Correlate for Lightness in Terms of CIE Chromaticity Coordinates and Luminous Reflectance*

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This is a report on a side-line experiment of the OSA Committee on Uniform Color Scales. It gives new data on L/Y ratios in terms of CIE chromaticity coordinates, based on observations made by seventy-six observers on forty-three colored ceramic tiles. The mean results are given in tabular and graphical form and compared with similar results obtained previously by other investigators.

INDEX HEADINGS: Color; Colorimetry; Color vision.

SEVERAL investigations have shown that luminance does not correlate well with the perception of brightness in heterochromatic comparisons.[1–6] Similarly, it has been found that the luminous reflectance of colored objects does not correlate well with the lightness perceived.[7–9] In general, the various experimental results have shown that saturated colors require less luminance (or a lower luminous reflectance) than less saturated colors in order to appear equally bright (or light). An exception to this general rule has often been found for colors in the yellow region. Here luminance (or luminous reflectance) correlates fairly well with brightness (or lightness).

Brightness (or lightness) index B (or L) may be specified by the CIE luminance (or luminous reflectance) of the equally bright (or light) gray. Constant ratios of B/Y (or L/Y), where Y is the luminance (or reflectance) of the tested color, form smooth loci on the CIE chromaticity diagram which illustrate the strong dependence of brightness (or lightness) on chromaticity. These loci may also be used to construct surfaces of constant brightness (or lightness) in the CIE (x,y,Y)-space (see, for example, Ref. 7).

The purpose of the present note is to report another investigation which provides new L/Y ratios in terms of CIE chromaticity coordinates. This investigation was carried out by the Committee on Uniform Color Scales of the Optical Society of America under the chairmanship of D. B. Judd.[10] It constitutes a side-line experiment which the members of the Committee consider relevant to their over-all problem of arriving at a color space represented by several hundreds of painted color chips that sample the paint gamut as uniformly as possible by the regular rhombohedral lattice-sampling method.[11]

The Committee used a set of 43 hexagonal ceramic tiles of approximately 5 cm inside diameter, colored by C. E. Foss with matte-finish paints formulated by H. R. Davidson. The color of each tile (U-tile, 1 to 43) was determined by spectrophotometry and computation with respect to CIE standard illuminant C and the 1931 CIE standard observer. The color coordinates (x,y,Y) thus determined are given in Table I. Figure 1 shows the corresponding 43 chromaticity points (x,y) plotted in the 1931 CIE chromaticity diagram.

Also used in the experiment was a set of 10 achromatic tiles of the same size and shape as the 43 chromatic tiles. The achromatic tiles (N-tiles, 1 to 10) represented a neutral scale with nominal Munsell values 5.6/ to 7.4/ in steps of 0.2. The chromaticity coordinates of these tiles were approximately the same; the average was $x_N=0.3153$, $Y_N=0.3218$; individual tiles did not deviate from this average by more than $\Delta x=\pm 0.0004$, $\Delta y=\pm 0.0008$. The luminous reflectances of the N-tiles varied approximately in accordance with their nominal Munsell values; their actual values are given in Table II.

The observations were made by 76 observers who had normal color vision, located in different laboratories in the United States and Canada. Thirty-nine of the 76 observers used the following 23 U-tiles: 2, 3, 5, 8, 9, 10, 12, 14, 15, 18, 20, 22, 24, 25, 27, 29, 31, 34, 35, 37, 39, 41, 43; the other 37 observers used the remaining 20 U-tiles plus U-tiles numbers 5, 9, and 43, which were included in both groups. All viewing was done with

* This paper has been prepared on behalf of the members of the Committee on Uniform Color Scales of the Optical Society of America.

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3 R. E. Harrington, J. Opt. Soc. Am. 44, 113 (1954).
4 A. Chapanis and R. M. Halsey, J. Opt. Soc. Am. 45, 1 (1955).
5 E. J. Breneman, J. Opt. Soc. Am. 48, 228 (1958).
6 C. L. Sanders and G. Wyszecki, Commission Internationale de l'Eclairage, Proc. 15th Session, Vienna, 1963; Vol. B, p. 221; Bureau Central de la CIE, 57, rue Cuvier, Paris 5; CIE Publ. No. 11 (1964).
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8 G. Wyszecki and C. L. Sanders, J. Opt. Soc. Am. 47, 840 (1957).
9 C. L. Sanders and G. Wyszecki, J. Opt. Soc. Am. 48, 389 (1958).

10 The names of the present members of the OSA Committee on Uniform Color Scales are listed in J. Opt. Soc. Am. 56, 1273 (1966).
11 Some aspects of the work of the OSA Committee on Uniform Color Scales have been reported on in the following publications: G. Wyszecki, J. Opt. Soc. Am. 44, 725 (1954); D. B. Judd, J. Opt. Soc. Am. 45, 673 (1955); D. L. MacAdam, J. Opt. Soc. Am. 53, 754 (1963); D. B. Judd, Proc. Int. Farbtagung Lucern 1965, (Verlag Musterschmidt; Göttingen, 1966), p. 287.

an illuminance of at least 500 lx of daylight (natural or artificial, resembling CIE source C), falling uniformly on a table covered with a matte gray sheet with a luminous reflectance corresponding closely to Munsell value 6/. The viewing angle was between 20 and 45 degrees from the vertical.

TABLE I. 1931 CIE chromaticity coordinates (x,y) and luminous reflectances (Y) of chromatic samples (U-tiles), luminous reflectances (Y_N) of corresponding achromatic samples (N-tiles) observed to have the same lightness as the U-tiles, and ratios L/Y.

U-Tile No.	Chromaticity coordinates x	y	Luminous reflectance U-Tile Y	N-Tile Y_N	Ratio L/Y $(L=Y_N)$
1	0.2955	0.5321	30.99	42.20	1.36
2	0.2816	0.4652	30.24	37.92	1.25
3	0.3341	0.4813	30.08	36.20	1.20
4	0.3777	0.4976	29.08	36.46	1.25
5	0.2520	0.4038	29.22	37.38	1.28
6	0.2922	0.4238	28.25	35.04	1.24
7	0.3439	0.4416	28.14	33.16	1.18
8	0.3838	0.4466	26.20	30.87	1.18
9	0.4379	0.4599	28.53	33.29	1.17
10	0.2299	0.3383	28.59	36.20	1.27
11	0.2661	0.3603	28.16	35.04	1.24
12	0.3075	0.3801	28.00	33.41	1.19
13	0.3544	0.3982	29.59	33.66	1.14
14	0.3959	0.4100	28.75	31.83	1.11
15	0.4415	0.4193	28.91	32.92	1.14
16	0.4764	0.4238	28.54	35.81	1.26
17	0.2258	0.2926	28.71	38.18	1.33
18	0.2474	0.3082	28.58	35.81	1.25
19	0.2804	0.3248	28.35	33.29	1.17
20	0.3196	0.3448	29.26	30.99	1.06
21	0.3581	0.3599	29.58	33.29	1.13
22	0.4026	0.3765	29.42	33.29	1.13
23	0.4426	0.3827	29.74	35.94	1.21
24	0.4888	0.3934	28.12	35.68	1.27
25	0.2342	0.2595	28.28	36.59	1.29
26	0.2632	0.2796	29.21	37.52	1.28
27	0.2978	0.3023	30.24	31.71	1.05
28	0.3310	0.3211	28.42	30.64	1.08
29	0.3713	0.3355	29.68	33.66	1.13
30	0.4068	0.3488	29.68	35.68	1.20
31	0.4580	0.3571	29.19	36.46	1.25
32	0.4864	0.3602	30.09	41.07	1.36
33	0.2512	0.2400	29.66	39.13	1.32
34	0.2790	0.2626	30.25	35.68	1.18
35	0.3058	0.2796	29.09	34.41	1.18
36	0.3398	0.2994	29.54	34.16	1.16
37	0.3785	0.3157	28.86	34.66	1.20
38	0.4208	0.3240	29.60	37.78	1.28
39	0.4580	0.3288	29.40	37.92	1.29
40	0.2960	0.2432	29.50	39.00	1.32
41	0.3258	0.2576	28.74	36.07	1.26
42	0.3642	0.2708	28.84	38.05	1.32
43	0.3919	0.2790	28.34	37.92	1.34

The observational procedure, details of which had been worked out by Howett, was the same for each group of observers and is illustrated in Fig. 2. The 10 N-tiles were laid out in front of the observer. The N-tiles were arranged in such a way that a chromatic tile (U-tile) could be brought conveniently near each

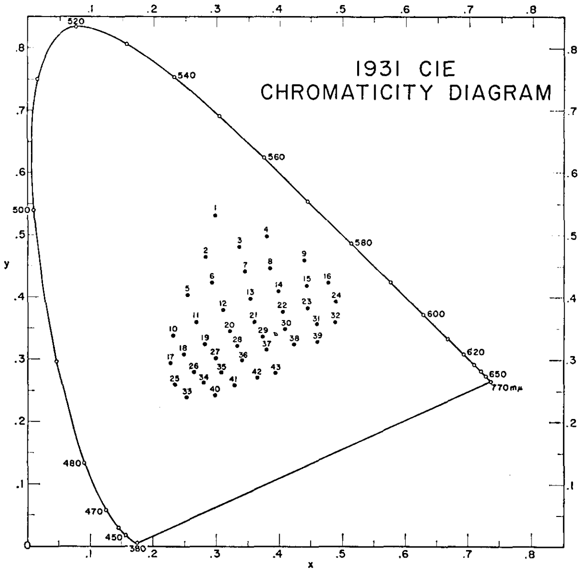

FIG. 1. 1931 CIE chromaticity diagram showing location of chromaticity points of 43 U-tiles.

N-tile in an edge-alongside-edge position. The arrowed path shown in Fig. 2 indicates the movement of the chromatic tile in going from the darker grays toward the lighter grays. Each observer was told to find the N-tile in the series of grays that had a lightness as close as possible to the lightness of the U-tile given to him. Two samples are defined as having the same lightness if they appear to be reflecting the same total amount of light regardless of the chromaticness of the light. In the case where the observer judged the U-tile to have a lightness not matched by any one of the 10 N-tiles, he was allowed to interpolate between neighboring N-tiles or to extrapolate beyond the two ends of the scale. His judgment was recorded in terms of the nominal Munsell values (possibly interpolated or extrapolated) used in the identification of the N-tiles.

The judgments made by different observers for the same U-tile were averaged and converted into luminous

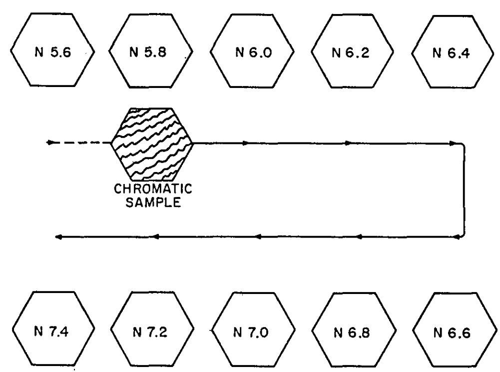

FIG. 2. Schematic diagram showing arrangement of 10 achromatic samples (N-tiles) and a chromatic sample (U-tile) for making lightness-equality judgments.

reflectances Y_N, by use of the actual calibration data of the N-tiles (Table II). The results are recorded in Table I. The given Y_N value is the luminous reflectance of an achromatic sample which is judged to have the same lightness as the corresponding chromatic sample of luminous reflectance Y. The Y_N value may be called the lightness index L of the chromatic sample as has been suggested in the literature.[7–9]

Ratios of L/Y are informative because they readily show the magnitude of the discrepancy between the luminous reflectance (Y) and the lightness index (L) of a chromatic sample (Table I). All 43 ratios are greater than unity, which means that all chromatic samples observed appear lighter than achromatic samples of the same luminous reflectance. The ratios vary from values close to unity (for example, U-tile No. 27) to a value as high as 1.36 (for example, U-tile No. 32).

Systematic trends of the ratios with chromaticity of the chromatic samples can be illustrated by drawing smooth loci of constant L/Y ratios in the CIE chromaticity diagram (Fig. 3). The discrepancies between the observed ratios and the ratios which are indicated by the smooth family of loci are shown at the chromaticity points (open circles) at which observations were made. For example, for sample No. 42, the observed ratio is 1.32 (see Table I), while the smooth loci drawn in Fig. 3 suggest a ratio of 1.30 for that chromaticity point. The discrepancy of -2 is written at that point, which is obtained by taking 100 times the difference between 'smoothed ratio' and 'observed ratio', that is 100 (1.30–1.32). The discrepancies found at the other points of observation are given in the same way. They vary from -5 to $+5$ but do not show a systematic trend across the chromaticity gamut. Although no special effort has been made to assess the significance of these discrepancies, we concluded that they are small compared with the uncertainties expected to be inherent in the observations and calibration of the experimental materials.

The loci of constant L/Y ratios as seen in Fig. 3 resemble stretched ovoids, or portions of ovoids, with a common major axis in the blue–yellow direction going through the achromatic point ($x_N=0.3153$, $y_N=0.3218$) representing the achromatic samples (N-tiles) for which $L/Y=1.0$. In moving away from the achromatic point (N) the ratios increase rapidly toward the red, purple, blue and green, but less rapidly toward the yellow.

Figure 3 may be used in the production of chromatic samples of constant lightness index. For example, if we wanted to repaint the chromatic tiles U-1 to U-43 retaining their present chromaticities but changing their luminous reflectances so as to make them appear equally light, the following procedure could be followed:

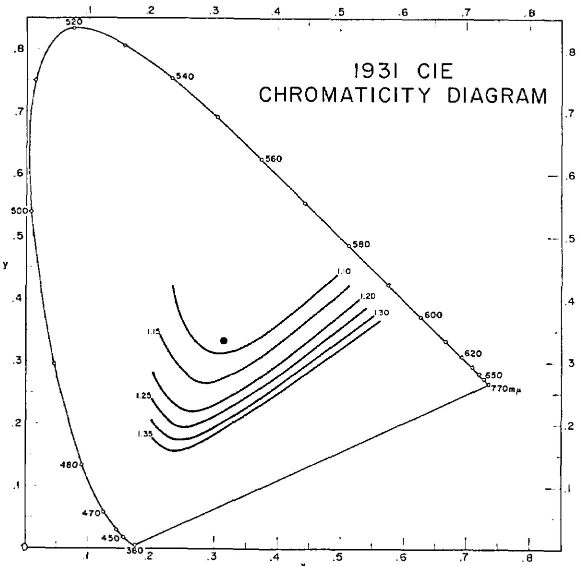

FIG. 3. 1931 CIE chromaticity diagram showing smooth loci of constant L/Y ratios derived from observations made with chromatic samples whose chromaticities are represented by open circles in the diagram. The number given beside each open circle is 100 times the difference between the 'smoothed ratio' and the 'observed ratio' for that chromaticity. The solid dot represents the chromaticity point for the achromatic samples used in the study.

Y_N may be set equal to 30.05, which corresponds to Munsell value 6. Then the chromaticity point of each chromatic sample is entered into Fig. 3 and the (smoothed) L/Y ratio is read off for each point. The inverse ratio (Y/L) found for each point is multiplied by 30.05 to give the luminous reflectance of the chromatic sample required for equality in lightness. In the case of U-42 this calls for a luminous reflectance of $30.05/1.30=23.12$. The luminous reflectance adjusted in this way for each chromatic sample would make each sample appear just as light as an achromatic sample of luminous reflectance $Y_N=30.05$. Each possible pair of chromatic samples would also appear equally light, as the transitivity law seems to hold.[8] Sets of chromatic samples at lightness levels different from $Y_N=30.05$ may be determined by means of the

TABLE II. Nominal Munsell values, actual Munsell values, and corresponding luminous reflectances of achromatic samples (N-tiles).

Nominal Munsell value	Actual Munsell value	Luminous reflectance Y_N
N5.6	5.83	28.12
N5.8	6.05	30.64
N6.0	6.26	33.16
N6.2	6.48	35.94
N6.4	6.65	38.18
N6.6	6.81	40.37
N6.8	7.01	43.21
N7.0	7.11	44.67
N7.2	7.37	48.62
N7.4	7.61	52.46

same loci of Fig. 3, provided that Y_N is not too high or too low. It has been shown in an earlier study that the L/Y ratios are essentially independent of the level of Y_N[9].

In many ways the results reported here confirm those of earlier studies, although some deviations may be noticed. Figure 4 shows loci of constant L/Y ratios based on average data taken from the studies of Refs. 7 to 9. These loci are for observing conditions very similar to those employed in the present study, but are based on the observations of only two observers. Figure 5 shows loci of constant B/Y ratios obtained for 20 observers reported in Ref. 6. In that study, the observing conditions were somewhat different; a 10°-bipartite photometric field of a MacAdam-type binocular colorimeter was used with a dark surround. The analysis of the observational data makes use of the 1964 CIE Supplementary Standard Observer rather than the 1931 CIE Standard Observer used in the present study. Nevertheless, the shapes and orientations of the loci are similar to those of Fig. 3.

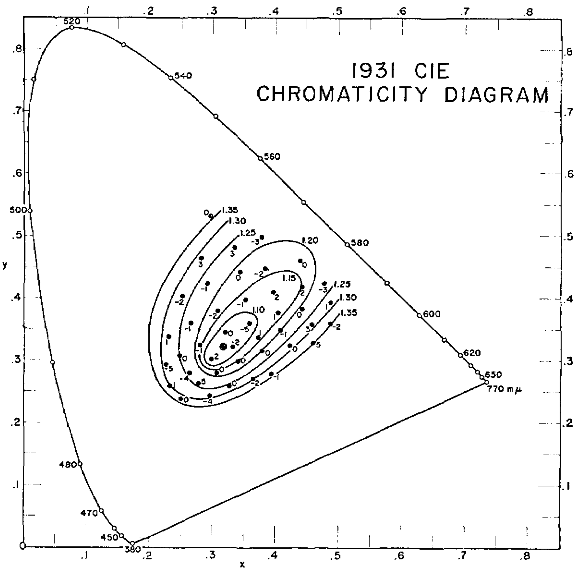

FIG. 4. 1931 CIE chromaticity diagram showing smooth loci of constant L/Y ratios for the average of two observers (after Refs. 7–9).

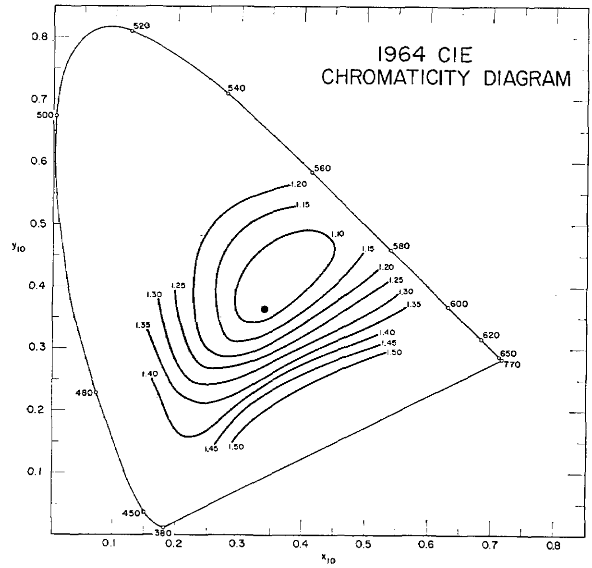

FIG. 5. 1964 CIE chromaticity diagram showing smooth loci of constant B/Y ratios for the average of 20 observers (after Ref. 6).

W. R. S. Garton, Imperial College, London, speaking at 50th Anniversary Meeting of Optical Society in Washington, D. C.