Individual differences of the contribution of chromatic channels to brightness

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Perceived brightness is considered to be a combined consequence of outputs of the luminance channel and the chromatic channels in the visual system. The differences of logarithmic spectral luminous efficiencies between heterochromatic brightness matching and flicker photometry that were obtained from 16 subjects were examined by using principal component analysis. The luminous-efficiency difference between the two methods is described by only two principal components. Individual characteristics of the contribution of chromatic channels to brightness can be specified by measuring luminous efficiencies at 470 and 660 nm.

INTRODUCTION

The problem of the discrepancy between the terms luminance and brightness has been discussed for two decades.[1,2] More-saturated colors, such as red and blue, are perceived to be brighter than less-saturated colors, such as white and yellow, when they are equated in luminance. This is sometimes referred to as the Helmholtz–Kohlrausch effect.[3,4] The difference between luminance and brightness is attributable to their definitions. Luminance is defined by

$$L_v = K_m \int L_{e,\lambda} V(\lambda) \mathrm{d}\lambda \,, \qquad (1)$$

where L_v is luminance, $L_{e,\lambda}$ is the spectral radiance, $V(\lambda)$ is the CIE photopic luminous-efficiency function, and K_m is the maximum spectral luminous efficacy. The CIE $V(\lambda)$ function is an average of the data for a large number of observers. The data in that study were mainly measured by flicker photometry.[5] In flicker photometry a minimum flicker is determined at the flicker frequency between a critical color fusion frequency and a critical fusion frequency. The criterion of the minimum flicker is therefore considered to be mediated by the achromatic or so-called luminance channel and to be unaffected by the chromatic channel. On the other hand, brightness is evaluated by direct brightness matching. Since brightness matching is static, the criterion of brightness seems to be evaluated by not only the luminance channel but also the chromatic channels.

The contribution of chromatic channels to brightness is also based on another fact, that the spectral luminous-efficiency function obtained by heterochromatic brightness matching has a broader curve than that obtained by flicker photometry[6–13] and that the difference between the two curves is quite similar to the saturation-discrimination function obtained by measurements of just-noticeable colorimetric purity.[14–16] Since the saturation-discrimination function is assumed to reflect the ratio of the amount of activities of the chromatic channels to that of the luminance channel,[17,18] the difference between the two curves is considered to be related to the contribution of the chromatic channels to brightness.[18–20]

The contribution of the chromatic channels to brightness is also examined by the additivity test of brightness. Flicker photometry obeys the additivity law,[21,22] whereas heterochromatic brightness matching does not.[23–26] For example, when two opponent colors, red and green, are mixed in the brightness-matching procedure, the additivity fails in a manner that reduces the brightness. The outputs of the chromatic channels are at a minimum and cause the reduction-type additivity failure. For this reason we consider the difference between the spectral luminous-efficiency function measured by heterochromatic brightness matching and that obtained by flicker photometry to be the contribution of the chromatic channels to brightness.

Another problem of brightness perception is the individual variations of luminous efficiencies. The CIE TC1-02 report[27] presents an average of the data of the spectral luminous-efficiency functions based on brightness matching for point sources, 2° and 10° fields. Ikeda and Nakano[28] reported that the individual variations of the 2° data that are normalized at 570 nm are as much as 1.8 log units (~60 times) at the short-wavelength region. Yaguchi and Ikeda[29] also pointed out the individual variations of brightness perception. They measured the luminous-efficiency functions for brightness matching from four observers. The bichromatic additivity test was also examined for the same observers. The reduction-type additivity failure is particularly marked for the observer whose luminous-efficiency curve is broad. Yaguchi and Ikeda believe that one of the causes of individual variations may be the difference of the contribution of the chromatic channels to brightness. Palmer[30] measured luminous-efficiency functions for brightness with a 10° field from 24 observers. He classified three types of observer from the shape of the luminous-efficiency function. Type 1 observers' luminous-efficiency curves resembled the CIE $\bar{y}_{10}(\lambda)$ color-matching function. Type 2 observers had a double-peaked function, which failed the additivity law. Type 3 observers were more additive, although their curves were broader

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than $\bar{y}_{10}(\lambda)$. Ikeda *et al.*[31] analyzed the luminous-efficiency functions from 51 observers for a 2° field and 70 observers for a 10° field by principal component analysis. They found that the luminous-efficiency functions for brightness that were obtained from any observer can be composed with two components.

In the present paper the logarithmic ratio of luminous efficiencies obtained by heterochromatic brightness matching to those obtained by flicker photometry [log(HBM/FP)] are analyzed, and a simple test of specifying the individual characteristics for brightness is proposed.

EXPERIMENTS

The experiments were performed by a conventional Maxwellian-view system with three channels. Two of the three channels provided a reference stimulus and a monochromatic test stimulus. These two stimuli were presented in a 2° bipartite field in the direct brightness matching and in a 2° full field in the flicker photometry. Another channel provided a 4° white field for adapting. The wavelength of the test field was obtained with a monochromator that had a half-bandwidth of ~3 nm. The retinal illuminance of the reference field was 100 Td, and the chromaticity coordinates were $x = 0.33$ and $y = 0.34$.

In both methods a white adapting field was presented to avoid the effect of chromatic adaptation. The retinal illuminance and the chromaticity coordinates of the adapting field were the same as those of the reference field. The test and reference fields were presented for a duration of 7 s, and then the adapting field was presented for 3 s. This procedure was repeated until a brightness match or a minimum flicker was obtained. Brightness matches and minimum flicker were determined by the method of adjustment. The flicker frequency for flicker photometry was 18.5 Hz. Five adjustments were carried out successively for each test wavelength. Sixteen observers with normal color vision checked by the Ishihara plates participated in the experiment. The subjects ranged in age from 22 to 40 years.

RESULTS

The upper graphs of Fig. 1 show the spectral luminous-efficiency curves by flicker photometry (open squares) and those by direct brightness matching (filled circles) obtained from four observers. The solid curves represent the CIE $V(\lambda)$, and the dashed curves show Judd's modified CIE $V(\lambda)$, which is now called the 1988 CIE $V_M(\lambda)$.[32] The luminous efficiencies that were obtained by flicker photometry agree with the CIE $V(\lambda)$ at the middle- to long-wavelength region. The differences between the present data and the CIE $V(\lambda)$ or the 1988 CIE $V_M(\lambda)$ were observed for wavelengths shorter than 450 nm. One plausible explanation of the discrepancy could be the individual difference of the contribution of the short-wavelength-sensitive cone. This explanation, however, contradicts the evidence that the short-wavelength-sensitive cone does not participate in the flicker photometry.[33] Another possibility is the individual difference of the spectral absorption of the lens.

The lower graphs of Fig. 1 show log(HBM/FP). The luminous efficiencies obtained by direct brightness matching show higher sensitivity than do those obtained by flicker photometry in the short- and long-wavelength region except for observer YY, who shows no significant difference between the two methods. Figure 2 shows log(HBM/FP) for all 16 observers.

PRINCIPAL COMPONENT ANALYSIS

Figure 2 shows large individual variations. To know what causes the individual variations, the differences between the logarithmic values of the spectral luminous efficiencies of direct brightness matching and flicker photometry shown in Fig. 2 were examined by principal component analysis with the use of the statistical analysis system. As a result, the contribution factor was 91.9% for the first component and 5.4% for the second component. The cumulative contribution factor was 97.3%, which means that the difference between two methods can be represented by only two principal components. Figure 3 shows the spectral characteristics of the first eigenvector (open circles) and the second eigenvector (filled circles). The first eigenvector implies the mean value of log(HBM/FP) from 16 observers. Figure 4 shows the comparison between the first eigenvector and the saturation-discrimination functions by Wright and Pitt,[14] Priest and Brickwedde,[15] and Kimura.[16] To compare the relative shapes of those curves, the eigenvectors are multiplied by 5. The shape of the spectral characteristics of the first eigenvector resembles the saturation-discrimination function. The first principal component therefore could be related to the overall contribution of chromatic channels, that is, the contribution of both red/green and yellow/blue chromatic channels to brightness. The second eigenvectors show positive values in the short-wavelength region and negative values in the long-wavelength region. The second principal component changes the balance of the amount of the contribution of the chromatic channel at the short-wavelength region and that at the long-wavelength region.

The spectral characteristics of the logarithmic ratio of luminous efficiencies obtained by brightness matching to those obtained by flicker photometry are expressed as

$$D_i(\lambda) = k_{1i}E_1(\lambda) + k_{2i}E_2(\lambda), \qquad (2)$$

where $D_i(\lambda)$ is the difference of luminous efficiencies between the two methods for observer i, $E_1(\lambda)$ and $E_2(\lambda)$ are the first and second eigenvectors, respectively, k_1 is the first-component score, and k_2 is the second-component score. $E_1(\lambda)$ and $E_2(\lambda)$ are independent of the observer. Figure 5 shows the distribution of the first- and second-component scores for individuals. These component scores can be used to specify the individual characteristics in the contribution of the chromatic channel to brightness. The predicted curves that use Eq. (2) are shown as solid curves in Fig. 2. These curves show good agreement with the experimental data for all observers.

TEST OF SPECIFYING INDIVIDUAL CHARACTERISTICS IN HETEROCHROMATIC BRIGHTNESS MATCHING

The present analysis shows that if we know only two component scores for an individual, his/her characteristics in

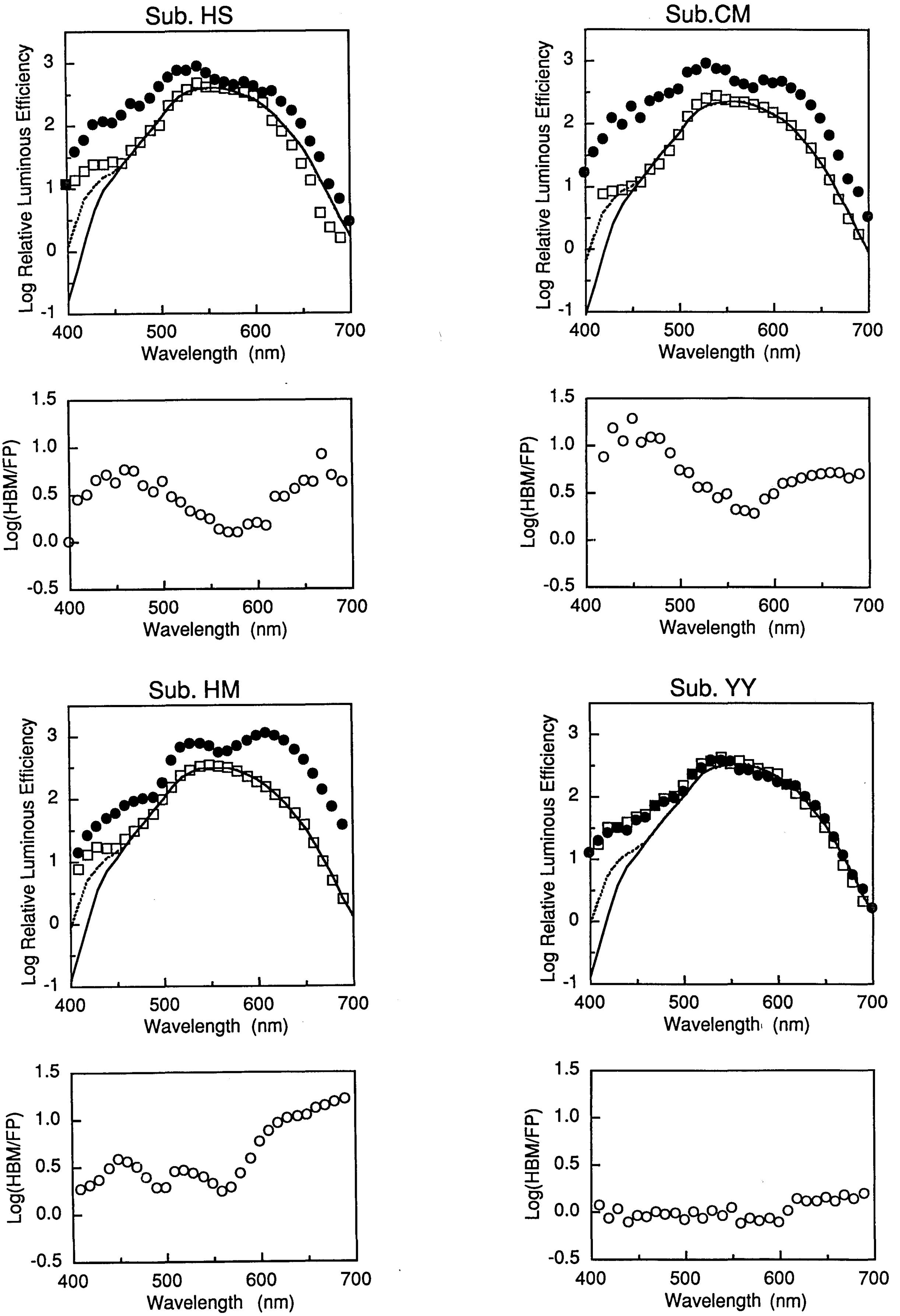

Fig. 1. Upper graphs, luminous-efficiency functions obtained by direct brightness matching (filled circles) and those obtained by flicker photometry (open squares) for four observers. Lower graphs, the differences between two methods.

heterochromatic brightness matching can be specified. Although the individual component scores are obtained from the individual spectral luminous-efficiency function, considerable work is required for one to measure a whole spectral range of the luminous-efficiency function. For an application field, a simple test to check individual char-

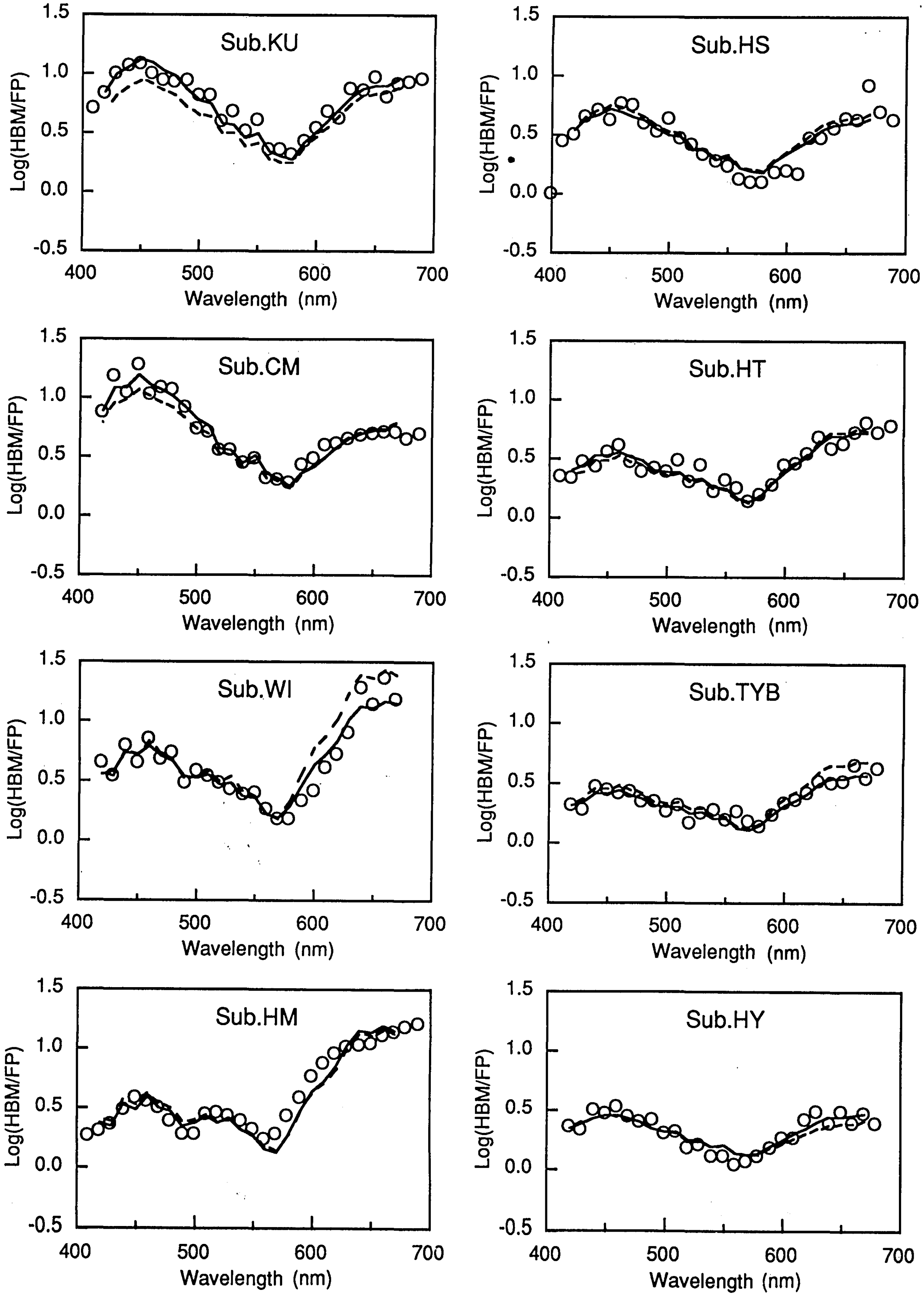

Fig. 2. Continues on facing page.

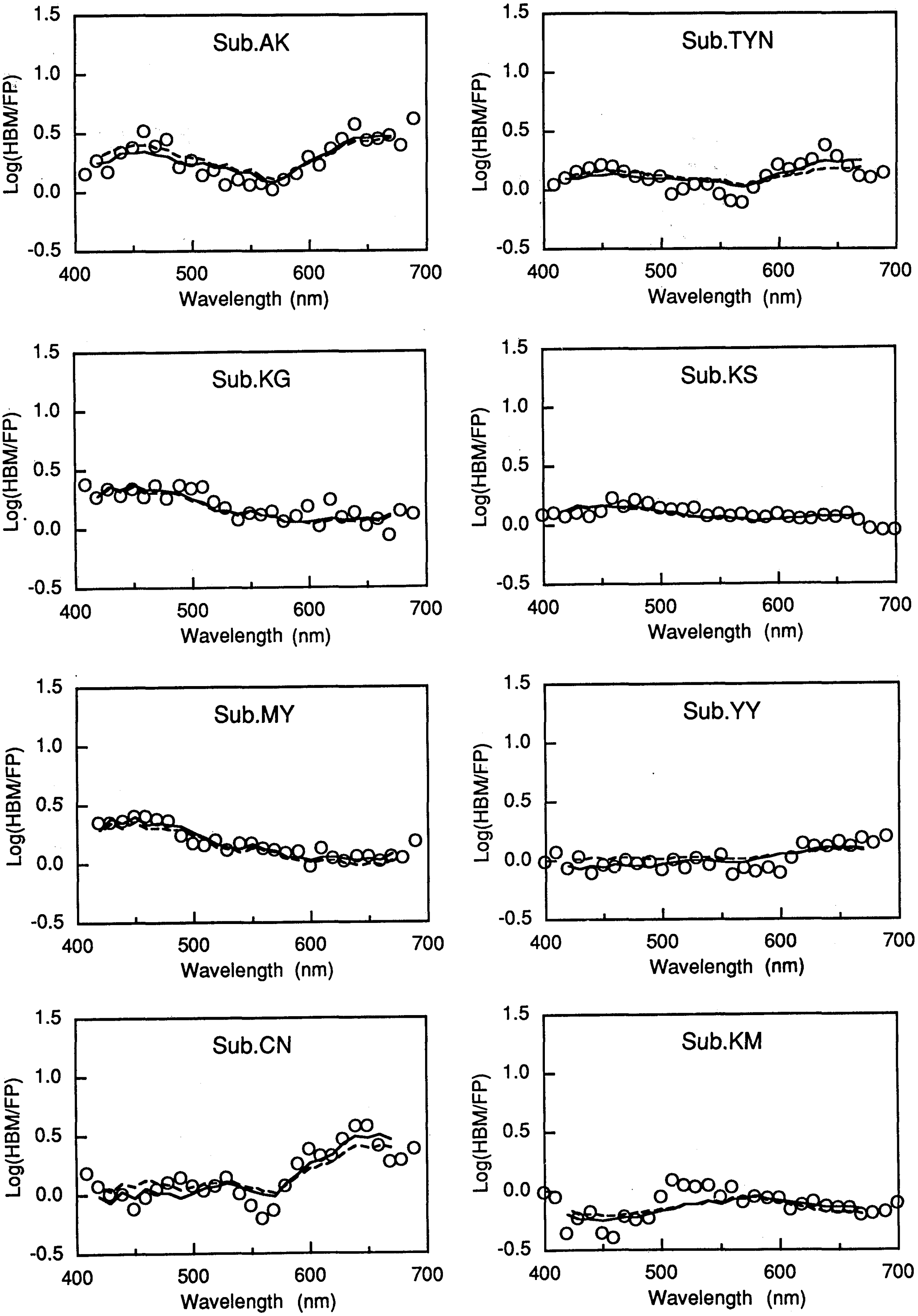

Fig. 2. Differences between the logarithmic luminous efficiencies obtained by direct brightness matching and those obtained by flicker photometry. Open circles are experimental data, solid curves are derived by linear combination of two eigenvectors, and dashed curves are predicted by linear combination of two eigenvectors, except that two-component scores are estimated with luminous efficiencies at 470 and 660 nm.

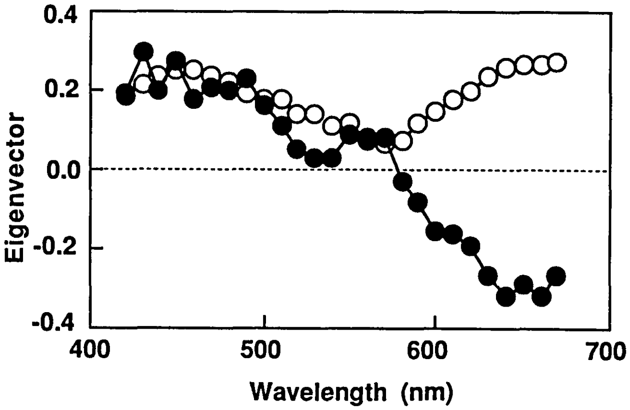

Fig. 3. Spectral characteristics of the first eigenvectors (open circles) and the second eigenvectors (filled circles).

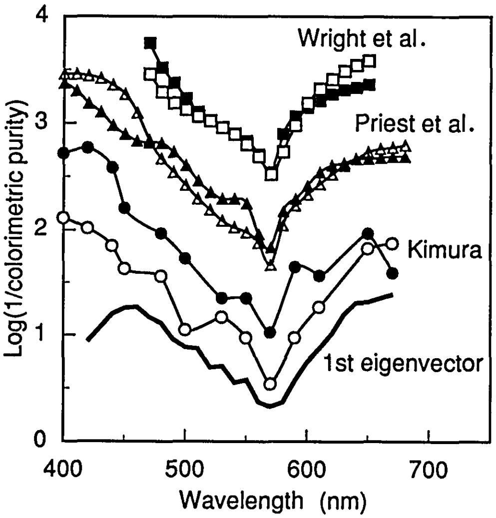

Fig. 4. Comparison between the saturation-discrimination function[14–16] and the first eigenvector. The first eigenvectors are multiplied by 5.

acteristics for brightness matching is preferred. For this reason we tried to predict two-component scores by using the luminous efficiencies at two representative wavelengths. Figure 6(a) shows the relation between the first-component score and the sum of log(HBM/FP) at 470 nm and that at 660 nm. The correlation coefficient was $r^2 = 0.997$. Similarly, Fig. 6(b) shows the relation between the second-component scores and the difference of log(HBM/FP) at the same two wavelengths. The correlation coefficient was $r^2 = 0.870$. In both cases high correlation coefficients were obtained. Two-component scores for individuals can be estimated by using the regression lines described as

$$k_{1i}' = -0.02 + 1.98[D_i(470) + D_i(660)], \qquad (3)$$

$$k_{2i}' = -0.06 + 1.66[D_i(470) - D_i(660)], \qquad (4)$$

where $D_i(470)$ and $D_i(660)$ is log(HBM/FP) at 470 and 660 nm, respectively. The estimated scores k_{1i}' and k_{2i}' are then substituted for k_{1i} and k_{2i}, respectively, in Eq. (2). The predicted curves by this procedure are shown as dashed curves in Fig. 2. Again, these curves show good agreement with the experimental data.

The present analysis is quite consistent with the analysis by Ikeda *et al.*[31] They found that luminous efficiencies at only two wavelengths, 460 and 640 nm, are required for one to predict the spectral luminous-efficiency curve for heterochromatic brightness matching.

CONCLUSIONS

It was found in the present study that the difference between the luminous-efficiency function by heterochromatic brightness matching and that by flicker photometry is predicted by only two principal components and that the individual characteristics for heterochromatic brightness matching were specified by using the ratio of luminous efficiencies at only two wavelengths.

There are many possible causes in individual variations of visual functions such as color-matching functions and luminous-efficiency functions. The spectral absorption of the eye lens and that of macular pigments could be considered to be main causes.[34] The absorption of ocular media,

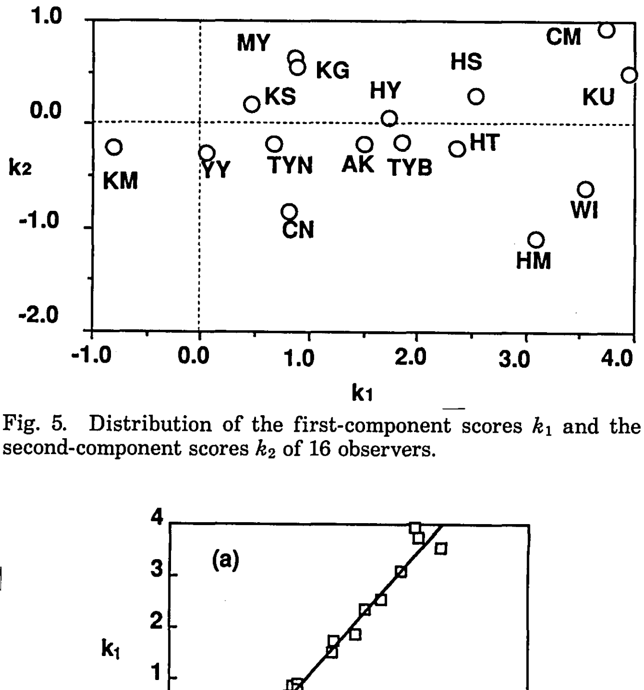

Fig. 5. Distribution of the first-component scores k_1 and the second-component scores k_2 of 16 observers.

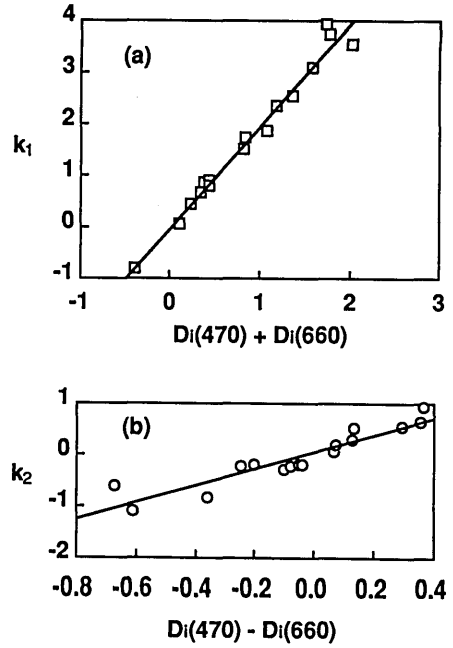

Fig. 6. (a) Relation between the first-component scores k_1 and the sum of $D_i(470)$ and $D_i(660)$. (b) Relation between the second-component scores k_2 and the difference of $D_i(470)$ to $D_i(660)$.

however, affects both flicker photometry and heterochromatic brightness matching. With regard to the difference between the luminous efficiencies obtained by the two methods, the effect of the ocular media is canceled out. For this reason we believe that the two principal components could be directly related to the contribution of chromatic channels to brightness.

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