluorescent lamp EDL-50 K was used as a sample light source to ensure uniform brightness. This light has a correlated color temperature of 5,000 K, a color rendering index Ra at 99, and R_9–R_{15} are all over 95. The illuminance on the color chip was controlled by placing a screen

Table 1 Colorimetric specifications for the 39 test color chips and a N 6/background chip in experiment. Colorimetric values x, y, Y of test color chips, when illuminated by fluorescent lamp indicated.

Color chip no.	Munsell notation	CIE specification		
		x	y	Y
1	5R 2/ 4	0.471	0.339	3.24
2	5R 4/ 4	0.431	0.355	12.40
3	5R 6/ 4	0.409	0.358	30.50
4	5R 8/ 4	0.393	0.357	59.57
5	5R 4/ 2	0.388	0.354	12.52
6	5R 4 /8	0.505	0.347	12.76
7	5R 4/12	0.562	0.334	12.96
8	5R 4/14	0.602	0.330	13.81
9	5Y 4/ 4	0.444	0.429	11.99
10	5Y 6/ 4	0.420	0.415	29.61
11	5Y 8/ 4	0.403	0.405	57.10
12	5Y 9/ 4	0.401	0.403	76.31
13	5Y 8/ 2	0.380	0.384	56.84
14	5Y 8/ 8	0.452	0.443	55.92
15	5Y 8/12	0.490	0.465	57.12
16	5Y 8/14	0.504	0.472	56.78
17	5G 2/ 4	0.289	0.432	2.59
18	5G 4/ 4	0.308	0.409	10.72
19	5G 6/ 4	0.321	0.398	28.09
20	5G 8/ 4	0.329	0.389	56.82
21	5G 5/ 2	0.336	0.378	19.28
22	5G 5/ 4	0.316	0.400	18.87
23	5G 5/ 8	0.281	0.445	18.50
24	5G 5/10	0.257	0.473	17.75
25	10B 2/ 4	0.230	0.282	3.31
26	10B 4/ 4	0.274	0.314	12.01
27	10B 6/ 4	0.297	0.330	29.78
28	10B 8/ 4	0.308	0.336	57.80
29	10B 5/ 2	0.319	0.340	19.61
30	10B 5/ 4	0.287	0.322	19.25
31	10B 5/ 8	0.228	0.287	19.04
32	10B 5/10	0.203	0.269	19.47
33	5P 2/ 4	0.326	0.275	3.45
34	5P 4/ 4	0.338	0.305	12.16
35	5P 6/ 4	0.341	0.322	30.22
36	5P 8/ 4	0.344	0.331	59.29
37	5P 4/ 2	0.342	0.327	12.02
38	5P 4/ 8	0.328	0.269	12.33
39	5P 4/10	0.319	0.246	12.57
Background	N6/	0.343	0.352	29.82

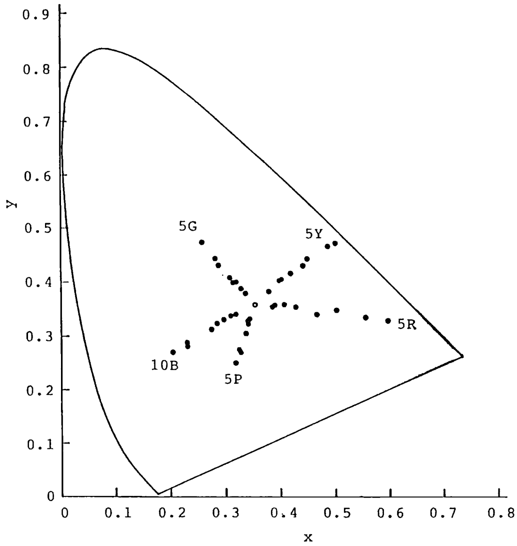

Fig. 1 CIE 1931 (x, y) chromaticity diagram showing location of chromaticity points of 39 test color chips and a N 6/background in experiment.

in front of the light source, changing the number of light sources.

Twelve different illuminance levels were used: 0.01, 0.03, 0.1, 0.3, 1, 3, 10, 30, 100, 300, 1000, and 3000 lx.

3. Procedure

At first, the subjects were allowed 20 min for dark adaptation before the experiment was started. After this 20-min period, they were exposed for 3 min to a 0.01 lx illuminated surface which was the same as the background N 6 non colored sample light source. Next, the subjects with no fixation point of either eye carried out direct brightness matching of the color chips on a 0.25 step gray scale. When the subjects felt brightness existing between the step, the gray value was then estimated by interpolation. Then, the color appearance was estimated with the chromatic to achromatic component ratio. At that time, the observation time was not specifically limited. Under the same illuminance, different colored chips were observed. Next, the illuminance was changed gradually from low to high illuminance.

These experiments were repeated five times after the preliminary experiment.

The luminance (L) of the color chips and of the gray scale was calculated by $L=\rho E/\pi$ (cd/m^2), ρ being the reflectance and assumed to have a value of Y/100. E is the illuminance in lx.

The subjects were 5 males with normal color vision. Their color vision was tested with Ishihara plates.

4. Results

From the results of these experiments, the average *B/L* ratio of five subjects for illuminance levels are shown in **Fig. 2.** The figures on the left show the relationship between the illuminance levels and *B/L* ratio according to different hues when the value of stimuli are varied. The figures on the right show the relationship between illuminance levels and *B/L* ratio when the chroma of stimuli are varied.

The characteristics under the conditions with a constant chroma of 4 show that the difference in the *B/L* value due to illuminance levels was small. Also, when the stimulus value on each hue is the same and the chroma is different, there is a strong influence of illuminance levels on *B/L* values.

When a stimulus 5 R hue was used with decreasing illuminance, the *B/L* value of low chroma stimulus increased beyond the high chroma stimulus value. When illuminance levels increased to about 3 lx, even when the chroma was different, the result showed the same *B/L* ratio. Also, when the illuminance level increased beyond 3 lx, as the illuminance levels increased, the stimulus of the high chroma showed a corresponding high *B/L* value. When illuminance levels were increased to more than 3 lx, with any stimulus, the *B/L* values became larger than 1.0, and it became obvious that the effect of colorfulness was added and the brightness and illuminance no longer matched. In the case of maximum chroma, 5 R 4/14 stimulus, with an illuminance of 0.01 lx, the *B/L* value was 0.38. When the illuminance was 3,000 lx, the *B/L* value was 1.74, and there was a large difference of 1.36 between these 2 *B/L* values. In particular, in the case of the red group stimulus, the amount of chroma strongly influenced the brightness of different illuminance levels.

When a 5 Y hue stimulus at a decreasing illuminance was used, the stimulus of higher chroma showed a lower *B/L* value, and as the illuminance levels increased, the smaller the differences between the stimulus became. Also, at the maximum illuminance, 3,000 lx, regardless of the chroma of the stimulus, the *B/L* value became about 1.0. In the case of the yellow color stimulus with an increasing illuminance level, the colorfulness did not affect the brightness.

When a stimulus of 5 G hue was used, compared to the other stimuli, the change in the *B/L* value due to illuminance levels was the smallest. It was found that in the case of the 5 G stimulus, the influence of the illuminance level was small even when the Munsell value or chroma were different.

When a stimulus of 10 B hue was used, beyond the 3 lx illuminance level, as the illuminance level was increased, the stimulus of the high chroma showed a greater *B/L* value. When the illuminance was lower than 3 lx, as the illuminance level was decreased, the activity of the rods increased accordingly, the sensitivity of brightness increased, and the *B/L* value gradually increased. Therefore, compared to the other hue stimuli, the rod activity was greatest with the 10 B stimulus.

When a 5 P hue stimulus was used, the characteristics of both red and blue hues were shown. Then, when the illuminance level increased, the stimulus of the high chroma showed a higher *B/L* value. When the illuminance level decreased to below 3 lx, the *B/L* value decreased very little due to the rod activity.

The above results indicate that when the illuminance level increases, stimulus of red, green, blue, and purple, which includes red and blue elements, gives a brighter effect, and the *B/L* value becomes greater than 1.0. This is the Helmholtz-Kohlraush effect[7,8] and is thought to contribute to the brightness of the chromatic channels.[6] When yellow-type stimuli were used, the colorfulness did not affect the brightness.

5. Discussion

The *B/L* value had the characteristic that the stimuli with higher chroma were influenced more by the illuminance level, independent of the hue. For any stimulus other than that with the hue of 5 Y, the *B/L* value became larger than 1.0 as the illuminance level increased. The area with the *B/L* value of 1.0 is perceived to be brighter than the luminance of the stimulus. This may be caused by the chromaticity effect through a colored stimulus, which contributes to brightness with visual responses on chromatic channels. The increase in the illuminance level may cause the responses to increase. Therefore, if no color effect is assumed, both colored and non colored stimuli have the same brightness. In this case, the *B/L* value should be maintained at 1.0 if the illuminance level increases. However, for a stimulus of 5 R hue, the *B/L* value was larger than 1.0 at the illuminance levels

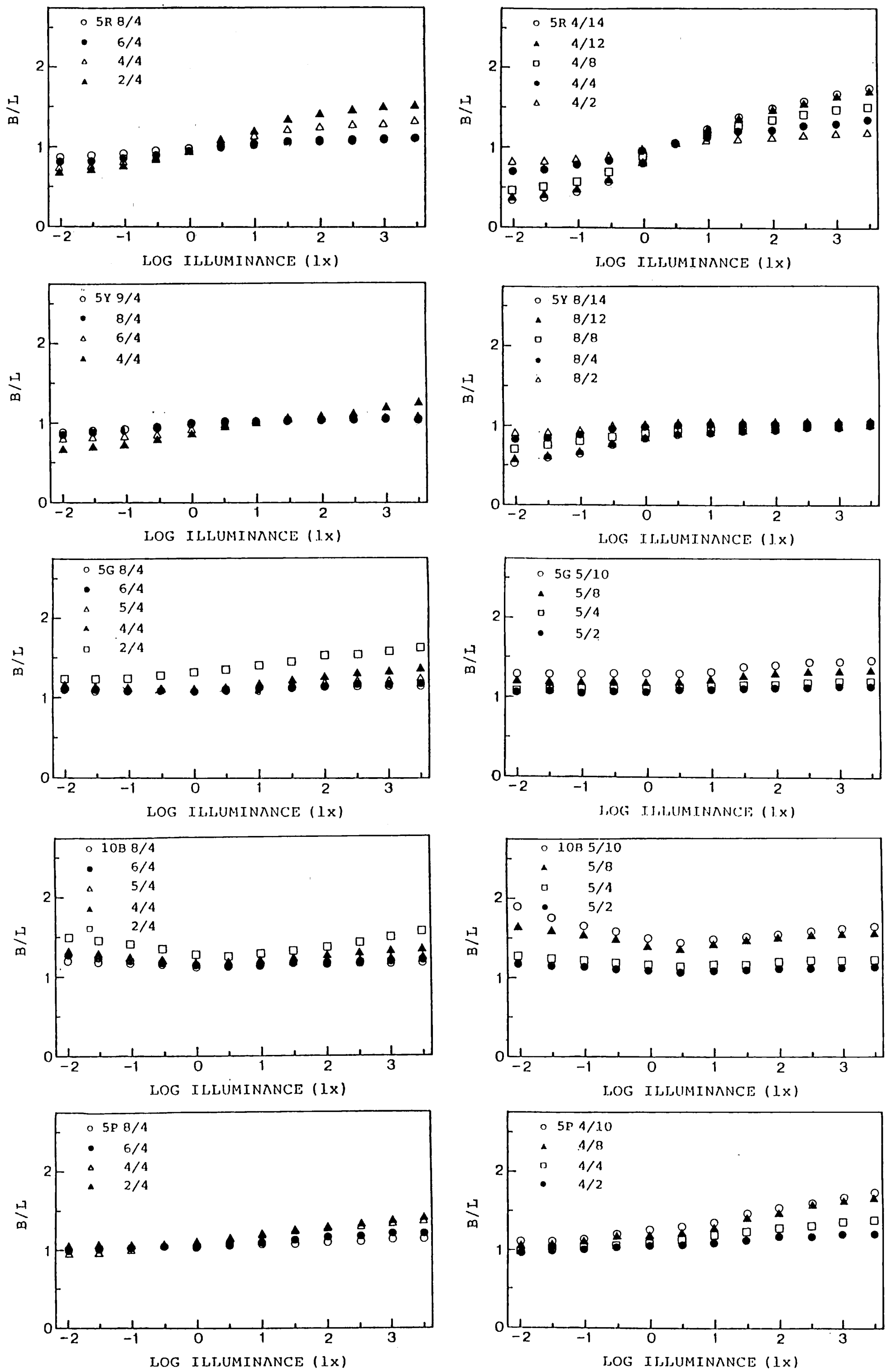

Fig. 2 Average B/L ratio of five subjects for log illuminance level. Each symbol represents the experimental results.

of higher than about 3 lx, and as the illuminance level became higher, the B/L value increased. For a stimulus of 10 B hue, the minimum B/L value appeared at the illuminance level of almost 3 lx and, as the illuminance level became higher than 3 lx, the B/L value increased. In the same manner as the stimulus of 5 R hue, a stimulus with a higher chroma had a more remarkable effect. The B/L value increased as the illuminance level became lower than 3 lx. In particular, for a stimulus of 10 B 5/10, the B/L value was as large as 1.90 at the illuminance level of 0.01 lx. This may occur because the response of the rod started when the illuminance level decreased to about 3 lx and, as the illuminance level decreased further, the response of the rod became stronger to increase the B/L value. Thus, in the illuminance level of higher than about 3 lx, the responses of visual chromatic channels may contribute to the brightness with the Helmholtz-Kohlrausch effect wherein only cones form the responding photopic levels and the color appearance has an effect on the brightness in the region where the B/L value is larger than 1.0.[6-8]

To investigate the relationship between the colorfulness of a stimulus and the brightness, the changes of chromatic components of each stimulus depending on the illuminance level are shown in **Fig. 3**. The figure shows different ehromas under a constant value of each hue. This indicates that a stimulus of higher chroma increases the chromatic components as the illuminance level increases. Next, we found the correlation between the chromatic component in the photopic levels with the illuminance level of higher than 3 lx and the B/L values of larger than 1.0 corresponding to the contribution of chromatic responses to the brightness. As shown in **Table 2**, they resulted in an extremely good correlation. However, the result for 5 Y hue was omitted because the B/L value was never larger than 1.0. Therefore, the portion having B/L values of larger than 1.0 in the illuminance level of larger than about 3 lx was caused by the contribution of the chromaticity intensity of the stimulus in the photopic levels. It was proven that a stimulus of higher chroma had a larger effect.

Next, equal B/L values were found to depend on B/L values obtained by experiments. Then the trace was drawn on a chromaticity diagram which enabled any traces to be shown easily in two-dimensional forms. **Figure 4** shows equal B/L contours on the CIE 1931 (x, y) chromaticity diagram. The coodinates of equal B/L values were obtained by using experimental values of B/L data and line-

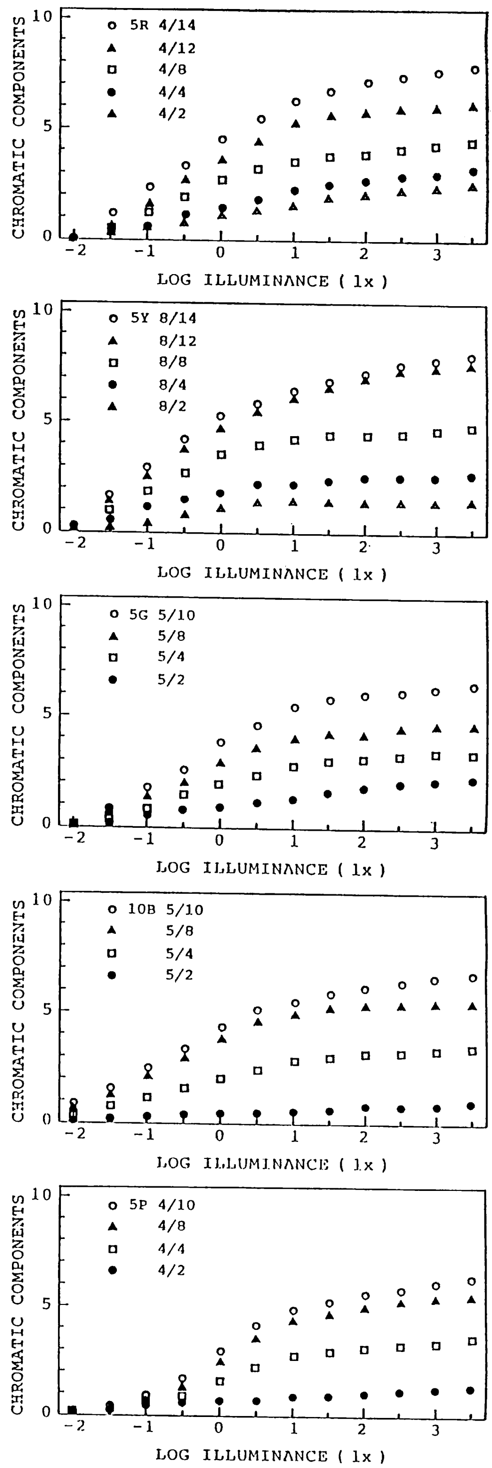

Fig. 3 Average chromatic components of five subjects for log illuminance level. Each symbol represents the experimental results.

Table 2 The correlation of chromatic components with contribution of chromatic channels to the brightness under the illuminance levels of 3 to 3,000 lx. Contribution of chromatic channels to the brightness = B/L value -1.0.

Color chip	Correlation coefficient
5R 4/ 2	0.986
5R 4/ 4	0.970
5R 4/ 8	0.983
5R 4/12	0.967
5R 4/14	0.986
5G 5/ 2	0.952
5G 5/ 4	0.912
5G 5/ 8	0.949
5G 5/10	0.953
10B 5/ 2	0.955
10B 5/ 4	0.942
10B 5/ 8	0.984
10B 5/10	0.986
5P 4/ 2	0.951
5P 4/ 4	0.945
5P 4/ 8	0.945
5P 4/10	0.958

arly interpolating the distances on the chromaticity diagram for each hue. The data of value 4 were used for 5 R and 5 P stimuli and the data of values 4 and 5 were used for 5 G and 10 B stimuli because the difference between measured values 4 and 5 was as small as less than 5%. Then equal B/L contours were drawn by connecting the coordinates corresponding to B/L values of 1.2, 1.5, and 1.7 with lines. However, for the 5 Y stimulus, the B/L values were too small to obtain the coordinates corresponding to B/L values of 1.2, 1.5, and 1.7, which made it impossible to draw the equal B/L contour. At the illuminance level of 10 lx, the contribution of colorfulness to brightness perception was small to decrease the experimental B/L values, and thus the coordinate corresponding to the B/L value of 1.7 could not be obtained. The result showed that the equal B/L contours extended to the yellow-blue region. As the illuminance level decreased, the red-green region extended further in comparison with the yellow-blue region. In particular, the chromaticity diagram also showed that the tendency was more remarkable in the red region, and the illuminance level had a large effect on the brightness perception for red-type colors. These shapes were relatively similar to those measured by Sandars and Wyszecki[12] using color chips for stimuli at the illuminance level of 650 lx, Ikeda, Huang and Ashizawa[11] in the illuminance levels from 0.01 lx to 1,000 lx, and Okajima *et al.*,[13] at the illuminance level of 1,200 lx, where the fine shapes and sizes were considerably different depending on the experiments. This may be caused by differences of experimental conditions including different backgrounds and light sources and individuals. There are only a few B/L values measured by using color chips for stimuli, and it is difficult to obtain definite results from such inadequate data. Thus to develop standard data, it may be necessary to investigate the differences of experimental conditions and individuals. It was found that the shapes of equal B/L values were relatively similar to those of Uchikawa, Uchikawa and Kaiser,[14] and Ayama, Huang and Ikeda[15] who measured B/L values on chromaticity diagrams with colored light. They have the similar tendency as the results ob-

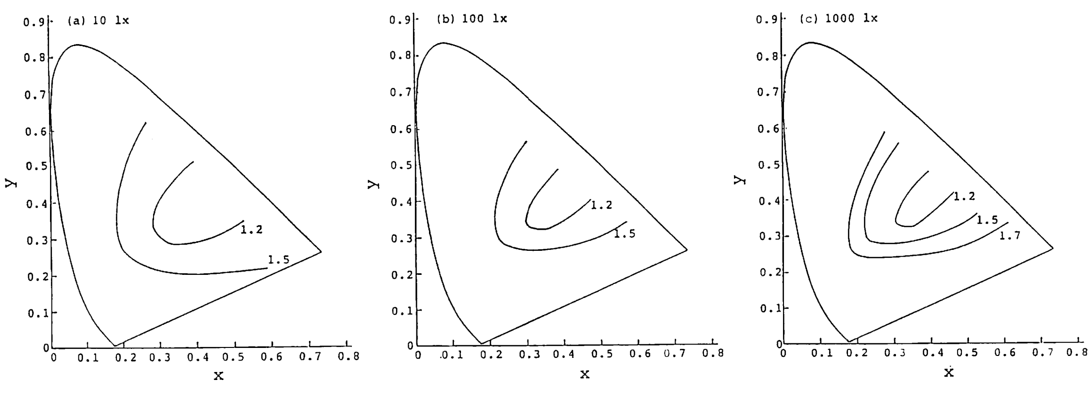

Fig. 4 Equal B/L ratio contours on the CIE 1931 x, y chromaticity diagram. The illuminance levels are (a) 10 lx, (b) 100 lx and (c) 1,000 lx. The figures indicated on the contours are B/L values.

tained by Okajima *et al.*[13] who measured B/L values depending on different modes of the light source and surface colors. While different modes cause the sizes of B/L values to differ, the shapes of the equal B/L value may indicate the same tendency on the chromaticity diagram.

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