# Equating colors for saturation and brightness: the relationship to luminance

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Received October 30, 1981; revised manuscript received May 5, 1982

With a modified step-by-step brightness-matching procedure, a series of colors, with dominant wavelengths from 400 to 670 nm, was adjusted so that the saturations and brightnesses of the colors appeared equal to those of the reference, which was a mixture of 570-nm and white light. The results show that equally bright and equally saturated colors are not equal in luminance. We also report a saturation function of spectral lights derived by utilizing these equally bright and equally saturated colors. Finally, our equally saturated colors do not plot as a circle in the 1976 CIE $u'$, $v'$ space, which indicates some limitations of this uniform chromaticity diagram.

## INTRODUCTION

Colored lights can be physically described by the dimensions of wavelength, purity, and luminance. The perceptual correlates to these physical dimensions are hue, saturation, and brightness.[1] However, the relations between the physical and perceptual dimensions are merely correlated; they are not identities. It has been shown that colors with purities equal to 1.0 are not equally saturated[2–4] and that monochromatic colors equated in luminance are not equally bright.[5–7]

Several investigations[5,7,8] have shown that, when a log luminous-efficiency function measured by heterochromatic flicker photometry is subtracted from that measured by heterochromatic brightness matching, the resultant curve is similar in shape to saturation functions of monochromatic lights obtained by various methods.[2–4,9,10] Furthermore, it has also been shown that, when colors with the same dominant wavelength are adjusted to appear equally bright, the more-saturated colors are lower in luminance.[11,12] These results indicate that the discrepancy between the luminance and the brightness[13] of colored lights is related to their saturation.

It is implied that, when purities of colored lights with different dominant wavelengths are adjusted so that these colors appear equally bright and are equal in luminance, these colors may appear equally saturated. In order to produce colored lights that appear equally saturated, Kaiser *et al.*[14] mixed monochromatic colors with white light until they were both equally bright (by heterochromatic brightness matching) and equal in luminance (by heterochromatic flicker photometry). The saturations of these stimuli, measured by a saturation-estimation scaling method, were not equal; the colors of shorter dominant wavelengths were distinctly less saturated than those of longer dominant wavelengths.

In the research reported below we further investigate the relationship among luminance, brightness, and saturation of colored lights. The research reported herein also shows how the step-by-step (cascade) brightness-matching procedure is adopted as a reliable saturation-matching procedure. We found that colors equal in brightness and in saturation are not equal in luminance.

## APPARATUS

A conventional five-channel Maxwellian-view system (Fig. 1) was used. The source, XL, was a single 1-kW xenon-arc lamp. Two chromatic channels were produced by means of grating monochromators M1 and M2 in channels 1 and 3, respectively. Channels 2, 4, and 5 produced white light. Three fields, A1, A2, and A3, were presented to the observer (Fig. 1, insert). The top field, A3, came from channel 5 and constituted a reference white field. The bottom two fields, A1 and A2, were variable in luminance and purity, the latter ranging from 0.0 to 1.0. The lower-left-hand field was produced by combining channels 1 and 2 through beam splitter B1. The lower-right-hand field was produced by combining channels 3 and 4 using beam splitter B2. Monochromators M1 and M2 were set to half-bandwidths of 8 nm. The 1931 CIE chromaticity coordinates of the white lights from channels 2 and 4 were $x = 0.326$, $y = 0.399$ and $x = 0.320$, $y = 0.396$, respectively.[15] The white light from channel 5 was a visual match with that of the white lights from channel 2 and 4.

Neutral-density wedges W1, W2, W3, and W4 were driven by stepping motors controlled by a microcomputer. The observer could, with the computer, move any wedge in any direction. Wedges W1 and W2 could be moved simultaneously at equal speeds in opposite directions to change the purity of the lower-left-hand field. Wedges W3 and W4 could also be moved in the same manner to change the purity of the lower-right-hand field. Either pair of those wedges could be moved to increase or decrease its density simultaneously at equal rates to change the luminance of the fields without changing their purities. When any one wedge moved alone, both luminance and purity of the associated field changed.

Sector disks SD1 and SD2 were placed in focal planes conjugate with the exit slits of the monochromators (chromatic channel) and the focal plane of the source (white channel). These sector disks were driven by stepping motors controlled by an Iconix timer and were used for flicker photometry of the chromatic-plus-white light of channel 1 with the white light in channel 4. Shutter SH was used to deliver flashes of white light from channel 4 during the increment-threshold experiment.

During the saturation-matching experiment, all three circular fields, A1, A2, and A3, were used. Each field subtended a visual angle of 45′ and was separated from the other by a visual angle of 30′. The two bottom fields served as the chromatic-plus-white field and the top as a reference white. The top reference-white field was maintained at 51 td throughout all experiments.[16] For some of the experiments the right field was shifted laterally so that it was superimposed

Reprinted from **Journal of the Optical Society of America,** Vol. 72, page 1219, September 1982

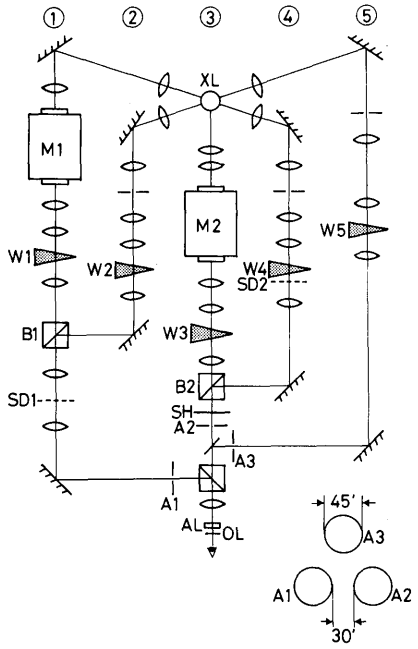


Fig. 1. Schematic diagram of the apparatus and the three circular fields as seen by the observer (bottom right). See text for details. Numbers shown at the top represent the channel numbers.

upon the left field. During the flicker-photometry experiment the right field subtended a 45′ visual angle. However, during the increment-threshold experiment, an aperture was used to reduce the visual angle to 3′.

The observer's right eye was held in position by a dental bite board attached to an $x, y, z$ adjustable amount. Ophthalmic lenses OL were used as required to provide sharp images of the fields, and the display was viewed through an achromatizing lens AL to correct for axial chromatic aberration.[17]

## METHOD AND PROCEDURE

The research reported below used two observers, HU and KU, a female and a male, 28 and 29 years of age, respectively. Both had normal color vision as tested by the Farnsworth–Munsell 100 Hue Test, the Standard Pseudoisochromatic Plates,[18] and the AO-HRR pseudoisochromatic plates.

Three experiments were performed. The first experiment was the saturation-matching procedure. The second was the brightness- and saturation-validation experiment. The final experiment evaluated the luminance of the equally bright and equally saturated colors by heterochromatic flicker photometry and increment-threshold methods.

### Saturation Matching

In the first experiment the observers performed a step-by-step saturation-matching procedure.[19] The experimenter put a slightly desaturated 570-nm light in the lower-right-hand field. The observer adjusted the 570-nm light so that the lower-right-hand field and the top (white) field were equally bright. A white stimulus was then placed in the lower-left-hand field. Monochromator M1, which contributes to the lower-left-hand field, was adjusted so that its wavelength was slightly different from 570 nm. (At the beginning of a trial the luminance contributed by M1 was below threshold.) The variable field was initially the lower-left-hand field and the reference the lower-right-hand field. They alternated with each other as the step-by-step procedure progressed.

In a trial, the observer adjusted the mixture of the chromatic-and-white light, which was initially white, so that the brightness and saturation of the variable field matched the brightness and saturation of the reference field. At the end of each trial, the observer varied the luminance of the variable field so that its brightness matched that of the top field. When this was accomplished, the variable field became the reference, and a new wavelength was chosen for the other, which became the variable field. In this way saturation matching between fields that were nearly identical in hue and saturation was facilitated.

The wavelength differences between the lower fields varied from 1 to 3 nm near 570 and 490 nm to as much as 10 nm near 520 nm and at the spectral extremes. HU used a total of 56 steps from 410 to 670 nm, whereas KU used 49 steps from 400 to 665 nm. In one series of trials the wavelengths progressed from 570 nm toward the long wavelengths and back again toward 570 nm. In the other series the wavelengths progressed from 570 nm toward the short wavelengths and back again toward 570 nm. HU made two repetitions during each trial, and KU made one. Both observers performed four series of trials together, making the total of eight repetitions at each wavelength for HU and four for KU.

### Brightness and Saturation Validation

In this experiment we checked to see if "equally bright and equally saturated" [20] colors were obtained in the step-by-step procedure. A well-known problem with the step-by-step procedure is the accumulation of errors. Thus it is important to determine whether the objectives of the first experiment were achieved.

Twelve stimuli with different dominant wavelengths for HU and eleven for KU were chosen from the stimuli produced in the lower-left-hand field in the saturation-matching experiment. Each of these colors was placed in the lower-left-hand field. The observer adjusted the white light in the lower-right-hand field to produce a heterochromatic brightness match with the left. HU performed this task 15 times for each dominant wavelength, and KU 10 times.

To check for equality of saturations of the colors, the observers performed saturation estimates of the same stimuli by the method of constant sum. In this procedure the observer estimated the perceived percentage chromatic content of the stimuli determined in the first experiment as well as for two other kinds of stimuli: equally bright monochromatic lights and two dummy stimuli for each dominant wavelength. The dummy stimuli were desaturated but of different purities from those set by the observers in the first experiment. The purpose of using these extra stimuli was twofold. First, the saturation estimates of the monochromatic stimuli provided a reference with which to compare the saturation estimates of the stimuli obtained in the first experiment. Second, the dummy stimuli made it pointless for the observers to respond with the same estimate for all stimuli. They were forced to make a judgment on each trial and could not be aware of whether the stimuli (except for the spectral stimuli) came from the first experiment or not. All stimuli were presented in the lower-left-hand field four times in random order. The top achromatic white reference was always present to provide the observer with a baseline for his responses.

### Luminance Measurement

In this experiment the luminances of the colors generated in the first experiment were measured by means of heterochromatic flicker photometry. We also measured the amount of white light required to be just noticeable when it was superimposed upon the equally saturated fields, i.e., we performed an increment-threshold experiment.

The lower-right-hand field, which now contained only white light, was shifted so that it was superimposed over the left field. For the flicker-photometry experiment, the white field remained at a 45′ visual angle. Sector disks SD1 and SD2 in channels 1 and 4 (see Fig. 1) provided the alternation between the white and colored fields. Again, the same colored fields determined in the first experiment were used. Flicker frequencies were adjusted for each observer so that a narrow range of luminance adjustment was required to obtain the minimum flicker criterion. The observer's task was to adjust the amount of white light to achieve a minimum-perceptible flicker. HU performed 12 repetitions for each of the dominant wavelengths; KU made 8 repetitions; both used the method of adjustment.

For the increment-threshold experiment, the visual angle of the white field was reduced to 3′. By means of the shutter SH in channel 3, this white field was flashed on for 10 msec, once per second. By using the method of limits, the observer's task was to report when the flash superimposed upon the colored field was visible for ascending series or invisible for descending series. HU performed the task for a total of 12 trials and KU for a total of 8 trials.

## RESULTS AND DISCUSSION

The first question that needs to be answered is whether the step-by-step procedure resulted in "equally bright and equally saturated" stimuli. Figure 2 shows the log relative luminance of the white light set equally bright to the equally saturated fields, as a function of the dominant wavelength. As can be seen, there are no systematic deviations from equal brightness for HU, but small systematic deviations are evident for KU. The maximum deviation was only 0.03 log unit for HU and 0.07 log unit for KU.

Figure 3 shows the results of the saturation-estimation experiment. Saturation was expressed as the percentage of chromatic content perceived in the stimuli. On the abscissa we plot the dominant wavelength of these colors. The equally saturated stimuli generated in the first experiment were reported as having approximately 40% chromatic content (filled symbols). Deviations from this level, as a function of dominant wavelength, are negligible when compared with the estimation of chromatic content of equally bright monochromatic (purity = 1.0) stimuli (open symbols).

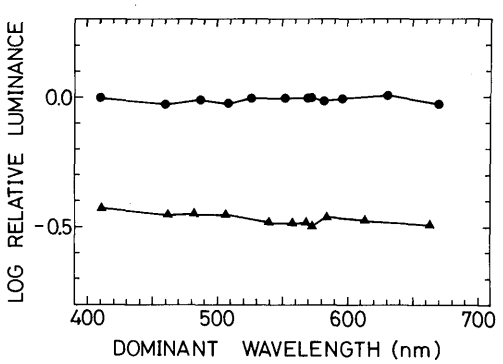


Fig. 2. The log relative amount of white light required for a brightness match with stimuli set for equal brightness and saturation. The abscissa represents dominant wavelengths of these stimuli. Observers: HU (●), KU (▲). The data are displaced 0.5 log unit for clarity.

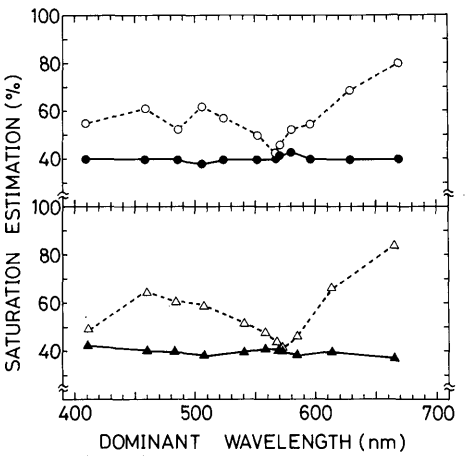


Fig. 3. The saturation estimation expressed as the percentage of chromatic content perceived in the stimuli as a function of dominant wavelength. Observers: HU (●, ○), KU (▲, △). Open symbols represent monochromatic lights set for equal brightness and filled symbols stimuli set for equal brightness and saturation.

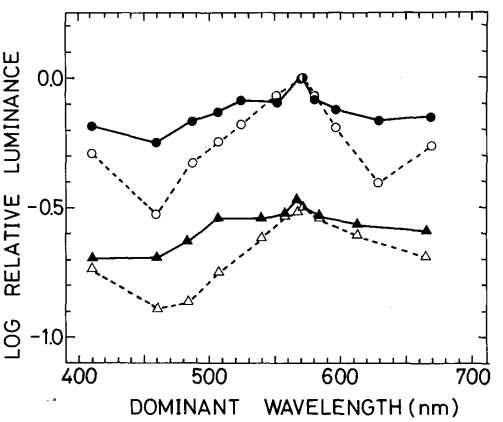


Fig. 4. The log relative luminance of white light required for minimum flicker as a function of dominant wavelength. Observers: HU (●, ○), KU (▲, △). Open symbols represent equally bright monochromatic lights and filled symbols equally bright and equally saturated stimuli. The sets of data are displaced 0.5 log unit for clarity.

Figure 4 shows the log relative amount of white light required for minimum flicker as a function of dominant wavelength. Two sets of functions are again shown, one for equally bright monochromatic stimuli (open symbols) and one for the equally saturated stimuli generated in the first experiment (filled symbols). The white-light luminance for flicker photometry with the equally bright monochromatic lights is what would be expected from the results of the same experiment reported by Kaiser and Comerford.[4] It is clearly seen that the equally saturated stimuli from the first experiment were not equal in luminance as measured by heterochromatic flicker photometry. The range of white light required for minimum flicker with the equally saturated stimuli (filled symbols) is

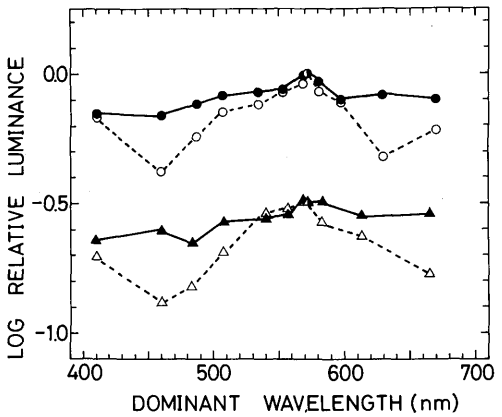


Fig. 5. Same as Fig. 4 but for increment threshold.

not so great as that with the monochromatic stimuli (open symbols). The equally saturated stimuli are lower in luminance at shorter and longer dominant wavelengths than at 570 nm.

Figure 5 shows the results of the increment-threshold experiment. Ward and Tansley[21] showed that, when two fields were equated for luminance by the minimally distinct border method, the amount of white light required for an increment threshold for both fields was constant. Thus, if our equally saturated fields were equal in luminance, then the amount of white light required for an increment threshold should remain constant for all dominant wavelengths. As is shown in Fig. 5, the results for increment thresholds are approximately the same as those for the flicker (Fig. 4).

The step-by-step brightness-matching procedure was used by Gibson and Tyndall[22] to determine the luminous-efficiency function, which became part of the CIE standard luminous-efficiency function. However, as is shown in Figs. 2, 4, and 5, our step-by-step saturation-matching procedure did not equate *luminance* of the stimuli but equated their *brightness*. The reason for these results is probably that we employed the top white reference field (see Fig. 1) so that the observer could keep the brightness of the stimuli constant. Luminance of the stimuli gradually changed as dominant wavelength increased or decreased with the step-by-step procedure.

In order to see how the saturation and luminance of equally bright colors vary as functions of excitation purity, we replotted HU's saturation estimations and luminances for dominant wavelengths of 572, 460, and 630 nm in Fig. 6. HU's saturation and luminance values were taken from Figs. 3 and 4.[23] As can be seen from Fig. 6, as the excitation purity increases, saturation increases and luminance decreases. However, the rate of saturation increase and the corresponding luminance decrease is wavelength dependent. For example, luminance decreases more slowly for 572 nm than for 460 and 630 nm as the excitation purity of these colors increases. By following the arrows in Fig. 6 one can easily see that luminance difference exists for equally saturated colors.

Wyszecki[24] reported loci of constant lightness-to-luminance (L/Y) ratios of Munsell chips (which were approximately equal in luminance) in the 1931 CIE chromaticity diagram. The loci at constant L/Y ratios do not correspond with those of constant value and chroma of Munsell chips, indicating that Munsell colors with constant L/Y ratios are not equally saturated. Munsell colors of constant value and chroma have higher L/Y values in the blue and red regions than in the yellow region. This tendency is consistent with the present results shown in Fig. 6.

It would be of interest to compare the results shown in Fig. 4 with the predictions made by the Guth *et al.*[25] and Ingling and Tsou[26] color-vision models. Figure 7 shows the luminance predicted by the Guth *et al.* [Fig. 7(a)] and Ingling and Tsou [Fig. 7(b)] models for equally bright and equally satu-

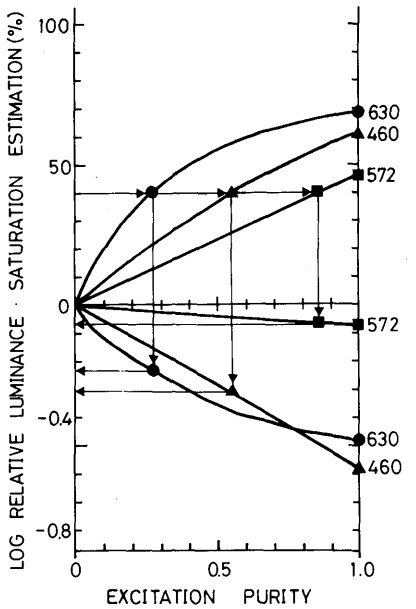


Fig. 6. HU's saturation estimations and log relative luminance for three dominant wavelengths of 572 (■), 460 (▲), and 630 (●) nm. The data were replotted from Figs. 3 and 4. Excitation purity is expressed in terms of the CIE $u'$, $v'$ uniform chromaticity diagram.

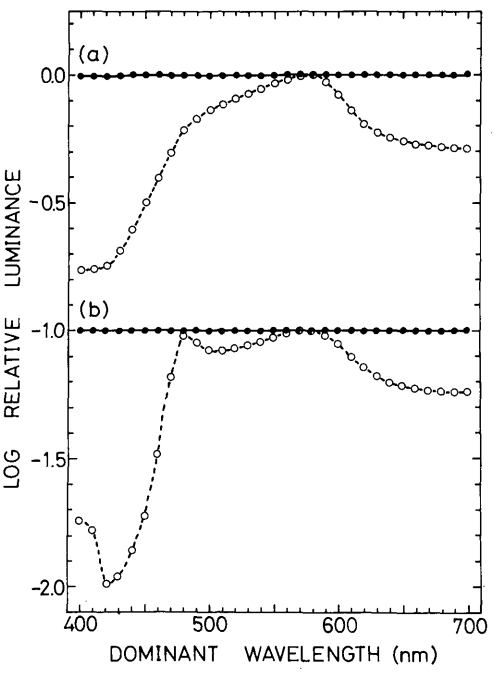


Fig. 7. (a) The log relative luminance predicted by Guth *et al.*[25] for equally bright and equally saturated lights (filled symbols) and equally bright monochromatic lights (open symbols). (b) Same as (a) but predicted by Ingling and Tsou.[26]

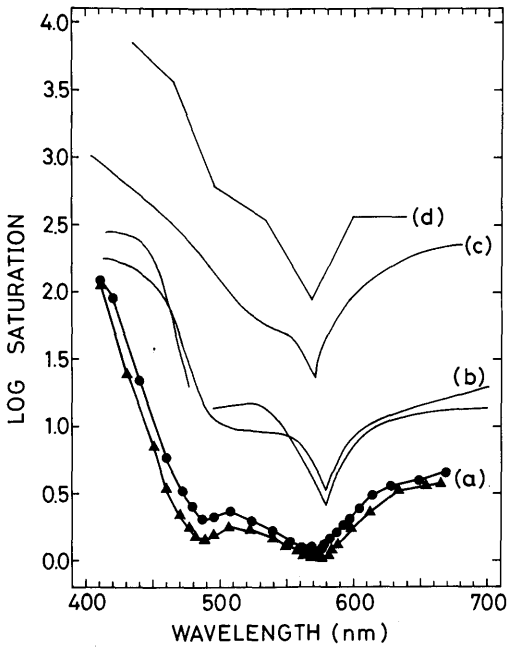


Fig. 8. Saturation function derived with different methods. (a) From equally saturated stimuli obtained by the present step-by-step saturation-matching procedure. Observers: Hu (●), KU (▲). (b) The ratio of chromatic components derived by Jameson and Hurvich.[27] (c) Saturation-discrimination experiment by Priest and Brickwedde.[9] (d) Physiological saturation-discrimination experiment by De Valois and Marrocco.[28]

rated lights (filled symbols) and for equally bright monochromatic lights (open symbols). The luminance of equally bright monochromatic lights obtained in the present experiment (open symbols in Fig. 4) is fairly well predicted by these models. However, both of these models predict that equally bright and equally saturated colors are equal in luminance (solid curves in Fig. 7). As is seen from Fig. 4, our data for equally bright and equally saturated colors are not equal in luminance.

Consider the saturation of a spectral light as represented by Eq. (1). This equation is the same form as that used in saturation-discrimination experiments[9,10]:

$$S = (L_\lambda + L_w)/L_\lambda, \quad (1)$$

where $L_w$ is the luminance of the white light of the mixture, $L_\lambda$ is the luminance of the spectral light ($\lambda$ is the wavelength) of the mixture, and $S$ is the saturation of the spectral light.

In Fig. 8, curves (a) are plots of log $S$ as a function of wavelength for observers HU and KU. Since the task of the observer in the first experiment was to equate the various dominant wavelengths for saturation, the amount of white light and spectral light required in the mixture was dependent on the saturation of the spectral light. Thus the procedure in the first experiment can be considered a new method for evaluating the saturation of spectral stimuli. Like the saturation-estimation method, our procedure is also a suprathreshold method. Saturation-discrimination experiments are examples of threshold methods.

It would be of interest to compare our suprathreshold functions with others in the literature. Curves (b) show the ratio of chromatic to achromatic components derived by Jameson and Hurvich[27] in their experiment on chromatic valences determined by their hue-cancellation procedure. Curve (c) shows the average of the well-known saturation-discrimination functions of Priest and Brickwedde.[9] Finally, curve (d) presents the functions of De Valois and Marocco[28] obtained by single unit records from the macaque monkey. It is our judgment that the Jameson–Hurvich function resembles our data more closely than do those of the other two investigations.

In 1976, the CIE presented a new uniform chromaticity diagram ($u'$, $v'$ space).[29] One of the tests to determine how well this space functions is to plot Munsell chips of equal value and chroma in this diagram. If these chips indeed represented equally saturated colors and the $u'$, $v'$ space were truly uniform, the chips would plot as circles about a white point. We plotted the equally saturated colors produced in our research in this diagram (Fig. 9). W in Fig. 9 indicates the white light used in our experiment. Figure 10 shows Munsell loci

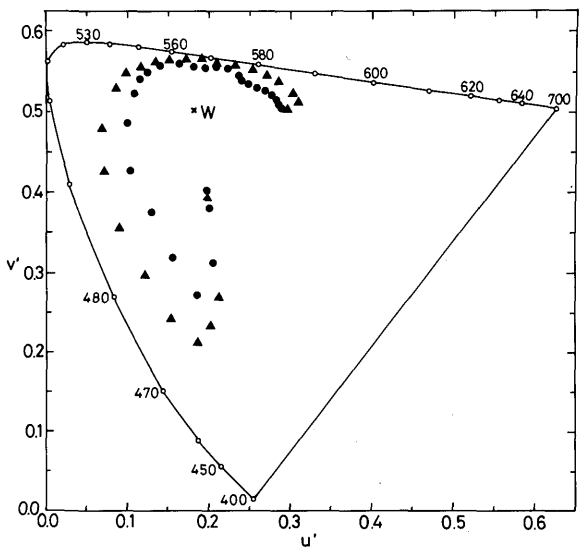


Fig. 9. The loci of equally saturated stimuli in the CIE $u'$, $v'$ uniform chromaticity diagram. Observers: Hu (●), KU (▲). W indicates the white light used in the present experiment.

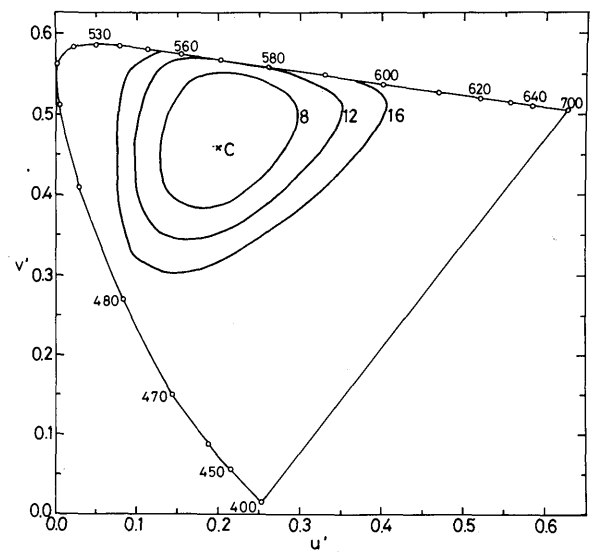


Fig. 10. The loci of Munsell chips of value 5 and chroma 8, 12, and 16 in the CIE $u'$, $v'$ uniform chromaticity diagram. C shows the position of CIE illuminant C.

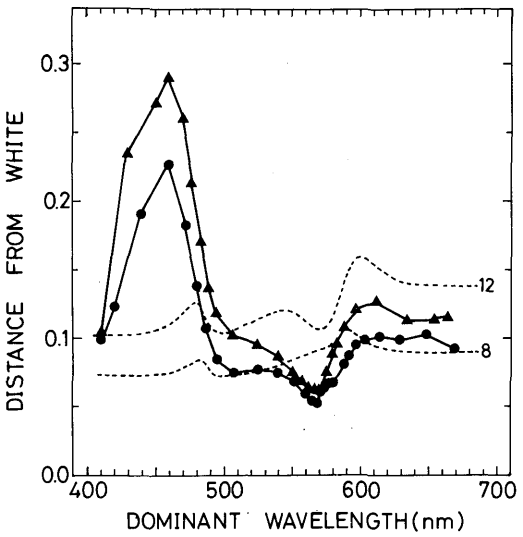


Fig. 11. The points show the distances of equally saturated stimuli from the white point (W in Fig. 8) in the CIE $u'$, $v'$ uniform chromaticity diagram. The abscissa represents dominant wavelength of these stimuli. Observers: HU (●), KU (▲). The dashed lines show the distances of Munsell chips of value 5 and chroma 8 and 12 from CIE illuminant C (C in Fig. 9) in the same diagram.

in the $u'$, $v'$ space. Figure 11 shows distances of our stimuli from the white point that we used (filled symbols) as well as those of Munsell chips (dashed lines). The distances of Munsell chips from CIE illuminant C are fairly constant for all dominant wavelengths. However, our stimuli have greater distances in the blue-and-violet region than in the yellow region. It should be noticed that Munsell chips of equal value have equal luminance reflectance, whereas our stimuli are of equal brightness. This difference may be one of the possible discrepancies between loci of Munsell chips and our stimuli.[30]

## ACKNOWLEDGMENTS

We wish to acknowledge support by the Natural Sciences and Engineering Research Council of Canada (APA 295) awarded to P. K. Kaiser and to thank G. Wyszecki, S. L. Guth, C. J. Bartleson, and the anonymous referee for their critical comments.

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30. Other possibilities may be that Munsell chips are object (related) colors and usually observed with a surrounding adaptation field, but our stimuli are aperture (nonrelated) colors and are observed with no surrounding field.