Tohru Tamura
Mitsuo Ikeda
Keiji Uchikawa

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

The Effect of Stimulus Duration on the Luminous Efficiency Functions for Brightness

Spectral luminous efficiency functions were obtained by direct heterochromatic brightness matching for four different stimulus durations: namely, 10-ms, 200-ms, 1-s, and continuous presentation. The functions clearly changed in their shape, depending on the stimulus duration for two of three subjects. They showed usual double peaks at about 540 and 600 nm, which were greatly enhanced when the duration was 1 s. The enhancement decreased both with longer and shorter duration. Linear combinations of cone outputs model was applied to our results. The logR-logG type mechanism in the long-wavelength region and the logG-logR-logB type mechanism in the middle-wavelength region were found for brightness perception. For the short-wavelength region, by lifting up the short-wavelength portion of the logR-logG mechanism, luminous efficiency functions could be expressed. In the long- and middle-wavelength region, the effects of the stimulus duration were explained by changing the negative input (originating from R or G cones) to the positive input as the stimulus duration increased from 10 ms to 1 s. The amount of the short-wavelength sensitive cones' contribution in the middle-wavelength region were small and there were no systematic changes for the stimulus durations. For the short-wavelength region, the amount of the shift of the logR-logG type mechanism was largest at the 1-s duration.

Introduction

It is well known that the luminous efficiency function for a moderate field size shows double peaks at about 540 and 600 nm, quite different from the CIE $V(\lambda)$, when the function is determined by the direct heterochromatic brightness matching technique.[1–3] It was shown to be necessary, therefore, to establish a new spectral luminous efficiency function for brightness. It was known, however, that there are various factors that affect the shape of the function, such as field size, the level of retinal illuminance, and the age of observers, and it has become important to systematically investigate the effect of these factors on the shape of the function.

It was found that stimulus duration is another factor that radically affects the shape of the brightness luminous efficiency function. This finding strongly suggests investigating the effect of stimulus duration on the luminous efficiency function, among other conditions, because, as our eyes roam, their gaze rests upon different objects for different lengths of time. In the present paper, luminous efficiency functions for brightness will be obtained for various stimulus durations and the effect upon the shape of the functions will be investigated.

Apparatus and Procedure

The apparatus we used consisted of a conventional Maxwellian view optical system equipped with two channels, one for test stimuli and the other for a reference field. In the experiment, a vertically divided bipartite circular field was prepared. No background field was used and the field of 2° diameter appeared in a dark surround. A dark bar dividing the two fields had a width of about 8′ of arc. On the right-hand side of the bipartite field a white reference of chromaticity coordinates $x = 0.37$ and $y = 0.39$ appeared with a fixed retinal illuminance 100 Td, while on the left-hand side a test stimulus of a certain wavelength appeared by way of a monochromator, the radiance of which was adjusted manually by a subject with the help of a neutral density wedge filter. When test stimuli were at the ends of

CCC 0361-2317/88/060363-06$04.00

spectrum, the intensity of the test light was not sufficient to obtain the same brightness as that of the 100 Td white reference. In such cases, neutral density filters were inserted in the reference channel to reduce the retinal illuminance.

The duration of the field appearance was controlled with mechanical shutters inserted in the optical paths. They were operated synchronously; this way, the entire bipartite field appeared for a fixed duration. Four different durations were investigated: namely, 10-ms, 200-ms, 1-s, and continuous presentation. For the shortest duration the fixation points of two dots vertically sandwiched the field. For other durations the fixation points were not used. Subjects used a biting board to fix their eye position. They viewed the field monocularly with their right eyes.

During an experimental session the duration was fixed to a certain value and the wavelength of the test stimulus was randomly chosen from 400 to 700 nm in 10-nm steps. The method of adjustment was used to equate the brightness of both fields. At each wavelength three determinations of matching were carried out. Three to five such tests were conducted for each stimulus duration (during each session). Besides the direct brightness matching, flicker photometry was conducted to obtain the luminous efficiency function of the CIE $V(\lambda)$ type. The test and reference fields were completely superimposed, but the shutters in those channels were operated out of phase to present the two lights alternatively with a flicker frequency of 5.5 Hz for one subject (MI) and 8.1 Hz for the other two subjects (CH and TT). The arrangement for these experimental sessions was exactly same as that for heterochromatic brightness matching.

Three males of normal color vision participated as subjects in the experiment. Their ages were 50 (MI), 28 (CH), and 23 (TT).

Results and Discussion

The luminous efficiency functions $V_b(\lambda)$ determined under the five different conditions by three subjects are shown in Figure 1. $V_b(\lambda)$ is given as the reciprocal of the relative energy $L_{e,\lambda}$ of the test light to maintain the same brightness as the reference white. The luminous efficiencies obtained for a white reference darker than 100 Td were corrected by a cascade method. To correct the data, the luminous efficiency of the adjacent test stimulus was also measured with the same neutral density filters as those inserted in the reference channel when the luminous efficiency to be corrected was obtained. The correction was done by adding the difference of log luminous efficiency between the data obtained with and without the neutral density filters to the luminous efficiency to be corrected.

Individual differences are quite evident both in the shape of the functions, already known from previous experiments,[2-5] and in the way the functions change according to stimulus duration.

Let us first look at the results from subject MI (Fig. 1a). All luminous efficiency functions, when they are obtained by the direct brightness matching method, show higher values than those obtained by flicker photometry, and exhibit the familiar double peaks at about 540 and 600 nm. The actual values, however, varied depending on the duration and were very much enhanced both at durations of 200 ms and 1 s. But the enhancement of the efficiency functions from 10-ms and continous presentation is smaller than that of the 200-ms and 1-s durations. Similar results were also obtained from subject CH (Fig. 1b), although in this case the efficiency enhancement is extraordinarily high at long wavelengths with 1-s duration. Thus it is quite evident, at least from these two subjects, that brightness luminous efficiency is affected by stimulus duration.

The effect, however, seems not to exist prominently for the third subject, TT, as seen in Fig. 1c. Very similar and uni-peaked luminous efficiency functions were obtained regardless of the stimulus duration and method of measurement employed.

Brightness luminous-efficiency has been normally explained by three channel responses, that of an achromatic channel and two chromatic channels. How these three responses are combined by model builders[6-8] to explain brightness perception differs, but all of them share the idea that the spectral sensitivities of the three channels are derived by linear transformation of the spectral sensitivities of three different cones, whereupon nonlinear combinations of the responses of the three channels are introduced. It seems, however, more reasonable to assume a nonlinearity at the cone response level, for the nonlinearity is evident at this stage.[9,10] Nakano et al.[11,12] recently succeeded in explaining their results of brightness additivity experiments by assuming nonlinearity at the cone stage. We also apply the Nakano–Ikeda–Kaiser model to the present results.

The model expressed a fixed brightness Br by the following equation

$$Br = a \log R + b \log G + c \log B \quad (1)$$

where R, G, and B are the amounts of light absorbed by each cone photopigment based on the spectral sensitivities of long-, middle-, and short-wavelength sensitive cones, $S_{r\lambda}$, $S_{g\lambda}$, and $S_{b\lambda}$, and they are calculated as follows:

$$\begin{aligned} R &= \int L_{e,\lambda} S_{r\lambda} d\lambda, \\ G &= \int L_{e,\lambda} S_{g\lambda} d\lambda, \\ B &= \int L_{e,\lambda} S_{b\lambda} d\lambda. \end{aligned} \quad (2)$$

We employ Smith and Pokorny's cone spectral sensitivities for $S_{r\lambda}$, $S_{g\lambda}$, and $S_{b\lambda}$.[13] Constants a, b, and c are the coefficients that determine the amounts of contribution of the respective cone outputs to brightness. The last term of Eq. (1) is assumed to drop out in the middle and long wavelength regions where the short-wavelength sensitive cones are inactive. That is,

$$Br = a \log R + b \log G \quad (3)$$

To see if the above model is applicable to the present results, the luminous efficiency curves of Figure 1 may be plotted on a $\log R$-$\log G$ diagram, such as shown in Figure 2a and b by closed circles as examples executed for the

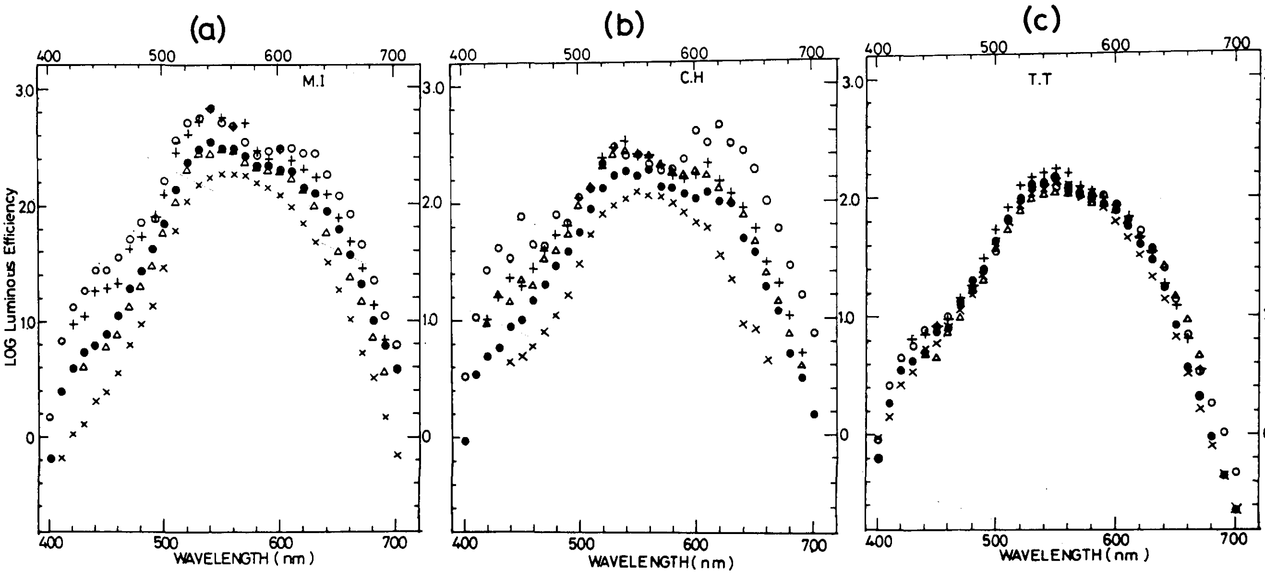

FIG. 1. Luminous efficiency functions for brightness for different stimulus durations for three subjects, MI(a), CH(b), TT(c); 10 ms, △; 220 ms, +; 1s, ○; continous presentation, ●. The result of flicker photometry is also shown by ×.

luminous efficiency curves of subjects MI and TT at 1s duration, corresponding to open circles of Figure 1a and c, respectively. Open circles in Figure 2 indicate data points obtained with the white reference darker than 100 Td. The abscissa denotes log$R$ and the ordinate log$G$. Relative values of these axes are real, but the values themselves are only relative because our luminous efficiencies as well as Smith-Pokorny's cone spectral sensitivities are represented relatively.

In Figure 2a, the points for wavelengths longer than 580 nm are expressed by a straight line, while those shorter than 580 nm but probably longer than 510 nm are expressed by another straight line, confirming the validity of Eq. (3). The points deviate from the straight line at shorter wavelengths, and this was expected from Eq. (1), in which region the short-wavelength sensitive cones become active. An exact point of deviation is not clear in Figure 2a, but it is quite clear in subject TT as seen in Figure 2b, and the data points begin to move upward from about 520 nm. With this in mind, the data points of 490 nm and shorter wavelengths for subject MI may be interpreted as deviations from a straight line. By using Figure 2's two straight lines, the coefficients a and b of Eq. (3) can be determined easily and the luminous efficiency curves of Fig. 1a–c can be expressed by Eq. (3) at least for the region longer than 510 nm. The coefficients a and b were determined by the least squares method.

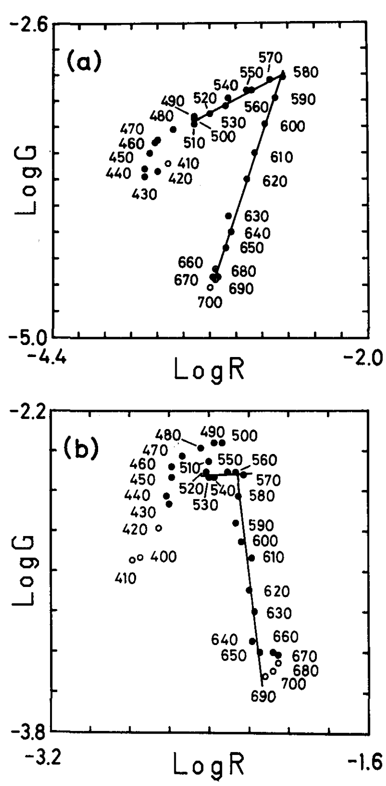

FIG. 2. Luminous efficiency functions for brightness plotted in a logR vs logG diagram are shown by closed circles for subject MI in 1-s duration (a) and for subject TT 1-s duration (b). Open circles represent the results obtained with a white reference darker than 100Td. The wavelength of each test light is indicated in nm.

To return to $V_b(\lambda)$ of Figure 1, we rewrite Eq. (1) in a form of $V_b(\lambda)$ by using the relation $V_b(\lambda) = 1/L_{e,\lambda}$ and Eq. (2), namely

$$\log V_b(\lambda) = \alpha \log(S_{r\lambda}) + \beta \log(S_{g\lambda}) + \gamma \log(dS_{g\lambda}) - Br/(a+b+c) \quad (4)$$

where

$$\alpha = a/(a+b+c),\ \beta = b/(a+b+c),\ \gamma = c/(a+b+c).$$

The parameter d is inserted to adjust the relative sensitivity between the long- and the middle-wavelength sensitive cones and the short-wavelength sensitive cones. This was necessary because the relation is not uniqly determined in the Smith-Pokorny fundamentals.

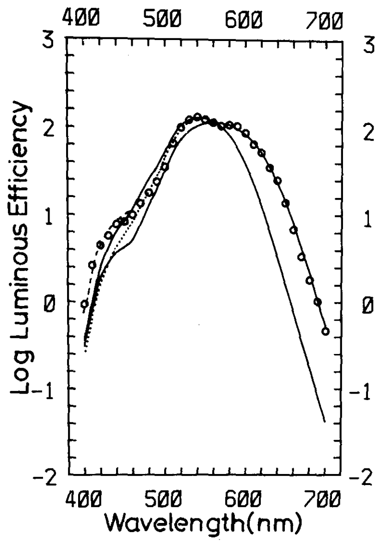

FIG. 3. Theoretical curves calculated by using Eq. (4) for subject TT, 1s duration. Open circles are replotted from Fig. 1a. Solid lines are the theoretical curves calculated by using only a and b for long-wavelength and middle-wavelength region. The dotted line shows the effect of adding coefficient c for considering the contribution of the short-wavelength sensitive cones. The dashed line shows the result of shifting the long-wavelength mechanism to fit the luminous efficiencies in the short-wavelength region.

For the region where data points are approximated by Figure 2's two straight lines, the coefficient c is zero and the term with γ in Eq. (4) vanishes. As we already know, for the two sets of coefficients a and b $V_b(\lambda)$ can be explicitly expressed by the remaining three terms. The results are shown as two solid curves in Figure 3 for subject TT, 1-s duration. Open circles are replots from Figure 1c of 1-s duration. These two theoretical curves express the experimental luminous efficiencies quite well, up to 530 nm. Below that point, the experimental values deviate slightly toward the lower direction to indicate that the short-wavelength sensitive cones are active. Following the Nakano–Ikeda–Kaiser model, the deviation may be explained by simply adding the third term of Eq. (4) without changing the a and b values used to explain the foregoing straight line in Figure 2. The coefficient c of Eq. (1) or γ of Eq. (4) was determined by using the least squares method so that the theoretical $V_b(\lambda)$ will fit the experimental data at wavelengths shorter than 530 nm, but longer than 460 nm. The result is shown as a dotted line in Fig. 3.

The luminous efficiencies again systematically deviate from the theoretical curve in the wavelength region shorter than 460 nm. Another theoretical curve, therefore, should be introduced here to express the luminous efficiencies. It is tempting to suggest that the short-wavelength sensitive cones solely determine the brightness perception in this region. We tried to express luminous efficiencies using only the short-wavelength sensitive cones, by making a and b of Eq. (4) equal zero. However, the fit was not quite satisfactory. When we look at the shape of the experimental luminous efficiency curve in that region, we notice that it is similar to that of the theoretical curve of the very first one for long wavelengths. Arbitrarily, we shifted the short-wavelength portion of the long-wavelength mechanism upward along the ordinate axis. The dashed line in Figure 3 shows the result. The agreement seems good. Such an upward shift might be justified if we can hypothesize that the activity of the long-wavelength mechanism is enhanced by the short-wavelength sensitive cone when the latter becomes active.

Similar curve fitting was carried out for all other conditions and subjects, and the results are shown in Fig. 4. In each panel the experimental data are shown by open circles replotted from Figure 1, but for subject MI we compensated for his lens absorption by adding the difference between his flicker photometry and Judd's modified $\bar{y}(\lambda)$ in the short-wavelength region. The theoretical curves are shown by solid lines. The results of 10-ms, 200-ms, 1-s, and continous presentation are shown from top to bottom, respectively. The vertical bars in each panel indicate the point where one system is replaced by another system. The agreement between the luminous efficiency curves for brightness and the theoretical curves calculated by using Eq. (4) is quite good.

The coefficients α and β for the long-wavelength region are summarized in Table I for all four stimulus durations and for all three subjects. Subjects MI and CH have positive values for α and negative values for β. An opponent mechanism of the log$R$-log$G$ type operates here for brightness perception. We notice that the effect of duration upon the luminous efficiency function existed for both subjects as seen in Fig. 1a and b. In terms of the coefficients α and β, the effect is exhibited in the β/α ratio, and its absolute value increases from 0.07 at 10 ms to 0.34 at 1s duration and decreases to 0.21 at continous presentation for subject MI, and from 0.14 at 10 ms to 0.44 at 1 s, and 0.20 at continous presentation for subject CH. We may conclude, therefore, that it is the ratio β/α that changes according to the stimulus duration. In other words, the relative contribution of the long-wavelength sensitive cones and the middle-wavelength sensitive cones changes so that the negative input to this mechanism becomes large compared to the positive one as the stimulus duration increases from 10 ms to 1 s, and becomes small for continous presentation. The situation differs for the third subject TT. It is an nonopponent mechanism that operates here, as the coefficients α and β are both positive. No systematical change of these coefficients can be found for different durations.

The coefficients of α, β and for the middle-wavelength region are shown in the upper part of Table II. The coefficients were obtained from the second straight lines in the log$R$-log$G$ plots such as Fig. 2. For almost all conditions except 10-ms duration for subjects CH and TT, we found negative values for α and positive values for β in this middle-wavelength region. We assume a log$G$-log$R$ type mechanism operates here. In the lower part of Table II three coefficients α, β, and γ are shown for the region where the short-wavelength sensitive cones become active, from 460 to 510 nm for subject MI, from 460 to about 530 nm for subjects CH and TT. Because we kept a and b of Eq. (1)

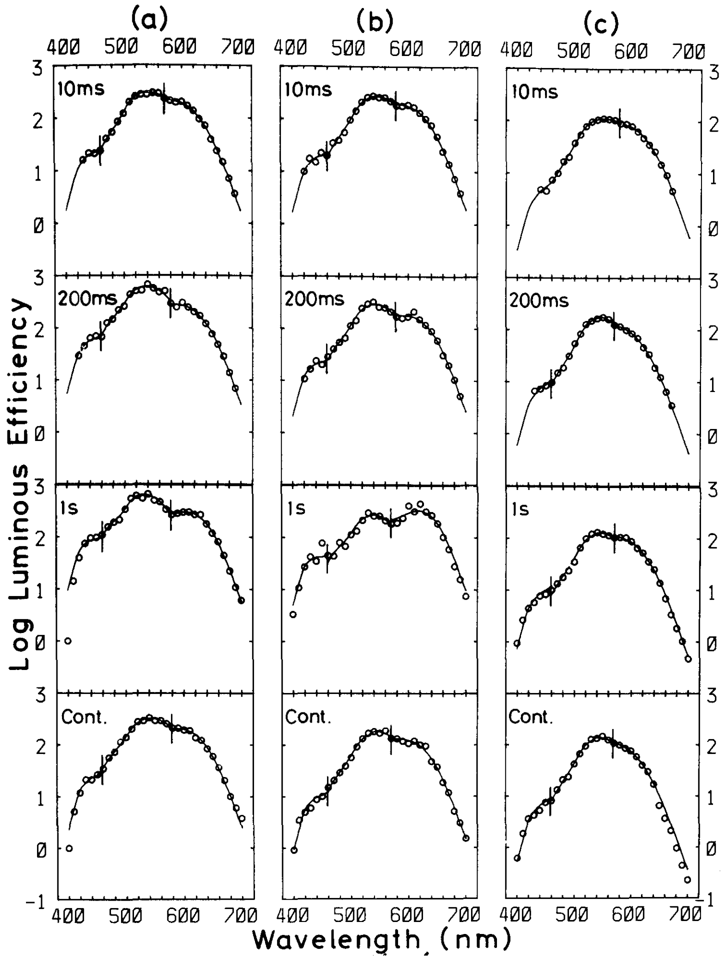

FIG. 4. Theoretical curves calculated using Eq. (4) for all three subjects, MI(a), CH(b), and TT(c), and four different stimulus durations, from top to bottom: 10-ms, 200-ms, 1-s, and continous presentation, respectively. In each panel, open circles are replotted from Fig. 1 and solid lines represent the theoretical curves for long-, middle-, and short-wavelength regions. The vertical bars indicate the point where one system is replaced by another system.

unchanged, the values of α and β are slightly different from those in the upper panel. We found negative values for γ for most cases except for the continous presentation for subject MI, 1-s presentation for subject CH, and 10-ms presentation for subject TT, and therefore, a log$G$-log$R$-log$B$ type mechanism is expected to operate here. The effect of the stimulus duration is found again in the relative contribution of the long- and middle-wavelength sensitive cones. The negative input into this mechanism becomes large compared with the positive one as the stimulus duration increases from 10 ms to 1 s, and becomes small for continous presentation. This change shows the same tendency as a log$R$-log$G$ type mechanism in the long-wavelength region. The effect of stimulus duration on short-wavelength-sensitive cones, however, is negligible. The short-wavelength sensitive cones' contribution is small but constant for different stimulus durations.

For the short-wavelength region, the values for the upward shift of the log$R$-log$G$ type are summarized in Table III for three subjects. The value increases as the stimulus

TABLE I. The coefficients α and β of the log$R$-log$G$ system operating in the long-wavelength region.

	Condition	MI	CH	TT
	10 ms	570–690 nm	580–690 nm	580–670 nm
	α=, β=	1.08, −0.08	1.17, −0.17	1.00, 0.00
	200 ms	580–690 nm	580–690 nm	570–670 nm
Long	α=, β =	1.27, −0.27	1.34, −0.34	0.76, 0.24
Wavelength	1 s	580–690 nm	570–700 nm	570–650 nm
	α =, β =	1.51, −0.51	1.78, −0.78	0.90, 0.10
	Continuous	580–690 nm	570–680 nm	570–640 nm
	α =, β =	1.26, −0.26	1.25, −0.25	0.76, 0.24

TABLE II. Upper part: The coefficients α and β calculated from the slope of the straight lines for the middle-wavelength region. Lower part: The coefficients α, β, and γ after consideration of the short-wavelength sensitive cones' contribution.

	Condition	MI	CH	TT
	10 ms	510–570 nm	530–580 nm	500–580 nm
	$\alpha=, \beta=$	−0.17, 1.17	0.04, 0.96	0.52, 0.48
	200 ms	510–580 nm	530–580 nm	550–570 nm
	$\alpha=, \beta=$	−0.47, 1.47	−0.36, 1.36	−0.60, 1.60
Middle	1 s	510–580 nm	530–570 nm	530–570 nm
Wavelength (1)	$\alpha=, \beta=$	−1.08, 2.08	−0.75, 1.75	−0.06, 1.06
	Continuous	510–580 nm	530–570 nm	530–570 nm
	$\alpha=, \beta=$	−0.08, 1.08	−0.07, 1.07	−0.02, 1.02
	10 ms	460–510 nm	460–530 nm	460–500 nm
	$\alpha=, \beta=, \gamma=$	−0.19, 1.25, −0.06	0.04, 0.98, −0.02	0.51, 0.46, 0.02
	200 ms	460–510 nm	460–530 nm	460–550 nm
	$\alpha=, \beta=, \gamma=$	−0.47, 1.48, −0.01	−0.37, 1.40, −0.03	−0.68, 1.82, −0.14
Middle	1 s	460–510 nm	460–530 nm	460–530 nm
Wavelength (2)	$\alpha=, \beta=, \gamma=$	−1.11, 2.13, −0.03	−0.75, 1.75, 0	−0.06, 1.11, −0.04
	Continuous	460–510 nm	460–530 nm	460–530 nm
	$\alpha=, \beta=, \gamma=$	−0.08, 1.04, 0.04	−0.07, 1.09, −0.02	−0.03, 1.09, −0.05

duration increases from 10 ms to 1 s and decreases for continous presentation.

Conclusion

A linear combination of log$R$,log$G$, and log$B$ can express the luminous efficiency functions for brightness quite well for both long- and the middle-wavelength regions. For the short-wavelength region, luminous efficiencies can be expressed by shifting the short-wavelength portion of the log$R$-log$G$ mechanism. The effect of the stimulus duration on luminous efficiency functions is clear, and can be explained by changing the relative contribution of the long- and middle-wavelength sensitive cones. These changes can be summarized by saying that the negative input to the log$R$-log$G$ mechanism for the long-wavelength region and log$G$-log$R$ for the middle-wavelength region becomes large comparing with the positive one when the stimulus duration increases from 10 ms to 1 s and becomes small for continous presentation. The value of upward shifting of log$R$-log$G$ in the short-wavelength region is largest at 1-s duration and getting small both for duration shorter than 1 s and for continous presentation. These findings present some problems to those who want to introduce a new photometric system that can evaluate lights in terms of brightness.

TABLE III. The amount of upward shifting of the log$R$-log$G$ mechanism to fit the luminous efficiencies in the short-wavelength region.

	Condition	MI	CH	TT
Short Wavelength	10ms	0.19	0.22	—
	200ms	0.36	0.29	0.09
	1s	0.49	0.45	0.16
	Cont.	0.27	0.21	0.10

1. M. Ikeda, H. Yaguchi, and K. Sagawa, Brightness luminous-efficiency functions for 2° and 10° fields, *J. Opt. Soc. Am.* **72,** 1660–1665 (1982).
2. D. A. Palmer, Visibility curves by direct comparison in a 10° field at 1000 Td, *J. Opt. Soc. Am.* **A2,** 578–583 (1985).
3. K. Sagawa and K. Takeichi, Spectral luminous efficiency functions in the mesopic range, *J. Opt. Soc. Am.* **A3,** 71–75 (1986).
4. K. Katori and M. Fuwa, Relative spectral luminous efficiency function of 2° and 10° fields determined by flicker photometry and direct heterochromatic brightness matching, *Light and Vis. Env.* **9,** 22–23 (1985).
5. M. Ikeda and Y. Nakano, Stiles' summation index applied to heterchromatic brightness matching, *Perception* **9,** 765–776 (1986).
6. S. L. Guth and H. R. Lodge, Heterochromatic additivity, foveal spectral sensitivity, and a new color model, *J. Opt. Soc. Am.* **63,** 450–462 (1973).
7. C. R. Ingling, Jr., and B. H.-P. Tsou, Orthogonal combination of the three visual channels, *Vision Res.* **17,** 1075–1082 (1977).
8. H. Yaguchi and M. Ikeda, Subadditivity and superadditivity in heterchromatic brightness matching, *Vision Res.* **23,** 1711–1718 (1983).
9. R. M. Boynton and D. N. Whitten, Visual adaptation in monkey cone recordings of late receptor potentials. *Science, N.Y.* **170,** 1423–1426 (1970).
10. J. M. Valeton and D. V. Norren, Light adaptation of primate cones: An analysis based on extracellular data, *Vision Res.* **23,** 1539–1547 (1983).
11. Y. Nakano, M. Ikeda, and P. K. Kaiser, Contributions of the opponent mechanisms to brightness and nonlinear models, *Vision Res.* **28,** 799–810 (1988).
12. M. Ikeda and Y. Nakano, Proceedings of The AIC-Wyszecki-Stiles Symposium on Color Vision Models (to be published).
13. V. C. Smith and J. Pokorny, Spectral sensitivity of the forveal cone photopigments between 400 and 500nm, *Vision Res.* **15,** 161–176 (1975).

Received March 15, 1987; accepted February 28, 1988.