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Luminance and Saturation of Equally Bright Colors†

Luminances and saturations of equally bright colors were measured by heterochromatic flicker photometry and a saturation scaling method, respectively. We used 19 dominant wavelengths from 410 to 670 nm and in the purple region, and 11 excitation purities from 0.0 to 1.0 in 0.1 steps for each dominant wavelength, as test stimulus colors. The results show that the luminances of equally bright colors with the same dominant wavelength decrease approximately linearly as the saturation estimates increase for all dominant wavelengths, but the slope of this luminance-versus-saturation function varies with dominant wavelength. It is implied that the chromatic content of colors differentially contributes to the brightness–luminance discrepancy depending on the dominant wavelength. We also plotted constant-luminance loci and constant-saturation loci in the 1931 CIE x,y *and the 1976 CIE* u′,v′ *chromaticity diagrams.*

Introduction

When the amounts of colored lights are adjusted so that they appear equally bright compared with a given reference light, the luminances of these colored lights are not always equal.‡ This brightness-luminance discrepancy has been shown by a number of investigators with various experimental conditions. Among these conditions are stimuli of different chromaticities, field sizes, luminance levels, and chromatic adaptations.[2-10] Although the degree of the brightness–luminance discrepancy depends on these experimental conditions it has been shown that, except in the yellow region, this discrepancy increases with purity. Lower luminances are required for equal brightness to a reference light when the colors are higher in purity than when they are lower.

Sanders and Wyszecki[9] measured the luminance B of an achromatic field which appeared equally bright as test colors with luminance L. They showed that the logarithmic brightness-to-luminance ratio, $\log(B/L)$, increased approximately linearly as the excitation purity of the test colors increased. Kaiser and Smith[10] also reported that when the luminance L of test colors was adjusted for a brightness match with a white reference of a given luminance B, $\log(B/L)$ increased as a function of excitation purity, which was consistent with the results of Sanders and Wyszecki.[9]

Because the saturation of colors increases with the purity, these investigations imply that the brightness–luminance discrepancy of colors is attributed to the saturation. In fact, some color vision models[11,12] predict the brightness–luminance discrepancy of colors by assuming that both the chromatic and the achromatic components of the colors contribute to the brightness, whereas only the achromatic component contributes to the luminance. This view provides one explanation for the observation that the brightness–luminance discrepancy is greater for more saturated colors.

However, Uchikawa et al.[13] have shown that when colors with different dominant wavelengths are equated in brightness and saturation to a reference yellow by mixing monochromatic and white lights, the luminances of these colors are not equal. Thus, in their investigation, it was shown that the brightness–luminance discrepancy was not accounted for only by saturation, but depended on dominant wavelength.

The purpose of the research reported in this article is to measure luminances and saturations of equally bright colors and to show how the brightness–luminance discrepancy of

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[‡] We use the terms luminance, brightness, purity, and saturation as defined in the CIE *International Lighting Vocabulary.*[1]

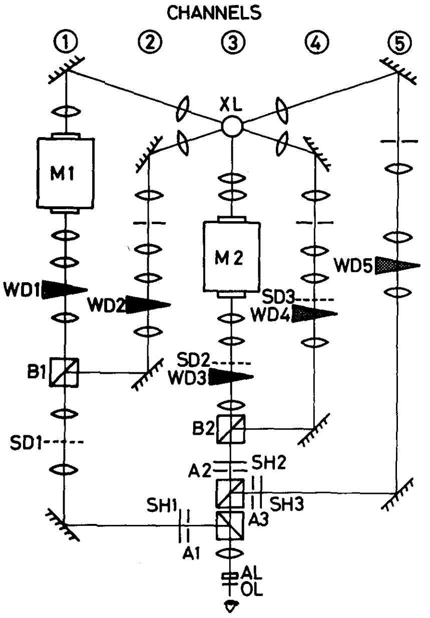

FIG. 1. Schematic diagram of the apparatus. See text for details.

colors is related to the saturation. We used 191 equally bright colored lights which covered almost the entire chromaticity diagram including the purple region. Luminances of these colors were measured by flicker photometry, and saturations of these same colors were measured by a scaling procedure.

Apparatus

We used a conventional five-channel Maxwellian-view system (Fig. 1) with a 1-kW xenon arc source XL. Two monochromatic lights were produced by means of grating monochromators M1 and M2 with half-bandwidth of 8 nm in channels 1 and 3. Channels 2, 4, and 5 produced white lights with the 1931 CIE x,y chromaticity coordinates of $x = 0.332, y = 0.333, x = 0.331, y = 0.336$, and $x = 0.341$, $y = 0.335$, respectively. Channels 1 and 2 were combined through a beamsplitter B1 to make a mixture of monochromatic and white lights. The luminance and purity of this mixture were varied by using two neutral-density wedges WD1 and WD2, one in each channel. The monochromator M2 in channel 3 was set at 670 nm. In some experiments, this 670-nm light was mixed with 410 nm, which came from channel 1, in order to produce purple colors.

Two circular stimulus fields were presented to the observers. One of these fields, formed by A1 or both A1 and A2 in the case of purple colors, was a mixture of monochromatic and white lights. The other field, either A2 or A3, contained a white light. The mixture and white fields were either adjacent to or superimposed on each other depending on the experiments, and could be temporally alternated by appropriately placed sector disks SD1, SD2, and SD3 in order to perform flicker photometry. There were also electromagnetic shutters SH1, SH2, and SH3 in all channels.

The observers, using their right eyes, viewed stimulus fields through an achromatizing lens[13] AL and, when necessary, an ophthalmic lens OL to provide sharp images of stimulus fields.

Method and Procedure

Two of the authors, KU (a 30-year-old male) and HU (a 29-year-old female), participated as observers. Both had normal color vision as tested by the Farnsworth–Munsell 100 Hue Test and AO–HRR pseudoisochromatic plates.

Three experiments were conducted. Experiment 1 was the brightness-matching experiment, experiment 2 the luminance-measurement experiment using flicker photometry, and experiment 3 the saturation-estimation experiment.

Experiment 1: Brightness Matching

The observers performed heterochromatic brightness matching between two circular fields. These fields subtended 45′ visual angle and were separated horizontally by 30′. The right field, from channel 5, was the reference white and fixed at constant luminance of 150 td. In the left field, from channels 1 and 2 or channels 1, 2, and 3, the mixtures of monochromatic and white lights were presented. Nineteen dominant wavelengths, 410, 430, 450, 470, 480, 490, 500, 510, 530, 550, 570, 590, 610, 630, 670, −496.9, −504.6, −534.6, and −561.1 nm, and 11 excitation purities from 0.0 and 1.0 in 0.1 steps for each dominant wavelength served as test stimuli. The excitation purities are expressed in terms of the 1931 CIE x,y chromaticity diagram.

The observer adjusted the intensity of the light mixture so that the test stimulus in the left field appeared equally bright as the white reference in the right field. In a session, test-stimulus colors with the same dominant wavelength were selected randomly, and each stimulus was presented five times. The observer repeated three sessions for each dominant wavelength making a total of 15 trials for each stimulus. It should be noted that the test-stimulus color with excitation purity equal to 0.0 was the white stimulus, and this white stimulus was used in all sessions with different dominant wavelengths. The luminances of this white test stimulus, used in the different sessions, were utilized for normalizing the data.

Experiment 2: Flicker Photometry

In order to evaluate luminances of the equally bright colors (determined in experiment 1), the observer performed heterochromatic flicker photometry between the test stimulus and the white light. The white light from channel 4 was used in this experiment. The white field of 45′ visual angle was superimposed upon and temporally alternated with the test field. The observer's task was to

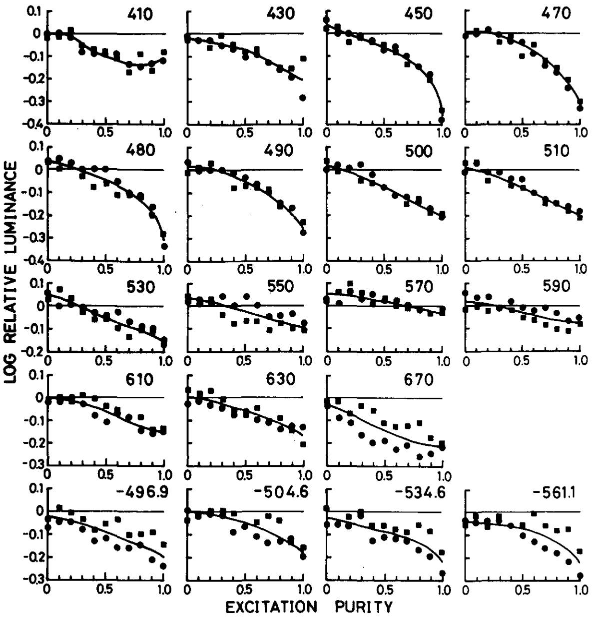

FIG. 2. Log relative luminance of equally bright colors as functions of excitation purity. The dominant wavelength is shown at the upper-right corner of each section. Observer: KU (●), HU (■). Solid curves, drawn by eye, represent the average luminance of the two observers.

adjust the amount of the white light to achieve minimum flicker criterion between the two fields. Flicker frequencies were chosen for each observer so that minimum flicker perception was obtained over a narrow range of luminance adjustments. In each session, the observer made five trials for each stimulus, which was chosen randomly from the stimuli with the same dominant wavelength. Two sessions were run for each dominant wavelength, yielding a total of ten trials for each stimulus.

Experiment 3: Saturation Estimation

The stimuli with excitation purities from 0.1 to 1.0 for all dominant wavelengths were used in this experiment. These stimuli, again, were the same stimuli obtained in experiment 1 and presented in the test field. The observer estimated the perceived percentage chromatic content of the stimuli by the method of constant sum.[13,15,16] In this procedure, the observer responded to a stimulus with, for example, "20% chromatic." Since the total percentage of chromatic and achromatic content was always 100%, 80% was assigned to achromatic content of the stimulus. In a session, each of the stimuli with the same dominant wavelength was chosen randomly and presented five times. The observer performed two sessions for a dominant wavelength making a total of ten trials for each stimulus. A white adaptation field from channel 5, subtending 5° visual angle, was presented between trials in order to reduce the chromatic-adaptation effect by a preceding stimulus. The luminance of this white adaptation field was 150 td.

Results and Discussion

Luminance of Equally Bright Colors

Figure 2 shows log relative luminance of equally bright colors for both observers as functions of excitation purity. The dominant wavelength is indicated at the upper-right corner of each section. Numerical values of these luminances are also shown in Table I. Luminances of test stimuli are normalized relative to the mean luminance of the white test stimulus (excitation purity = 0.0) for each observer. As mentioned above, the same white stimulus was used in all sessions with different dominant wavelengths. The mean luminance value of this white test stimulus was calculated using all values obtained in all sessions. Solid lines in Fig. 2 were drawn by the eye to represent the average luminance of the two observers.

Luminances of equally bright colors decrease for all dominant wavelengths as excitation purity increases. This tendency is, in general, consistent with the results reported by Sanders and Wyszecki[9] and Kaiser and Smith.[10] However there are two important features in which the present results are different from those previous data. First, for the dominant wavelengths of 410 and 430 nm, luminances do not decrease further at higher excitation purities. Since we used flicker photometry to measure luminances of the stimuli, this may be attributed to the fact that the CIE $V(\lambda)$, which is utilized to calculate luminance, has lower sensitivity than the luminous-efficiency function obtained by flicker photometry for shorter wavelengths (shorter than 450 nm). We calculated approximate values of luminance based on the CIE $V(\lambda)$ for the stimuli with 410, 430, and 450 nm, utilizing the differences between the CIE $V(\lambda)$ and the $V(\lambda)$ with Judd's correction.* It was found that the resultant luminances continuously decreased even at higher excitation purities for both 410 and 430 nm. Second, for the dominant wavelength of 570 nm, our results show a small decrease in luminance as excitation purity increases, while the previous results mentioned above did not show the brightness–luminance discrepancy in the yellow region. Our results are more nearly like those recently reported by Burns et al.,[8] who used flicker photometry to equate luminance of test stimuli.

Figure 3 shows loci of constant luminance in −0.025 log luminance steps in the 1931 CIE x,y chromaticity diagram [Fig. 3(a)], and in the 1976 CIE u',v' chromaticity diagram [Fig. 3(b)]. These loci were obtained by using the solid lines in Fig. 2. They are normalized to the luminance of the white-test-stimulus position; that is, the solid lines in Fig. 2 were shifted either upward or downward so that their log relative luminances at excitation purity = 0.0 were equal to 0. Since we measured luminances of equally bright colors, the reciprocal of relative luminance is equivalent to the

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* The CIE $V(\lambda)$ is 0.89, 0.37, and 0.09 log unit lower for 410, 430, and 450 nm, respectively, than the $V(\lambda)$ function with Judd's modification, which represents well the luminous-efficiency function obtained by flicker photometry.[17]

TABLE I. Log relative luminance and saturation estimates of equally bright colors for two observers KU and HU.

Dominant wavelength (nm)	Purity	Log relative luminance		Saturation estimate (%)	
		KU	HU	KU	HU
410	0.0	−0.0016	−0.0171	—	—
	0.1	−0.0022	−0.0092	2.8	2.4
	0.2	−0.0237	0.0240	10.5	16.0
	0.3	−0.0752	−0.0485	20.0	24.5
	0.4	−0.0894	−0.0745	24.0	30.5
	0.5	−0.0925	−0.0751	26.0	35.5
	0.6	−0.0925	−0.1090	27.0	37.0
	0.7	−0.1378	−0.1670	32.5	39.0
	0.8	−0.1511	−0.0902	36.5	42.0
	0.9	−0.1318	−0.1579	41.0	42.5
	1.0	−0.1166	−0.0824	54.0	53.0
430	0.0	−0.0107	−0.0292	—	—
	0.1	−0.0303	−0.0334	1.9	0.3
	0.2	−0.0296	−0.0576	4.9	3.7
	0.3	−0.0479	−0.0116	9.0	10.8
	0.4	−0.0700	−0.0491	20.0	16.0
	0.5	−0.0955	−0.0812	25.0	22.0
	0.6	−0.0937	−0.0715	28.0	30.0
	0.7	−0.1342	−0.1319	35.0	29.5
	0.8	−0.1596	−0.1543	38.5	36.5
	0.9	−0.1940	−0.1507	46.0	41.5
	1.0	−0.2829	−0.1060	65.0	57.0
450	0.0	0.0649	0.0221	—	—
	0.1	0.0010	0.0331	0.2	0.3
	0.2	−0.0016	−0.0425	2.5	3.3
	0.3	−0.0120	−0.0213	5.2	11.5
	0.4	−0.0296	−0.0364	10.5	15.5
	0.5	−0.0694	−0.0485	18.0	20.0
	0.6	−0.0648	−0.0806	24.0	25.5
	0.7	−0.1015	−0.1428	26.5	32.0
	0.8	−0.1469	−0.1452	36.5	34.0
	0.9	−0.1838	−0.2136	47.5	42.5
	1.0	−0.3802	−0.3417	70.0	62.0
470	0.0	−0.0081	−0.0068	—	—
	0.1	0.0017	0.0149	0.0	0.8
	0.2	0.0199	0.0247	1.1	1.1
	0.3	−0.0042	−0.0382	3.9	3.9
	0.4	−0.0250	−0.0122	7.2	4.5
	0.5	−0.0394	−0.1005	14.0	13.3
	0.6	−0.0863	−0.0497	22.0	17.0
	0.7	−0.1378	−0.1247	25.5	28.0
	0.8	−0.1650	−0.1483	34.5	35.0
	0.9	−0.2424	−0.1972	49.5	47.0
	1.0	−0.3337	−0.3012	69.0	61.5
480	0.0	0.0362	0.0266	—	—
	0.1	0.0506	−0.0038	0.0	0.4
	0.2	0.0291	0.0266	0.6	2.4
	0.3	−0.0009	−0.0340	3.9	5.0
	0.4	−0.0022	−0.0763	6.2	9.5
	0.5	−0.0009	−0.0636	13.0	20.0
	0.6	−0.0531	−0.1078	18.0	28.0
	0.7	−0.1033	−0.1144	25.5	35.0
	0.8	−0.1130	−0.1180	39.5	42.5
	0.9	−0.1602	−0.1954	56.0	48.5
	1.0	−0.3325	−0.2825	65.0	63.5
490	0.0	0.0375	−0.0122	—	—
	0.1	−0.0009	0.0136	0.0	0.2
	0.2	−0.0042	0.0344	1.1	4.1
	0.3	−0.0048	−0.0001	4.6	10.1
	0.4	−0.0133	−0.0794	8.9	18.0
	0.5	−0.0342	−0.0715	15.0	24.5
	0.6	−0.0603	−0.0769	20.5	36.5
	0.7	−0.0991	−0.0806	30.5	40.0
	0.8	−0.1499	−0.1622	44.0	50.5
	0.9	−0.1650	−0.1646	53.0	57.5
	1.0	−0.2781	−0.2311	62.5	68.0

TABLE I (*continued from previous page*)

Dominant wavelength (nm)	Purity	Log relative luminance		Saturation estimate (%)	
		KU	HU	KU	HU
500	0.0	0.0030	0.0351	—	—
	0.1	0.0173	−0.0098	0.1	0.5
	0.2	0.0108	0.0110	3.0	9.1
	0.3	0.0199	−0.0521	10.0	23.0
	0.4	−0.0218	−0.0636	16.5	36.0
	0.5	−0.0759	−0.0806	21.5	43.0
	0.6	−0.1052	−0.1138	26.0	45.0
	0.7	−0.1245	−0.1549	38.0	49.5
	0.8	−0.1414	−0.1265	44.5	53.0
	0.9	−0.1747	−0.1864	50.0	59.5
	1.0	−0.2061	−0.1845	55.5	66.0
510	0.0	−0.0140	0.0292	—	—
	0.1	0.0310	0.0377	2.4	4.9
	0.2	−0.0074	−0.0491	9.5	21.0
	0.3	−0.0101	−0.0129	17.5	34.0
	0.4	−0.0433	−0.0673	26.0	42.5
	0.5	−0.0400	−0.0769	27.5	46.0
	0.6	−0.0985	−0.0981	38.5	49.5
	0.7	−0.1299	−0.1525	42.5	53.0
	0.8	−0.1535	−0.1380	47.5	59.0
	0.9	−0.1553	−0.1827	53.0	64.5
	1.0	−0.1831	−0.2111	56.5	64.5
530	0.0	0.0460	0.0344	—	—
	0.1	0.0017	0.0683	0.2	1.2
	0.2	0.0056	0.0292	6.9	14.0
	0.3	−0.0074	−0.0340	12.5	27.5
	0.4	−0.0316	−0.0648	17.0	37.0
	0.5	−0.0433	−0.0624	25.5	42.0
	0.6	−0.0309	−0.0999	27.5	47.5
	0.7	−0.0694	−0.1386	34.5	47.5
	0.8	−0.0888	−0.1053	40.0	53.5
	0.9	−0.1046	−0.1090	42.0	57.0
	1.0	−0.1463	−0.1725	54.0	62.0
550	0.0	0.0225	0.0429	—	—
	0.1	0.0121	0.0279	1.1	0.3
	0.2	0.0115	0.0279	6.9	8.8
	0.3	0.0369	−0.0449	8.7	17.8
	0.4	0.0023	−0.0818	19.3	32.0
	0.5	0.0395	−0.0703	20.0	36.5
	0.6	−0.0022	−0.0679	30.5	37.0
	0.7	−0.0472	−0.1066	33.0	44.0
	0.8	−0.0466	−0.0781	37.5	46.5
	0.9	−0.0433	−0.0951	42.5	49.0
	1.0	−0.0792	−0.1144	48.5	54.5
570	0.0	0.0323	0.0208	—	—
	0.1	0.0121	0.0566	0.0	0.1
	0.2	0.0617	0.0977	1.4	5.2
	0.3	0.0323	0.0592	4.7	16.2
	0.4	0.0506	0.0103	9.5	24.5
	0.5	0.0238	0.0260	16.0	33.0
	0.6	0.0206	0.0025	21.0	36.5
	0.7	0.0062	−0.0147	23.5	37.0
	0.8	−0.0205	−0.0159	28.5	42.0
	0.9	−0.0329	−0.0268	32.0	43.5
	1.0	−0.0127	−0.0292	37.0	43.0
590	0.0	0.0571	−0.0074	—	—
	0.1	0.0441	0.0045	2.2	4.9
	0.2	0.0428	−0.0219	8.5	18.5
	0.3	−0.0107	0.0025	13.0	23.5
	0.4	0.0225	−0.0195	19.0	27.0
	0.5	−0.0061	−0.0497	27.0	34.5
	0.6	−0.0218	−0.0588	29.0	40.0
	0.7	−0.0074	−0.0763	35.5	44.5
	0.8	−0.0290	−0.1011	39.5	46.5
	0.9	−0.0570	−0.1084	45.0	49.5
	1.0	−0.0518	−0.0848	49.5	52.0

TABLE I (*continued from previous page*)

Dominant wavelength (nm)	Purity	Log relative luminance		Saturation estimate (%)	
		KU	HU	KU	HU
610	0.0	−0.0290	−0.0189	—	—
	0.1	−0.0224	−0.0032	3.2	6.8
	0.2	0.0036	−0.0153	13.0	17.0
	0.3	−0.0277	0.0142	18.5	29.0
	0.4	−0.0759	−0.0135	23.5	34.5
	0.5	−0.1088	−0.0388	31.5	41.5
	0.6	−0.0694	−0.0582	37.0	45.5
	0.7	−0.0949	−0.0787	44.0	48.5
	0.8	−0.1469	−0.0939	49.0	54.5
	0.9	−0.1602	−0.1398	53.5	61.5
	1.0	−0.1481	−0.1386	57.5	65.5
630	0.0	−0.0342	0.0260	—	—
	0.1	−0.0179	0.0155	1.5	5.0
	0.2	−0.0355	0.0292	12.8	15.0
	0.3	−0.0518	−0.0116	20.0	29.5
	0.4	−0.0759	−0.0612	27.5	35.5
	0.5	−0.0739	−0.0830	31.0	40.5
	0.6	−0.1021	−0.0515	41.5	48.0
	0.7	−0.1179	−0.1035	51.0	51.0
	0.8	−0.1420	−0.0933	57.5	56.0
	0.9	−0.1324	−0.1513	64.5	62.5
	1.0	−0.1330	−0.2105	70.5	70.0
670	0.0	−0.0407	−0.0231	—	—
	0.1	−0.0894	−0.0159	2.4	4.3
	0.2	−0.1070	−0.0697	9.7	16.5
	0.3	−0.1674	−0.0425	20.5	28.0
	0.4	−0.1995	−0.0648	24.5	35.0
	0.5	−0.1928	−0.1241	31.5	42.5
	0.6	−0.2279	−0.1277	44.0	49.0
	0.7	−0.2140	−0.1307	53.0	52.5
	0.8	−0.2599	−0.1156	60.0	61.5
	0.9	−0.2454	−0.1815	72.5	70.5
	1.0	−0.2200	−0.2021	81.0	78.5
−496.9	0.0	−0.0661	−0.0364	—	—
	0.1	−0.0453	0.0110	1.5	0.2
	0.2	−0.0453	−0.0129	10.5	8.5
	0.3	−0.0811	−0.0352	19.0	20.5
	0.4	−0.1312	−0.0860	25.0	30.0
	0.5	−0.1160	−0.0564	34.0	39.0
	0.6	−0.1602	−0.0376	44.5	43.0
	0.7	−0.1644	−0.1011	50.5	48.0
	0.8	−0.1499	−0.1035	57.5	53.0
	0.9	−0.2073	−0.0914	66.0	61.0
	1.0	−0.2357	−0.1374	71.0	70.5
−504.6	0.0	0.0030	−0.0407	—	—
	0.1	−0.0159	−0.0068	0.4	0.0
	0.2	−0.0094	−0.0026	6.9	4.9
	0.3	−0.0244	0.0018	13.5	19.0
	0.4	−0.0857	−0.0068	21.5	26.5
	0.5	−0.0687	−0.0564	31.5	34.5
	0.6	−0.1064	−0.0485	39.5	41.0
	0.7	−0.1384	−0.0195	44.5	44.5
	0.8	−0.1287	−0.0358	55.0	51.0
	0.9	−0.1209	−0.1386	62.0	58.0
	1.0	−0.2007	−0.1579	70.0	72.5
−534.6	0.0	−0.0557	0.0136	—	—
	0.1	−0.0589	−0.0642	0.0	0.3
	0.2	−0.0720	−0.0165	4.6	5.4
	0.3	−0.0205	−0.0008	10.5	16.5
	0.4	−0.1179	−0.0612	19.0	23.0
	0.5	−0.1118	−0636	23.5	35.5
	0.6	−0.1209	−0.0775	33.5	41.0
	0.7	−0.1263	−0.0878	40.0	47.0
	0.8	−0.1747	−0.0570	48.5	54.0
	0.9	−0.2025	−0.0945	57.5	61.5
	1.0	−0.2690	−0.1761	68.0	75.5

TABLE I (*continued from previous page*)

Dominant wavelength (nm)	Purity	Log relative luminance		Saturation estimate (%)	
		KU	HU	KU	HU
−561.1	0.0	−0.0426	−0.0588	—	—
	0.1	−0.0492	−0.0207	0.0	0.0
	0.2	−0.0361	−0.0703	2.6	3.8
	0.3	−0.0433	−0.0225	9.0	12.8
	0.4	−0.0563	−0.0564	15.0	22.5
	0.5	−0.1070	−0.0594	21.5	31.5
	0.6	−0.1293	−0.0062	27.0	36.5
	0.7	−0.1602	−0.0582	31.0	44.0
	0.8	−0.1789	−0.0751	41.0	46.5
	0.9	−0.2170	−0.0794	49.5	52.5
	1.0	−0.2793	−0.1737	62.5	65.0

brightness-to-luminance ratio *B*/*L*, where, in this experiment, *B* represents the fixed luminance of the reference white and *L* the luminances of equally bright colors measured by flicker photometry. We plot these *B*/*L* ratios along the constant-luminance loci in the chromaticity diagrams.

It is seen that the spacing between constant-luminance loci appears closer in the blue region with dominant wavelengths of 470, 480, and 490 nm than in the other regions for both chromaticity diagrams, indicating that the greater brightness–luminance discrepancy occurs in this blue region. Although the closeness of constant-luminance loci is due to the chromaticity diagrams themselves, Fig. 2 generally shows that there are larger brightness–luminance discrepancies from purity = 0.0 to purity = 1.0 in the blue region than anywhere else. Moreover, our *B*/*L* ratios increase more slowly in the green and red regions when compared with those of Wyszecki,[6] which were measured with related colors. Our constant-luminance loci appear wider apart in these regions.

Saturation of Equally Bright Colors

Figure 4 shows saturation estimates (percent chromatic content) of equally bright colors for both observers as functions of excitation purity. The dominant wavelength is shown at the upper-right corner of each section. Solid lines in the figure, drawn by the eye, represent average saturation estimates of two observers. As expected, the saturation estimates of equally bright colors increase as excitation purity increases for all dominant wavelengths. For dominant wavelengths in the yellow region, 550, 570,

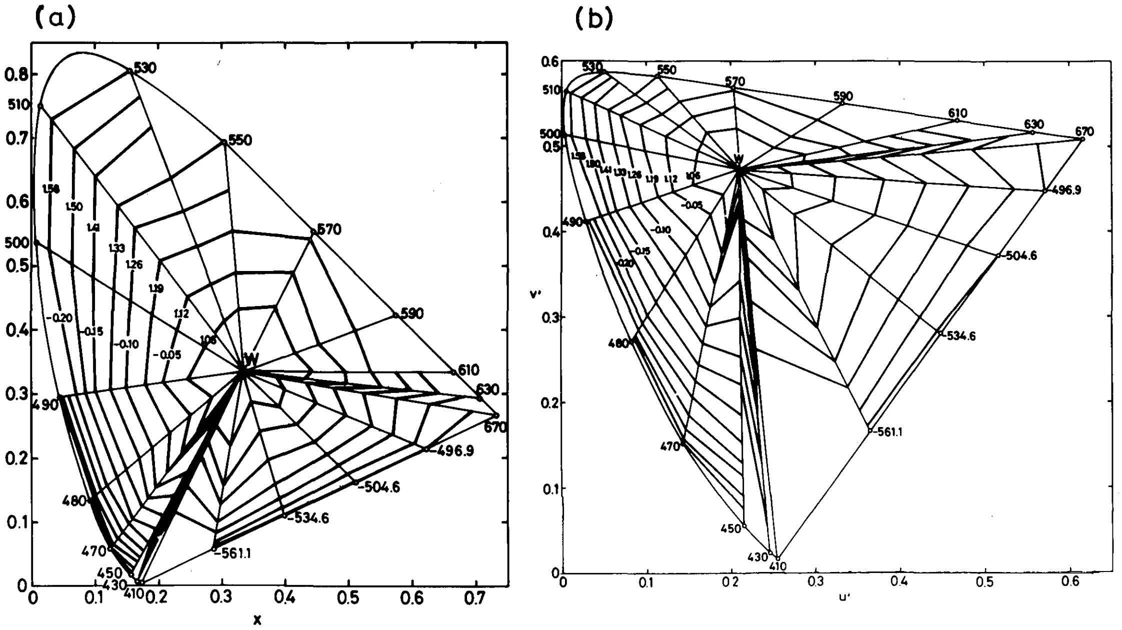

FIG. 3. (a) Constant-luminance loci in the 1931 CIE *x*,*y* chromaticity diagram, drawn in 0.025-log-unit steps. *W* indicates the white point used in the mixture light. The straight lines connecting *W* and each wavelength represent lines on which the stimulus colors were chosen. The numbers shown at each locus indicate *B*/*L* ratios and log relative luminances, respectively. (b) Same as (a), but shown in the 1976 CIE *u*′,*v*′ chromaticity diagram.

and 590 nm, saturation estimates increase more slowly than in other regions. Numerical values of the saturation estimates are shown in Table I.

Figure 5 shows constant-saturation loci in the 1931 CIE x,y chromaticity diagram [Fig. 5(a)], and in the 1976 CIE u',v' chromaticity diagram [Fig. 5(b)]. Mean saturation estimates are plotted in 5% steps for all dominant wavelengths in the figures. These constant-saturation loci tend to have larger intervals in the green region in Fig. 5(a) and in the purple region in Fig. 5(b). For the dominant wavelengths of 430 and 410 nm these loci do not plot smoothly but with dips at the lower purity values. The constant-saturation loci obtained in the present experiments are reasonably consistent with those obtained in the experiments we previously reported[13] using the saturation-matching method.

The 1976 CIE u',v' chromaticity diagram is one of the uniform-chromaticity diagrams developed most recently by the CIE.[18] This diagram is shown to be fairly uniform with Munsell color chips. However, our results do not support the uniformity of this diagram. Constant-saturation loci in a uniform chromaticity diagram should plot as circles about the white point.

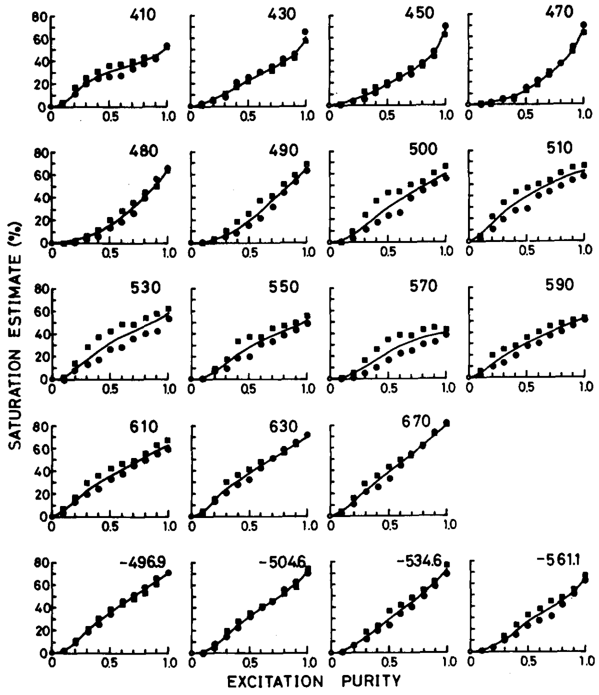

FIG. 4. Saturation estimates of equally bright colors as functions of excitation purity. The dominant wavelength is shown in the upper-right corner of each section. Observers: KU (●), HU (■). Solid curves, drawn by eye, represent the average saturation estimates of the two observers.

Relationship between Luminance and Saturation

As shown in Figs. 2 and 4, luminances of equally bright colors decrease and saturations increase as excitation purity

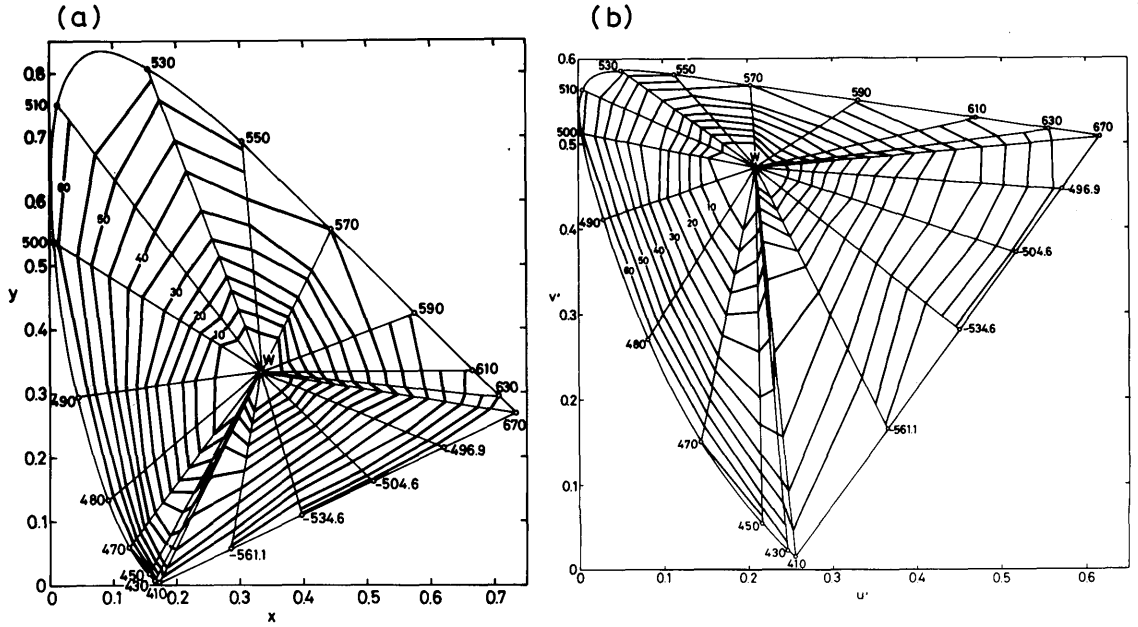

FIG. 5. (a) Constant-saturation loci in the 1931 CIE x,y chromaticity diagram in 5% saturation-estimate steps. W indicates the white point used in the mixture light. The straight lines connecting W and each wavelength represent lines on which the stimulus colors were chosen. The numbers at each locus indicate saturation estimates of the loci. (b) Same as (a), but shown in the 1976 CIE u',v' chromaticity diagram.

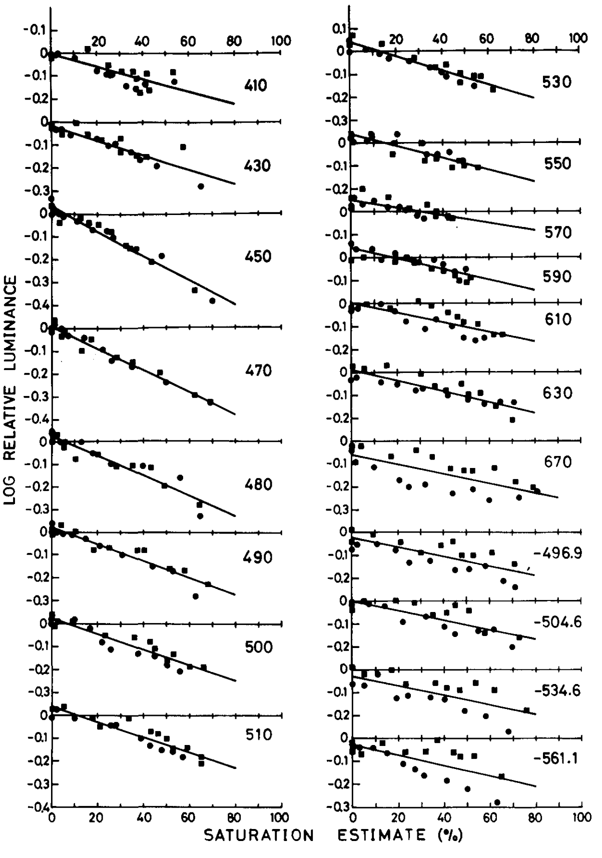

FIG. 6. Log relative luminance as functions of saturation estimates for equally bright colors. The dominant wavelength is shown in each section. Observers: KU (●), HU (■). Data points were replotted from Figs. 2 and 4. The lines in each section were derived by the least-squares method to give the best fit to the data points of the two observers.

increases. These relationships indicate that a correlation exists between the brightness–luminance discrepancy and the saturation of colors. In Fig. 6 we plot luminances of equally bright colors as a function of saturation estimates for each dominant wavelength in order to show how luminances of colors are related to their saturations. The dominant wavelength is shown on the right side in each section. Each point in Fig. 6 is determined by using the values of log relative luminance and saturation estimates, taken from Figs. 2 and 4, for each stimulus. Solid lines in the figure were drawn by the least-squares method to give the best fit to the data points of both observers.

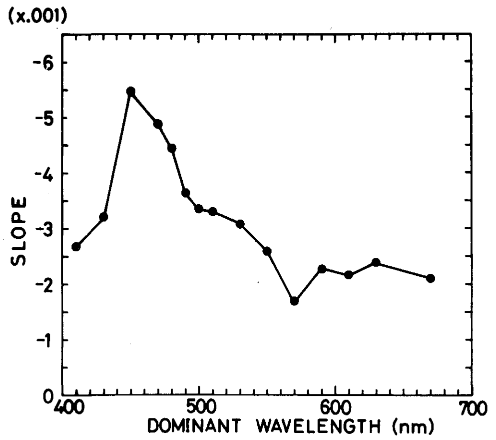

FIG. 7. Slope of the luminance-versus-saturation function shown in Fig. 6.

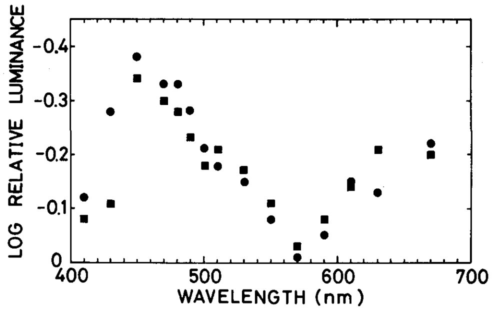

FIG. 8. Log relative luminance of equally bright monochromatic lights. Observers: KU (●), HU (■). The data points are replotted from Fig. 2.

In Fig. 6, it is clearly seen that log relative luminance decreases approximately linearly for all dominant wavelengths, though there are some discrepancies between the two observers for the dominant wavelength of 670 nm and in the purple region. The slopes of this luminance-versus-saturation function are different among different dominant wavelengths, indicating that the relationship between the brightness–luminance discrepancy and the saturation depends on the dominant wavelength. Figure 7 shows slopes of the luminance-versus-saturation function for all dominant wavelengths except those in the purple region. The absolute value of the slope is greatest for 450 nm and smallest for 570 nm, suggesting that the chromatic content of colors with the dominant wavelength of 450 nm has greatest contribution to the brightness–luminance discrepancy, but that with 570 nm was smallest in all colors measured. If the saturation of all dominant wavelengths contributed equally, we would except a flat function in Fig. 7.

It is of interest to plot the luminances and the saturation estimates of equally bright monochromatic lights as a function of wavelength. These are replotted from Figs. 2 and 4 and shown in Figs. 8 and 9, respectively. The luminance

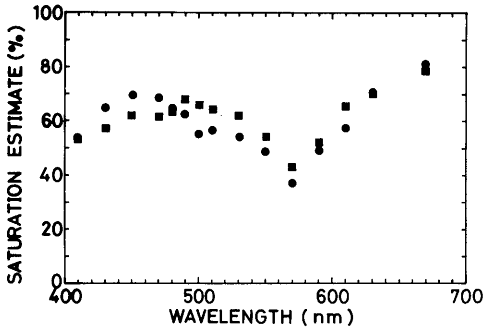

FIG. 9. Saturation estimates of equally bright monochromatic lights. Observers: KU (●), HU (■). The data points are replotted from Fig. 4.

functions shown in Fig. 8 are in good agreement with the results reported by Kaiser and Comerford.[19] The saturation-estimation functions shown in Fig. 9 are similar to those reported by Jacobs[16] with neutral adaptation. It is seen, when one compares Fig. 8 with Fig. 9, that the saturation-estimation function is shallower in shape than the luminance function. Since the log relative luminance decreases almost linearly as a function of the saturation for equally bright colors with the same dominant wavelength (as seen in Fig. 6), the difference in shape between Figs. 8 and 9 may be accounted for by the slope function shown in Fig. 7.

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