Luminous efficiency functions by heterochromatic brightness matching for a wide range of retinal illuminance

Hirohisa YAGUCHI* and Mitsuo IKEDA*

The present photopic photometric system is based on the CIE photopic relative luminous efficiency function V(λ), most of whose data were obtained by the flicker photometry. In recent years, however, it is pointed out that the CIE V(λ) does not necessarily represent the spectral sensitivity for the brightness perception. In the present experiment, the relative luminous efficiency functions were determined by the heterochromatic brightness matching method with a 2° visual field at fovea at the various retinal illuminance levels of 1 troland through 1000 trolands. At illuminance levels higher than 10 trolands, all the relative luminous efficiency curves showed a broader shape than the CIE V(λ). In some observers the relative luminous efficiency curves became broader with increasing the retinal illuminance. The present experimental results sugges that the brightness perception is contributed from the opponent-color channels.

1. Introduction

In the present photometric system, the photopic luminance L is defined by the following equation,

$$L = K_m \int_{380}^{780} L_{e,\lambda} V(\lambda) d\lambda. \quad \cdots\cdots(1)$$

K_m is the maximum luminous efficacy, $L_{e,\lambda}$ the spectral radiance, and $V(\lambda)$ the photopic relative luminous efficiency function recommended by the CIE in 1924. It is clear that $V(\lambda)$ plays an important role in calculating the luminance. It has been pointed out, however, that the CIE $V(\lambda)$ is not a faithful reproduction of the spectral sensitivity for the brightness perception. This is shown by the heterochromatic brightness matching which estimates directly the psychological brightness and yields broader relative luminous efficiency curve than the CIE $V(\lambda)$.[1]-[3] When we compare two lights of different color which give an equal luminance, these lights will not necessarily appear equally bright. In particular, a highly saturated color such as a blue appears brighter than a less saturated color such as a yellow. In the example such as this the luminance does not correspond to the brightness.[4]

In recent years the disagreement between the luminance and the brightness is becoming a serious problem in the photometry, mostly because of development of various monochromatic or quasimonochromatic light sources such as lasers and LEDs. For example, a few times as much luminance of white is required to make a brightness match between a red LED source and a white light of the CIE standard source A.[5] It is, therefore, needed to establish a new photometric system which corresponds to a psychological brightness.

It is well known that the shape of the relative luminous efficiency function depends on visual conditions such as the field size, the retinal location, the state of adaptation and the level of the retinal illuminance. For example, for a large field such as 10° visual angle or retinal peripheral vision, the relative luminous efficiency curve shifts towards the shorter wavelength with decreasing the retinal illuminance. With regard to the retinal illuminance the data have been provided by Bedford and Wyszecki[6], Walters and Wright[7] and Kinney[8]. The first authors investigated for very small fields such as a few minutes of arc, and the latter two for a low retinal illuminance level only. Before establishing a new photometric system we need a further data regarding to the effect of the experimental condition upon the relative luminous efficiency function.

In the present paper we will obtain the relative luminous efficiency functions by the heterochromatic

* Department of Information Processing, Tokyo Institute of Technology Graduate School, Nagatsuta, Midori-ku, Yokohama 227, Japan.

brightness matching for a wide range of retinal illuminance. We employ a visual field of 2° arc to correspond to the present CIE $V(\lambda)$.

2. Apparatus

A schematic view of the apparatus is shown in **Fig. 1**. The light source S was a xenon lamp of 500 W d.c. Three of the four channels of the optical system, which were set up for other experiment of brightness additivity test[10], were used in the present experiment. The channel II was not used. Each channel provided a Maxwellian view. Two channels, I and III, constructed a 2° bipartite circular field for brightness matching. The channel I provided the left half of the field with a monochromatic light through a monochromator MC1 and the channel III the right half with a white standard light. Each monochromatic light had a half band width of 3 nm. The radiance of a monochromatic light was controlled by the neutral density wedge filter W1. The radiance of the white standard light was controlled by both a neutral density wedge filter W4 and neutral density filters ND. A monochromatic light through a field stop FSt and a white standard light through FSr were combined by a beam splitter BSI, eventually to make a 2° bipartite circular field. The channel IV provided a white adapting light of 5°30' arc through FSa to eliminate the chromatic adaptation caused by the test light. Its luminance and chromaticity were equated to the white standard light. The adapting field and the bipartite photometric field were presented successively and repeatedly with each duration of four seconds. This duration was arbitrarily chosen. No fixation point was used, so the observer was allowed to scan over the bipartite photometric field to compare the brightness of each side.
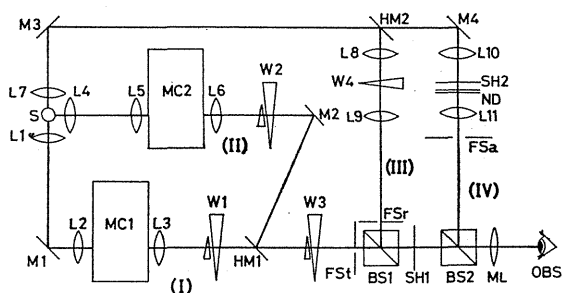

Fig. 1 *Schematic view of the experimental apparatus.*

Sixteen wavelengths from 400 nm through 700 nm at intervals of 20 nm and 570 nm were employed as the test monochromatic light. At high levels of the retinal illuminance, however, extremely short and long wavelengths were not employed because of the lack of intensity. The chromaticity coordinates of the standard light were $x=0.32$, $y=0.33$. Four retinal illuminance levels of 1, 10, 100 and 1,000 trolands were employed for the white standard light.

The measurement of the test monochromatic

lights was carried out with the EG&G radiometric system.

Four male observers KK, TN, SO and HY of the age from 22 to 28 years old were employed. All of them had normal color visions and were well experienced in psychophysical experiments.

3. Procedure

The observer was dark adapted for ten minutes prior to each experimental session. To obtain a brightness match between a monochromatic test light and the white standard light, the observer adjusted the illuminance of the former with the neutral density wedge filter W1 by the method of adjustment. Five adjustments were carried out successively at each wavelength. The next test wavelength was randomly chosen and another five adjustments were achieved. This procedure was continued until all seventeen test wavelengths were investigated. It took about fourty minutes for such an experimental session. The retinal illuminance of the white standard light was kept constant within the same session.

4. Results and discussion

The relative luminous efficiency curves have obtained are shown in **Fig. 2**. The ordinate gives the logarithmic relative luminous efficiencies and the
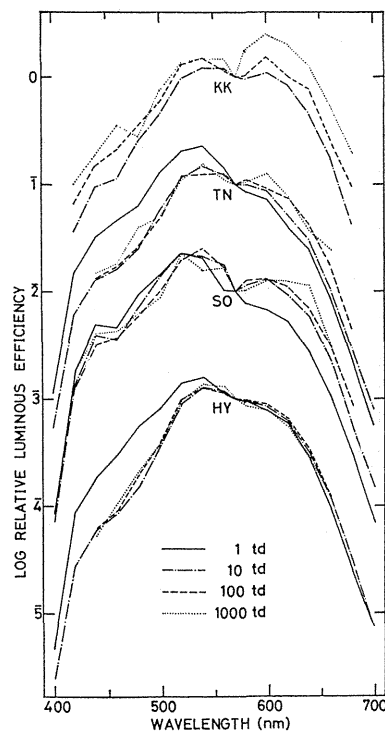

Fig. 2 *Relative luminous efficiency functions by the heterochromatic brightness matching at four levels of retinal illuminance. Subjects, KK, TN, SO and HY.*

abscissa the wavelength of the test light. All curves are normalized at the appropriate wavelength of 570 nm in order to make it easy to compare the shapes of the relative luminous efficiency curves for different retinal illuminance levels. The curves for different observers are displaced vertically by one logarithmic unit for clarity. The relative luminous efficiency functions at the level of 1, 10, 100 and 1,000 trolands are indicated by the solid, the dashed and dotted, the dashed and the dotted curves respectively. Curves of three observers SO, TN and HY represent arithmetic means from three sessions and that of KK from one session only. His relative luminous efficiency function at a level of 1 troland was not measured.

The most evident feature in Fig. 2 is the shift of the relative luminous efficiency curve towards the shorter wavelength when the retinal illuminance was lowest, namely, 1 troland. This is more clearly seen in **Fig. 3** where the logarithmic ratio of the relative luminous efficiency of 1 troland to those of 10 trolands are plotted against the wavelength. The relative luminous efficiency of the blue region increases relative to that of the red region, showing a kind of the Purkinje shift at the fovea. Similar results have been found by Walters et al.[7] and Kinney[8]. The foveal Purkinje shift is probably due to the activation of the small number of rods in 2° visual field of the fovea.
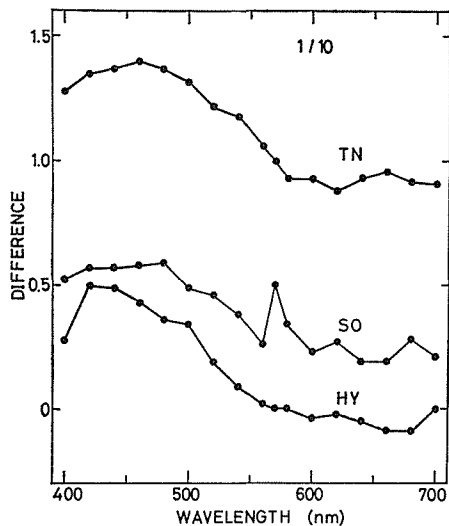

Fig. 3 *Logarithmic ratios of the relative luminous efficiencies at 1 troland to those at 10 trolands.*

At high levels of the retinal illuminance beyond 10 trolands, the relative luminous efficiency curves do not show significant change except for the observer KK. These conclusions were statistically confirmed by *t*-test. **Fig. 4** shows the differences between the relative luminous efficiency curves of different retinal illuminance levels plotted in the same manner as Fig. 3. The solid curves indicate the logarithmic ratios of the relative luminous efficiencies of 100 trolands to those of 10 trolands, the dashed curves indicate those of 1,000 trolands

to 10 trolands. Both curves of the observer HY are nearly flat, indicating that the relative luminous efficiency curve does not change according to the level of the retinal illuminance. The curves from the observer TN and SO show a slight variation. That is, the relative luminous efficiencies at the blue and red region slightly increase in comparison with those of green or yellow when the retinal illuminance increases. For the observer KK this effect is further emphasized.
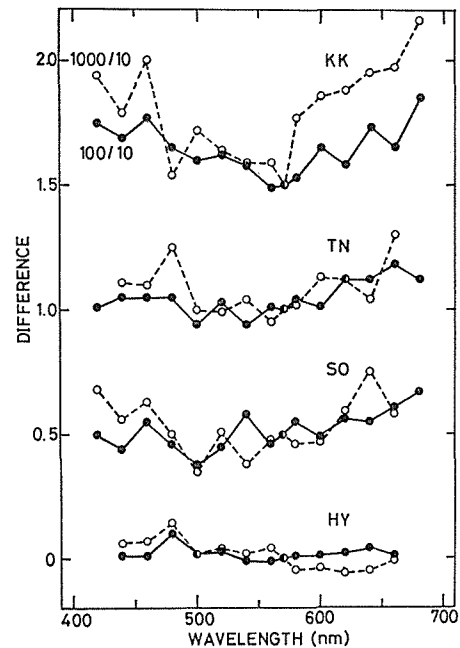

Fig. 4 *Same as Fig. 3, but for 100 trolands to 10 trolands (solid) and 1000 trolands to 10 trolands (dashed).*

It seems that there are two extreme types among observers at high retinal illuminance levels. One type shows a change in the relative luminous efficiency curve with the change of the retinal illuminance level, such as the observer KK, and another type shows no change, such as HY. The observers TN and SO are intermediates.

The increase of the relative luminous efficiency in short wavelength with increasing the retinal illuminance observed in the observer KK in particularly is inverse to the usual Purkinje effect. This inverse Purkinje effect was also found by Thomson[9] and Bedford et al.[6] The cause of this effect is not clear.

Differences between the logarithmic relative luminous efficiency functions for three levels above 10 trolands and the logarithmic CIE $V(\lambda)$ are shown in **Fig. 5**. The logarithmic ratios of each of 1,000, 100 and 10 trolands of the CIE $V(\lambda)$ are presented from the top to the bottom respectively. The identical symbols represent the data of the same observer; open circles for KK, open squares SO, closed circles TN, and closed squares HY. Every observer shows a large difference both in short and long wavelength regions. These curves are very similar to the
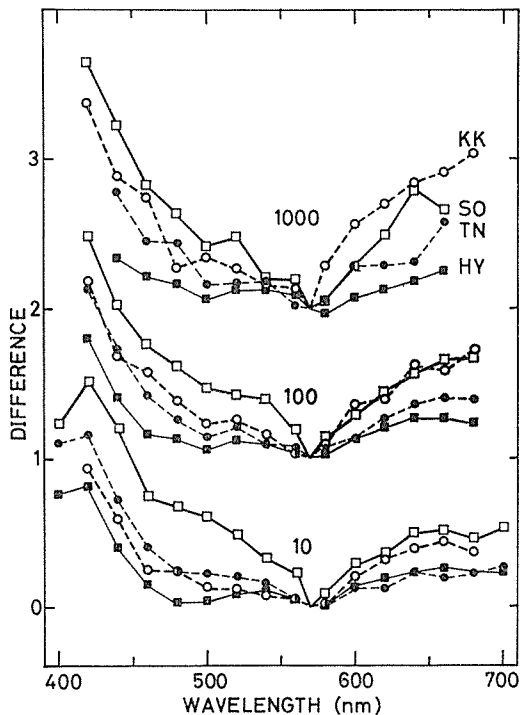
Fig. 5 *Logarithmic ratios of the relative luminous efficiencies by the heterochromatic brightness matching to CIE $V(\lambda)$.*

saturation discrimination function.

It has been suggested, from the study of the mechanism of color vision, that the relative luminous efficiency obtained by the flicker photometry such as the CIE $V(\lambda)$ is determined by the luminance channel only, while the relative luminous efficiency by the brightness matching method such as the present results is determined by both the luminance channel and the opponent-color channels.[10][11] The difference between the two efficiencies is, therefore, due to the presence of the activities of the opponent-color channels. Therefore, the relative luminous efficiencies by the heterochromatic brightness matching should show larger values at highly saturated colors such as blue and red than

at less saturated colors such as yellow, in agreement with Fig. 5. It is understood then from Fig. 5 that the contribution of the opponent-color channels to the brightness perception is larger in the observer SO (open squares) than in HY (closed squares).

Fig. 5 also indicates that the contribution from the opponent-color channels become larger and larger as the retinal iluminance increases in the observer KK (open circles) while it does not change in HY (closed squares).

Our experimental results suggest that the brightness perception is contributed from the opponent-color channels. The contribution seems to exist at short and long wavelengths, and the relative luminous efficiency function deviates greatly from the CIE $V(\lambda)$. Further, the contribution varies according to the retinal illuminance level, and makes the standardization of a new relative luminous efficiency function for brightness difficult. It is, therefore, needed not only to increase the number of the observers but also to understand the mechanism of the human color vision to some extent in order to establish the new function and to express the function in terms of activities of both the luminance and the opponent-color channels.

References

(1) G. Wagner and R. M. Boynton: J. Opt. Soc. Am. 62 (1972) 1508~1515.

(2) J. P. Comerford and P. K. Kaiser: J. Opt. Soc. Am. 65 (1975) 466~468.

(3) M. Ikeda and H. Shimozono: J. Opt. Soc. Am. 68 (1978) 1767~1771.

(4) H. Yaguchi and M. Ikeda: J. Illum. Engng. Inst. Jpn. 64 (1980) 566~577 (in Japanese).

(5) R. L. Booker: J. Opt. Soc. Am. 68 (1978) 949~952.

(6) R. E. Bedford and G. W. Wyszecki: J. Opt. Soc. Am. 48 (1958) 406~411.

(7) H. V. Walters and W. D. Wright: Proc. Roy. Soc. B131 (1943) 340~361.

(8) J. A. S. Kinney: J. Opt. Soc. Am. 54 (1964) 671~677.

(9) L. C. Thomson: J. Physiol. 109 (1947) 368~377.

(10) H. Yaguchi and M. Ikeda: KOGAKU 9 (1980) 44~51 (in Japanese).

(11) S. L. Guth and H. R. Lodge: J. Opt. Soc. Am. 63 (1973) 450~462.