# Brightness, not luminance, determines transition from the surface-color to the aperture-color mode for colored lights

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Received May 22, 2000; revised manuscript received October 24, 2000; accepted October 26, 2000

Whether a color stimulus appears in the surface-color or in the aperture-color mode depends on the luminance relationship between the center color stimulus and its surround. We investigated how chromaticity of a color stimulus affected the luminance level at which the appearance of the stimulus changed from the surface-color to the aperture-color mode. Mode estimation points were obtained for 10-cd/m$^2$ color stimuli with different chromaticities presented in the center of a white surround of variable luminance. The color stimuli tended to appear in the aperture-color mode as purity increased, similarly to the increase of the brightness-to-luminance ratio for equal-luminance colors. It was also found that the mode-transition sensitivity function was similar in shape to the brightness sensitivity function for 440–660-m monochromatic light. Our results indicate that brightness is a determining factor for mode transition between the surface-color and the aperture-color modes. We discuss a possible assumption for relationships between brightness and lightness limits of a surface color.
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*OCIS codes:* 330.1690, 330.1720, 330.5510.

## 1. INTRODUCTION

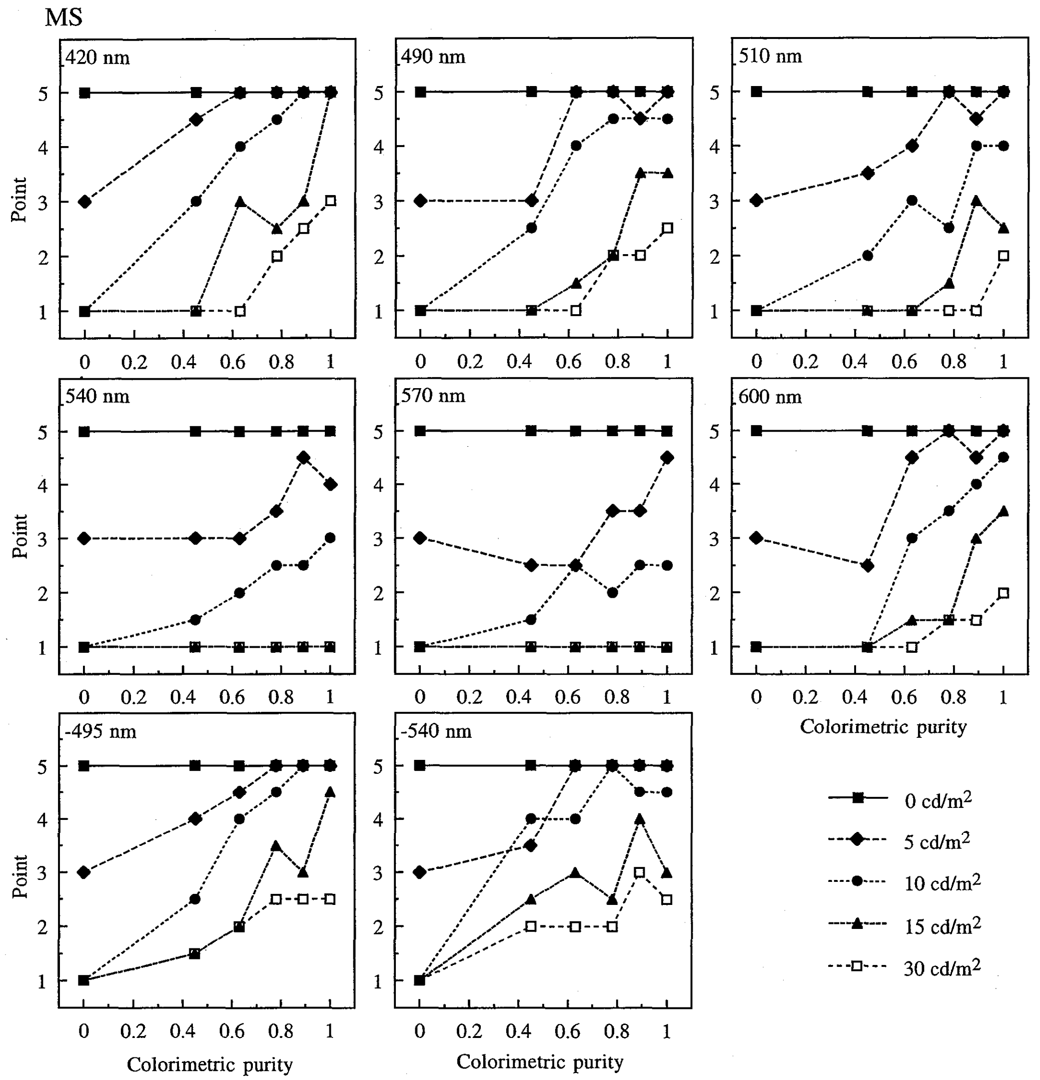
There are several modes of color appearance, of which surface and aperture-color modes are the most common in our everyday lives.[1,2] A color appears to be an attribute of the surface in the surface-color mode, whereas it appears to be emerging from an aperture in space in the aperture-color mode. It is known that these color appearance modes are determined by the luminance relationship between an object and its surround.[3–9]

When a center colored light is surrounded by some other lights that are more intense than the center light, the center light tends to appear in the surface-color mode. When the surround lights are much less intense than the center light, however, the center light tends to appear in the aperture-color mode. It has been pointed out that the physical properties of a stimulus, such as a real surface or a real light source, are not necessarily determining factors for the mode of color appearance but that the stimulus configuration, such as intensity, spatial arrangement, and illumination condition, determines the mode of color appearance.[4,6]

Some previous studies reported the intensity and chromaticity conditions of colored lights in which the lights appeared in the surface-color mode or in the aperture-color mode. Bonato and Gilchrist[7] measured the threshold at which achromatic targets transitioned from luminous to opaque for a range of backgrounds. Their results showed that a target began to appear luminous when its luminance was ~1.7 times that of a surface that appeared white in the same illumination. This value of 1.7 is bigger than that obtained by Evans,[8] who reported that the illuminant-mode threshold luminance for an achromatic surface was ~1.1 times that of a surrounding white. These discrepancies might be caused by differences in the criteria employed in those author's experiments.

Evans and Swenholt[10] obtained the zero-gray ($G_0$) luminance threshold of high-purity colored lights, which they equated to the point at which the stimulus appeared fluorescent. Although the criterion used in determining the $G_0$ threshold was the difference in appearance between gray-content and fluorescent colors, it seems quite similar to the criterion for transition from the surface-color to the aperture-color mode of appearance. Evans and Swenholt showed that the $G_0$ threshold as a function of wavelength resembled the saturation function of monochromatic lights. The ratio of the threshold luminance of the colored light to that of the surrounding white was 0.5 at ~570 nm and 0.01 at ~430 nm. These ratios for chromatic lights vary widely from those for achromatic light.[10–12] The chromatic content of colored lights seems to have quite a strong effect on the difference in appearance between the surface-color and the aperture-color modes.

A general hypothesis proposed previously is that when the visual system estimates a reflectance surface as being outside the optimal color locus (the limit of physically realizable surfaces for a given purity and lightness) the surface will appear in the aperture-color mode.[8,9] To explore this hypothesis Speigle and Brainard[9] measured the luminosity threshold of luminance for test stimulus chromaticities and experimental illuminants. They reported the contour plots of the luminosity threshold surfaces on $(x, y)$ chromaticity diagrams. Although the test stimulus chromaticities were restricted to a small area around the white points, it was clearly shown in their data that



(a)

Fig. 1. Continues on facing page.

the threshold luminance varied with the test stimulus chromaticity and illuminants.

These previous studies indicated that the threshold luminance for transition from the surface-color to aperture-color mode is not equal among colored lights but rather depends on the chromaticity of the colored light. However, it is not completely understood how the threshold luminance varies with the test stimulus chromaticity in an entire chromaticity diagram.

Moreover, when the luminance of a test color increases to become greater than that of the surround, the test color's appearance will change gradually from the surface-color to the aperture-color mode.[13] There is a range of luminance, described as "fluorence" by Evans,[8] where the test color appears to be a mixture of surface and aperture color. Thus the transition point from the surface-color to the aperture-color mode may not be clearly defined. There might have been some differences in the criteria for the level of the luminosity threshold as measured by the previous investigators, and therefore those results were not consistent.[7–9]

In the present paper we aim first to reveal how a test color changes its appearance from the surface-color to the aperture-color mode, depending on the chromaticity in the entire area of the CIE 1931 $(x, y)$ chromaticity diagram. The second purpose of our study is to show the relationship between brightness of a test color and the transition luminance from the surface-color to the aperture-color mode. In experiment 1, the observer estimated the mode of appearance for a test color of constant luminance presented in the center of a surrounding white field. The appearance of the test color could be changed from the surface to the aperture mode or vice versa by decreasing or increasing the luminance of the surrounding white field. In experiment 2, the brightness-to-luminance (B/L) ratio was measured for test colors of equal luminance. The B/L ratio was compared with estimation scores of modes for the same chromaticity. In experiment 3, to directly compare luminance, brightness, and appearance modes of a test color, we obtained the spectral luminous efficiency functions by using three different criteria: flicker photometry, heterochromatic brightness

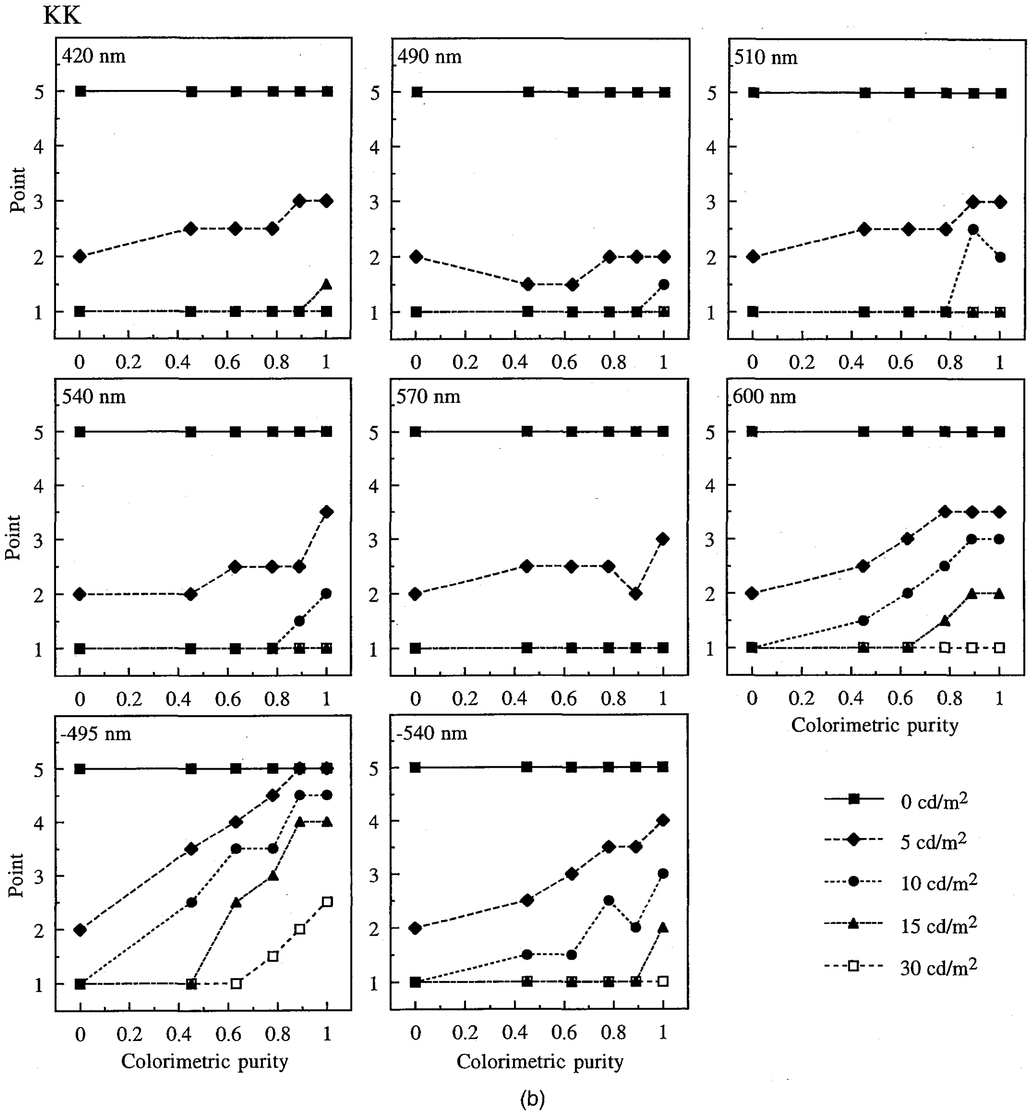


Fig. 1. Mode-estimation point as a function of colorimetric purity for observers MS and KK. The dominant wavelength is shown in each panel. The symbols indicate luminances of the surround stimulus.

matching, and upper-limit luminance adjustment for the surface-color mode.

## 2. METHOD

### A. Apparatus

We built a three-channel optical system with a 1 kW xenon arc to produce two monochromatic lights and a white light. The monochromatic lights were made by interference filters with half-bandwidths of ~10 nm. The white light and the two monochromatic lights illuminated a diffusing white surface ($MgO_2$) and were additively mixed there. The mixed light reflected from the white surface passed through a stimulus aperture in a white board placed in front of the observer. The size of the aperture was 5 mm in experiments 1 and 2 and 10 mm in experiment 3. The observer looked at this stimulus aperture. A projector over the observer's head illuminated the white board. The surface of this white board was the stimulus surround. The stimulus aperture was filled only with the mixed light.

The viewing distance was 30 cm. The test stimulus size was 1 deg of visual angle in experiments 1 and 2 and 2 deg in experiment 3. A shutter blade, painted with the same white as the surround, was placed in front of the test stimulus such that between trials the observer saw the white in the center. The surround white stimulus was a 30-deg-diameter circle in experiments 1 and 2 and a 15-deg-side square in experiment 3. The position of the observer's head was fixed with a bite board.

### B. Stimulus

In experiment 1 the luminance of the test stimulus was a constant 10 cd/m$^2$. The CIE 1931 $(x, y)$ chromaticity coordinates of the white test stimulus were (0.307, 0.353). Monochromatic lights with six dominant wavelengths, 420, 490, 510, 540, 570, and 600 nm, and two complementary dominant wavelengths −495 and −540 nm, were mixed with the white stimulus to produce the test stimuli. The colorimetric purities of the test stimuli were 0, 0.45, 0.63, 0.89, and 1.0. The CIE 1931 $(x, y)$ chromaticity coordinates of the surround white stimulus were (0.312, 0.372), and the luminance of the stimulus was set at 0, 5, 10, 15, and 30 cd/m$^2$.

In experiment 2 we used the same 41 test stimuli, but the luminance of the surround white stimulus was fixed at 10 cd/m$^2$. In experiment 3 the test stimulus was selected from 440–660-nm monochromatic lights in 20-nm increments. The luminance of the surround white stimulus and the reference white stimulus was 5 cd/m$^2$.

### C. Procedure

#### 1. *Experiment 1*

In experiment 1 the observer adapted to the surround white stimulus for 5 min before a trial started. During a trial the test stimulus was presented for 3 s; then the observer estimated in which mode the stimulus appeared to be. When the surround was intense enough the test stimulus appeared to be completely in the surface-color mode, whereas when the surround was dark enough the test stimulus appeared to be completely in the aperture-color mode. When the surround was neither intense nor dark, the test stimulus appeared to have characteristics of both the surface and the self-luminous colors. This transition-state appearance of the two modes occurred in some part of the intensity range of the surround white.

The observer assigned one point to a stimulus that appeared to be in the complete surface-color mode and five points to one in the complete aperture-color mode. The stimulus appearance between the surface-color and the aperture-color modes was divided into three levels. Two points were assigned to the stimulus appearance toward the surface-color mode, three points for equal modes, and four points toward the aperture-color mode. The observer used five levels over the whole stimulus appearance in this estimation method. A stimulus given more points was estimated to be more like the self-luminous color, and that given fewer points appeared more like the surface color. The observer could see a stimulus repeatedly before responding.

In each trial a stimulus was chosen randomly from the 41 test stimuli provided. A session consisted of 41 trials in one of 5 surround-intensity conditions. The observer repeated two sessions for the same surround-intensity condition. Two male observers with normal color vision, KK and MS, 22 and 27 years old, respectively, participated in this experiment.

#### 2. *Experiment 2*

In experiment 2 the observer performed brightness matching between the test stimulus and the surround white (10 cd/m$^2$). We employed the staircase method for this brightness matching. The test stimulus was presented for 3 s; then the observer reported whether the test stimulus was brighter or darker than the surround white. In each trial, two staircase series, one starting from a high-luminance level and the other from a low-luminance level, were randomly selected. In each series, the last four turning points of the observer's responses were averaged to yield a matched luminance of the test stimulus. Two matched luminances were obtained in a trial. Two trials were repeated, so the result was a mean of four matched luminances. The same two male observers as in experiment 1 participated in this experiment.

#### 3. *Experiment 3*

In experiment 3 the observer adapted to the surrounding stimulus for 1 min; then a trial started. The observer's head was fixed by a bite board, and his or her right eye was used. In each trial two adjustments were made for a wavelength, and a session consisted of 24 adjustments for all 12 wavelengths. Three criteria were used in experiment 3: minimum flicker, equal brightness, and mode transition. In each session one of the three criteria was employed. For any criterion, the observer adjusted the test light until the criterion was reached.

For the minimum-flicker criterion, the test and the reference white were alternated at 18 Hz. The observer carried out flicker photometry between the test and the reference white. Ten settings were obtained for a wavelength in five sessions. For the equal-brightness criterion, the test and the reference white were alternated at 1 Hz. The observer performed successive brightness matching between the test and the reference white. Twenty settings were obtained for a wavelength in ten sessions.

For the mode-transition criterion, the observer adjusted the intensity of the test light such that the light just began to appear in the transition state of the surface-

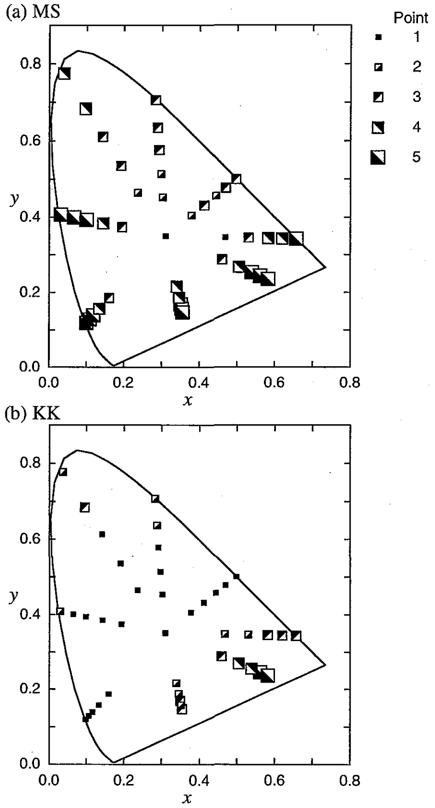
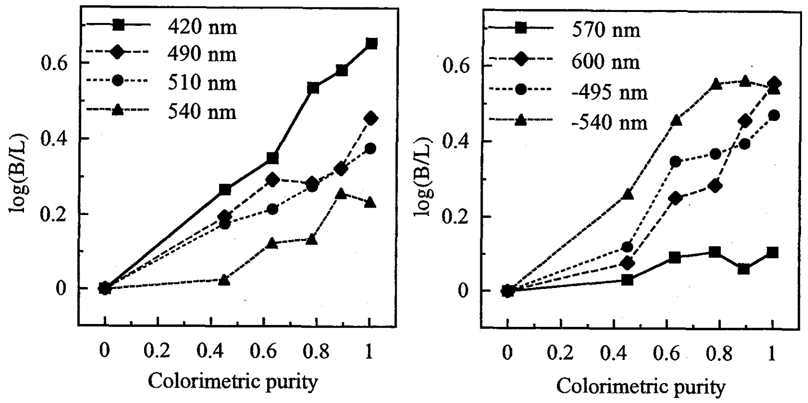


Fig. 2. Mode-estimation points on the CIE 1931 $(x, y)$ chromaticity diagram for a surround luminance of 10 cd/m$^2$ for observers MS and KK. The point values were rounded off to whole numbers.

(a) MS



(b) KK

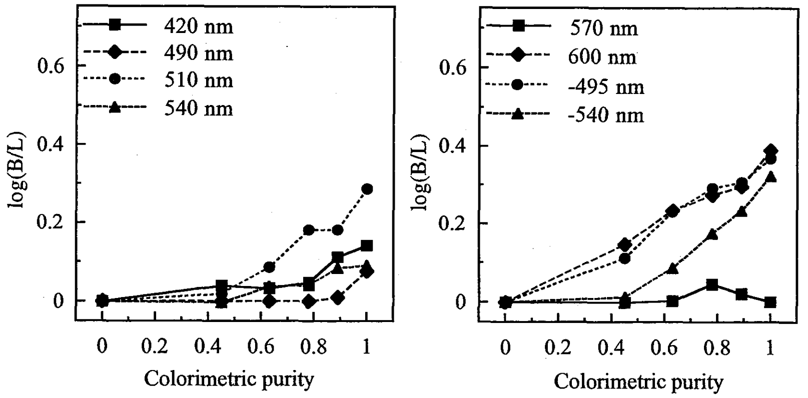


Fig. 3. Log (B/L) as a function of colorimetric purity for observer MS and KK. The surround luminance was 10 cd/m$^2$. The symbols indicate dominant wavelengths.

color to the aperture-color mode. Twenty settings were obtained for a wavelength in ten sessions.

Four observers (TM, male, 23 years old; YY, male, 28 years old; TS, male, 24 years old; and YI, female, 25 years old) with normal color vision participated in this experiment.

## 3. RESULTS

### A. Experiment 1

Figures 1(a) and 1(b) show the mode-estimation point as a function of colorimetric purity of the stimulus for the observers MS and KK, respectively. In each panel the dominant wavelength is shown at the upper-left corner, and different symbols indicate luminances of the surround stimulus. In the two repetitions the same estimation points were obtained in 55% and 72% of all stimuli for MS and KK, respectively. More than 90% of the stimuli had one point difference between two repetitions for both observers.

When the luminance of the surround was dark (0 cd/m$^2$), all test stimuli had 5 points for both observers, which indicated that the stimuli appeared to be completely in the aperture-color mode. In the surround-luminance conditions of 5–30 cd/m$^2$, almost all points increased with colorimetric purity in Figs. 1 (a) and 1(b). This tendency is clear for the short and long dominant wavelengths, 420 and 600 nm, and for the complementary dominant wavelengths, −495 and −540 nm. The middle dominant wavelengths, 490, 510, 540, and 570 nm, do not have a strong tendency to increase in Fig. 1(b) but an increase is still clearly shown in Fig. 1(a).

As the luminance of the surround increased, the estimation point decreased, but not uniformly, for all colorimetric purities. When the luminance of the surround was 30 cd/m$^2$, which was much higher than that of the test stimulus, the estimation point of the white (colorimetric purity, 0) stimulus was 0, indicating that the white stimulus appeared to be completely in the surface-color mode. However, some stimuli with higher purities had points of 2–3, which means that those stimuli appeared to be not entirely in the complete surface-color mode but partially in the aperture-color mode.

We replotted the estimation point for the surround luminance of 10 cd/m$^2$ on the CIE 1931 $(x, y)$ chromaticity diagram (Fig. 2) to show how the points of the stimuli changed according to the chromaticity coordinates. The symbol sizes in Fig. 2 represent the point values. Figures 2(a) and 2(b) show the data for observers MS and KK, respectively. It is again clearly shown that test stimuli tend to appear to be in the aperture-color mode as purity increases.

### B. Experiment 2

In experiment 2 we divided the matched luminance of a test stimulus by the luminance of the surround white (10 cd/m$^2$) to calculate the B/L ratio. Figures 3(a) and 3(b) show log (B/L) of all test stimuli for observers MS and KK, respectively. The mean standard deviations of brightness matching across all test stimuli are 0.04 and 0.03 for MS and KK, respectively. As the colorimetric purity increases, log (B/L) increases, which indicates that test stimuli appear brighter with higher purities than those with lower purities. These results are consistent with B/L ratios reported previously.[14–21] Observer MS found larger values of log(B/L) for high purities of all dominant wavelengths than did observer KK.

To compare the log(B/L) value with the mode-estimation point, we took the log(B/L) value from Fig. 3 and the estimation point at 10 cd/m$^2$ from Fig. 1 for a stimulus with the same colorimetric purity and dominant wavelength. In Figs. 4(a) and 4(b), log(B/L) of the test stimulus is plotted as a function of the estimation point for observers MS and KK, respectively. It turns out that log(B/L) increases almost linearly with the estimation point for all wavelengths except 420 and 490 nm for observer KK. In these cases the log(B/L) values are quite low, and estimation points are all 1 s. The linear relationship between log(B/L) and the estimation point for both observers seems to indicate significant correlation between mode and brightness.

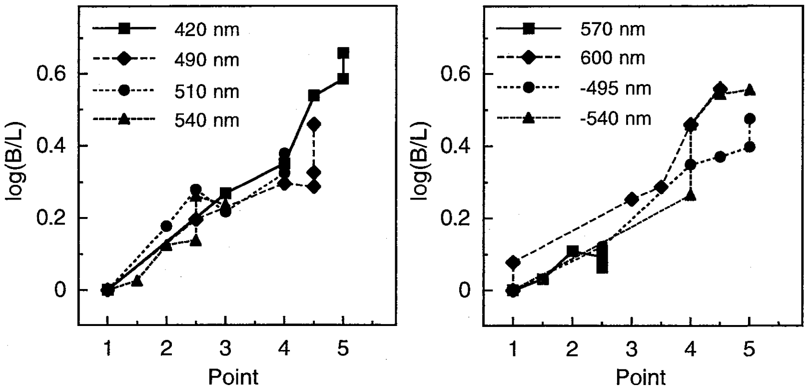
### C. Experiment 3

In Fig. 5 the log reciprocal of the monochromatic light intensity that produces each criterion is plotted as spectral sensitivity functions of four observers. The data obtained by the minimum flicker, the equal brightness, and the mode transition criteria are represented as solid triangles, solid squares, and open circles, respectively. Dashed curves with no symbols show the CIE $V(\lambda)$ function. The vertical positions of the three curves for each criterion are not normalized, so we can compare the relative heights of the three sensitivity functions. We normalized the minimum flicker and the CIE $V(\lambda)$ functions to 0 at 560 nm. The error bars show the standard deviations of all adjustments for each criterion.

It is shown in Fig. 5 that the minimum-flicker functions coincide quite well with the $V(\lambda)$ function for all observers, which confirms that the present minimum-flicker function represents the luminance of the stimuli. The equal-brightness functions are higher than the luminance functions, and the differences between these two functions are larger for shorter and longer wavelengths. This brightness-luminance discrepancy for monochromatic light is consistent with the findings of previous investigations.[20,21]

The mode function turned out to be similar in shape to that of the brightness function for all observers, although

(a) MS



(b) KK

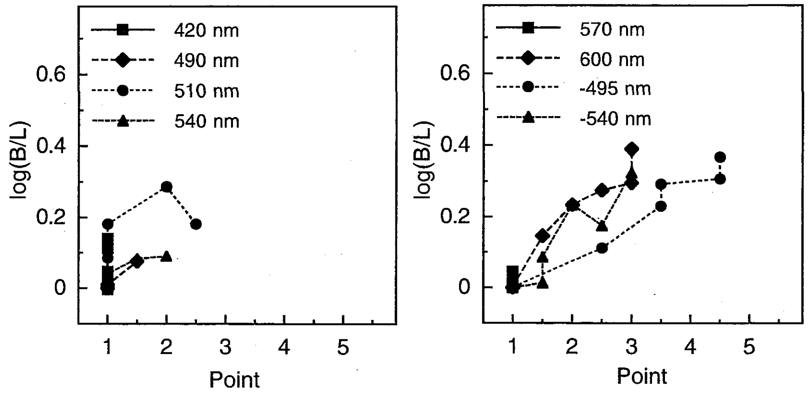


Fig. 4. Log (B/L) as a function of mode estimation point for observers MS and KK. The surround luminance was 10 cd/m$^2$. The symbols indicate dominant wavelengths.

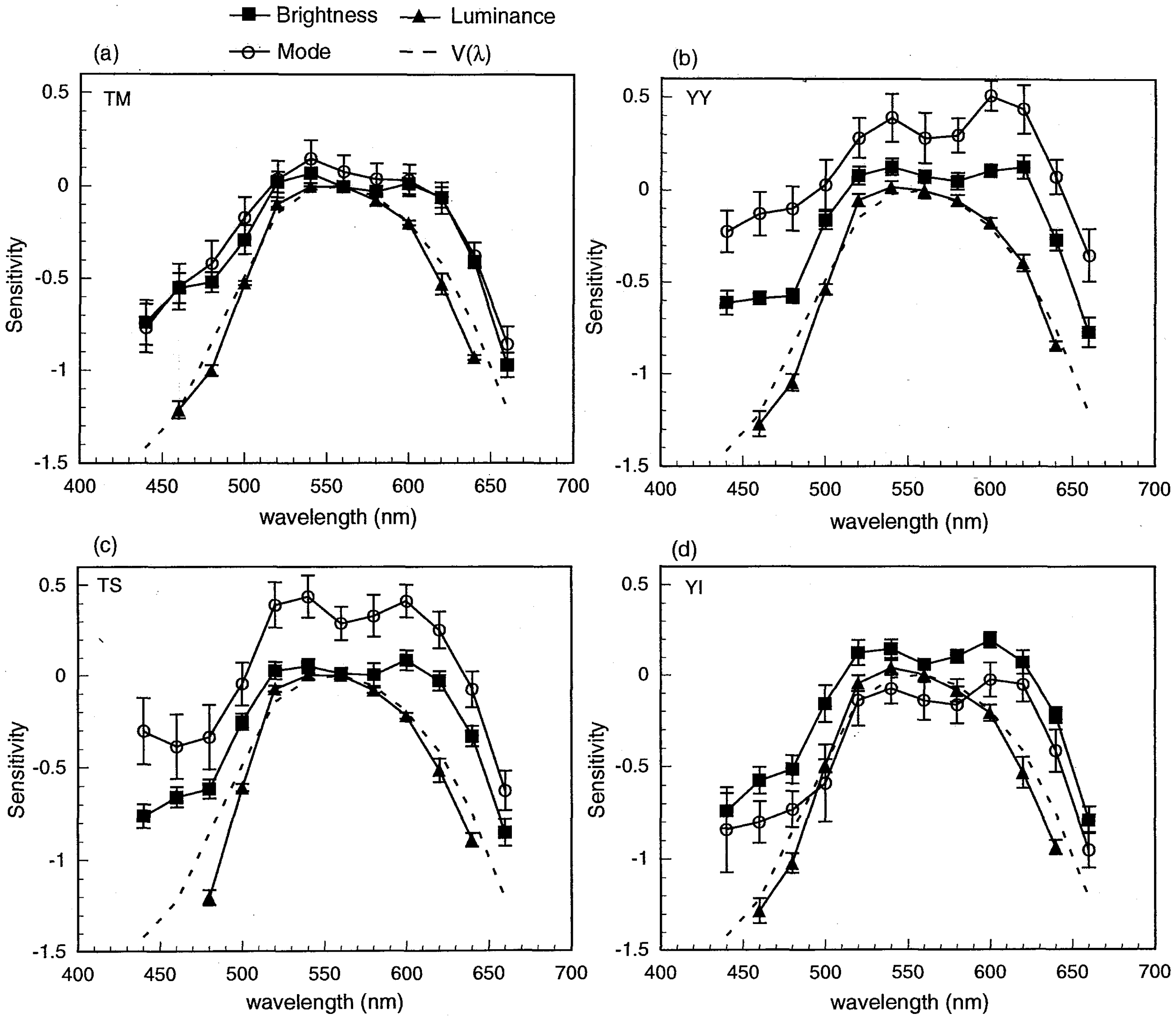


Fig. 5. Spectral sensitivity functions obtained by use of three criteria: minimum flicker (luminance), brightness matching, and mode transition. Error bars represent the standard deviations of the points.

its relative height is different among observers. The mode function is highest for observers TM, YY, and TS, but is lower than the brightness function for observer YI. To compare the shape of the mode function with that of the brightness function, we subtracted the luminance function from the brightness function and the mode function and the resultant two functions [B/L function and mode-to-luminance (M/L) function] are plotted in Fig. 6 as solid squares and open circles, respectively. The B/L and M/L functions were normalized to 0 at 560 nm. The M/L functions are quite similar to the B/L functions for all observers. At the middle wavelengths these two functions take minimum values, and at the short and long wavelengths they have larger values than 0.5, similarly to the saturation function of monochromatic lights.[20] The dotted curves in Fig. 6 are the optimal color functions, as we explain in Section 4.

## 4. DISCUSSION

Experiment 1 demonstrated that the appearance modes of colored lights change with colorimetric purity. These results confirmed previous reports that the luminosity threshold depended on the chromaticity of test colors. We found that colored lights of equal luminance gradually changed in appearance from the surface-color to the aperture-color mode as the luminance of the surrounding stimulus decreased or as the colorimetric purity of the test color increased, as shown in Figs. 1 and 2. This property holds for all stimuli of eight dominant wavelengths over the entire area of the chromaticity diagram.

In experiment 2 we found that the B/L ratio increased with colorimetric purity, as shown in Fig. 3. This increase in the B/L ratio for equal-luminance colored lights is consistent with the previous data. Here we noticed that the increase in the B/L ratio was quite similar to the change in the estimation point from the surface-color to the aperture-color mode, as shown in Fig. 4. This similarity would indicate that brightness, not luminance, of a color is the factor that determines the mode transition.

In experiment 3 we directly tested which visual attribute for the stimulus intensity—brightness or luminance—determined the mode transition of a color.

As a result we obtained that the mode function had the same shape as that of the brightness function for all observers, as shown in Figs. 5 and 6. The brightness of colored lights of equal luminance is not necessarily equal. This phenomenon is the well-known brightness–luminance discrepancy for colors. If the mode transition were determined by luminance of stimuli, we should have obtained a mode function similar to the luminance (minimum-flicker) function. However, our results indicate that the mode function has the same shape as that of the brightness function. Therefore we can reasonably conclude that the brightness of a colored light is the determining factor in the mode transition.

The mode functions are different in relative height among observers (Fig. 5). The criteria might be inconsistent among observers since there is some range of luminance of colored light in which the mode transition occurs so that the colored lights appear to be partly in the surface-color and partly in the aperture-color modes. Observers YY and TS might use the criterion that the stimuli have just appeared in the transition state. Observer YI, however, might use the criterion that the stimuli have fully appeared in aperture-color mode. Observer TM might employ a criterion somewhat between these two. These criterion differences could yield the present sensitivity differences in the mode functions. The brightness and luminance functions are consistent among observers. It is likely that the criteria of equal brightness and minimum flicker were stable among observers.

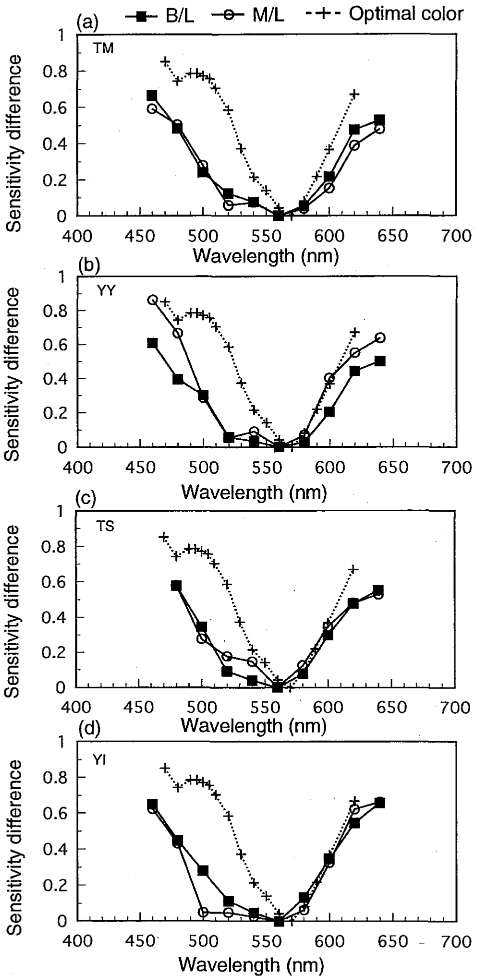


Fig. 6. Log(B/L) and log(M/L) as functions of wavelength. We determined each function by subtracting the luminance function from the brightness and the mode functions shown in Fig. 5. The B/L and M/L functions were normalized to 0 at 560 nm. Dotted curves are the optimal color functions calculated form the maximum visual efficiency. See text for details. Observers TM, YY, TS, and YI.

Evans[22] discussed the $G_0$ threshold in relation to brilliance and chromatic strength. When a stimulus was at the $G_0$ threshold with respect to its surround, it was said that a "brilliance match" was obtained. He used the word "brilliance" to designate a perceptual variable that was weaker than the reference stimulus when grayness was present and stronger when fluorence was seen. When a brilliance match was reached between a monochromatic stimulus and a white surround, the luminance of the central stimulus was below that of the surround by a factor that was characteristic of the wavelength. This factor was inversely proportional to the chromatic strength of the stimulus. Thus the $G_0$ threshold, the brilliance, and the chromatic strength seem to be conceptually similar to the mode-transition level, the brightness, and the B/L ratio in the present study, respectively.

It would be reasonable to have a hypothesis that the visual system in the brain can estimate the reflectance of a surface to explain the color constancy phenomenon.[23] We assume that the visual system might know the limit of the reflectance for a given color. Here we use "lightness" as a visual equivalence to a physical "reflectance." When the visual system judges lightness of a color as less than the lightness limit for that color, which is physically determined by the optimal color, the color appears to the observer to be in the surface-color mode. When the visual system judges that the lightness of the color exceeds the limit, the color appears to be no longer in the surface-color mode but in the aperture-color mode. In the case of an achromatic color the lightness limit is 100. For a chromatic color the lightness limit depends on the color's chromaticity, known as the maximum visual efficiency[24,25] or the optimal color locus.[26] More-saturated colors have smaller values of the lightness limit.

Here there is a fundamental question of whether it is possible for the visual system in the brain to known the lightness limit of a given color. We assume that the brightness of a given color is a visual estimate of the lightness limit of that color. As the luminance of a colored stimulus increases, the brightness of the stimulus increases, and when its brightness reaches the specific level defined for that color, relative to the surround, the visual system makes the decision that this stimulus is no longer of a surface but is self-luminant. Then the stimulus appears to the observer to be in the aperture-color mode. This limit level of brightness for the surface-color mode is a visual representation of the lightness limit of the stimulus.

In Fig. 6 the maximum visual efficiencies of colored stimuli with excitation purity of 0.9 are plotted for each dominant wavelength as dotted curves. We referred to MacAdam[25] to obtain these values. The data points are shown as the logarithmic function of the reciprocal ratio

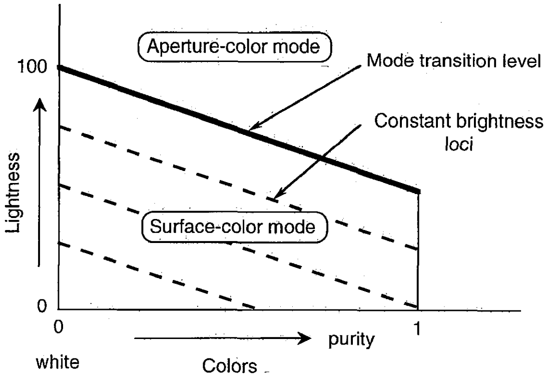


Fig. 7. Hypothetical relationship among lightness, brightness, and the mode-transition level, schematically drawn. The ordinate represents lightness, and the abscissa represents purity of colors. The thick solid line shows the mode-transition level determined by brightness of colors. Above this line, colors appear in the aperture-color mode, and below it they appear in the surface-color mode. The dashed lines show constant brightness loci.

between the maximum visual efficiency of each stimulus and that of the stimulus with 570-nm dominant wavelength. This function of optimal colors turns out to be quite similar to the B/L and the M/L functions, which would support our assumption that the brightness and the mode-transition threshold are related to the locus of the optimal color.

Figure 7 illustrates hypothetical relationships among lightness, brightness, and the mode-transition level. The ordinate represents lightness, and the abscissa represents purity of colors. The thick solid line shows the mode-transition level determined by brightness of colors. Above this line, colors appear to be in the aperture-color mode, and below this line they appear to be in the surface-color mode. The dashed line show the loci of constant brightness. The mode-transition level corresponds to the optimal color locus. The concept of relating lightness to optimal colors was discussed previously.[27] The degree of darkness according to the DIN color system was defined as the ratio between the luminance reflectance of the chromatic color and the luminance reflectance of the optimal color of the same chromaticity. The darkness of the DIN color system here is a perceptual attribute similar to the brightness.

It has been puzzling that a chromatic stimulus appears to be brighter than an achromatic stimulus of the same luminance and that more-saturated colors are brighter than less-saturated colors of equal luminance. Previous color-vision models assumed that the chromatic responses from the opponent-color channels were added to the response from the luminance channel to yield brightness, causing more-saturated colors of equal luminance to appear brighter.[28,29] In our assumption the visual system of an observer estimates the lightness of a color by comparing its brightness and the limit level of brightness. For this task to be performed, more-saturated colors must appear brighter than less-saturated colors of the same lightness according to the optimal color loci. It seems most likely that the brightness–luminance discrepancy is a phenomenon that results from estimation of lightness limits of colored stimuli by the visual system.

## ACKNOWLEDGMENTS

We thank D. H. Brainard and the anonymous reviewers for their critical comments.

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