Mesopic luminous-efficiency functions for various adapting levels

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The luminous-efficiency functions for a centrally viewed 10° field were measured by heterochromatic brightness matching for various retinal illuminance levels of a reference field at various adapting levels. The subject was always presented with a 45° white adapting light except when the test field for brightness matching was substituted for the adapting field for 500 msec. In order to investigate the contributions of rods and cones to the brightness sensation, the luminous-efficiency curves obtained from two subjects were analyzed with the Ikeda–Shimozono formula. When the subject was presented with an adapting light above about 100 trolands (Td), the luminous-efficiency function became photopic at any luminance level of the test field; similarly, when the test field was at 100 Td, the luminous-efficiency function was photopic at any adapting level.

INTRODUCTION

Many investigations[1–4] show that the shape of the luminous-efficiency curve for a brightness criterion changes continuously and extensively in the retinal illuminance range from about 0.01 to 100 trolands (Td). Even above 100 Td, the luminous-efficiency curves for brightness change slightly.[5] The shape of the luminous-efficiency curve depends not only on the intensity of light but also on the state of adaptation of the eye. It is important to investigate the effects from the adaptation level of the eye as well as the intensity of the test light in order to establish a mesopic luminous-efficiency function.

Recently, Ikeda and Shimozono gave a theoretical expression of the mesopic luminous-efficiency function.[4] Their model is simple: The logarithm of a mesopic luminous-efficiency function can be represented as a linear combination of the logarithm of a photopic luminous-efficiency function and the logarithm of a scotopic one, on the condition that these luminous-efficiency functions are determined by heterochromatic brightness matching. Furthermore, this model gives an estimate of how much the photopic component and the scotopic component contribute to the brightness sensation.

Here the luminous-efficiency functions for brightness were measured for various retinal illuminance levels of a test light at various adapting levels by the method of heterochromatic brightness matching. The curves obtained experimentally are analyzed with the Ikeda–Shimozono formula to quantify the influences of the intensity level of the test light and the adapting level to the luminous-efficiency function.

APPARATUS

A conventional Maxwellian-view system with three channels was used. Two of the three channels provided a bipartite field subtending 10° of visual angle; the other channel provided a large white field of 45° for adapting. The wavelength of the test stimulus was obtained with a monochromator that had a half-bandwidth of about 3 nm. Although white light is sometimes used for conventional brightness matching, we chose instead a reference of 570 nm for ease of calibration. The 570-nm reference was provided by another monochromator. The retinal illuminances of the reference field were set with neutral-density filters. The adapting light was provided by a xenon lamp of 500-W dc through a heat-absorbing filter and neutral-density filters. The chromaticity coordinates of the adapting field were $x = 0.35$ and $y = 0.39$, when calibrated at 1000 Td.

The wavelengths of the two monochromators, the neutral-density wedge filters inserted in each monochromatic channel, the solenoid shutters inserted in all channels, and the observer's response were driven and processed by an LSI 11 microcomputer system.

PROCEDURE

After about 10 min of dark adaptation, the subject was presented with one of six adapting levels: 0, 0.1, 1, 10, 100, and 1000 Td. After about 1 min of light adaptation, the subject started to match the brightness of the test light to the brightness of one of four reference light levels: 0.1, 1, 10, and 100 Td. A test wavelength was chosen randomly from 29 wavelengths covering 410–690 nm in 10-nm steps; however, a few extreme wavelengths could not be used at some reference levels because of lack of intensity. The subject viewed the 45° adapting field continuously except when the 10° test field was substituted. The 10° test field was presented for a duration of 500 msec whenever the subject pushed a button, as long as the interval between presentations was greater than 2 sec. A 50-msec dark interval preceded the 10° test field to aid in elimination of aftereffects from the adapting field. The brightness matching was carried out by the method of adjustment. Three adjustments were made successively for a certain test wavelength. Two males, HY (31 years of age) and SS (23 years of age), with normal color vision served as subjects. Four sessions for HY and three sessions for SS were used for most combinations of reference and adapting levels. The no-adaptation condition was not used with SS.

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RESULTS

Luminous-efficiency functions for four retinal illuminance levels of reference light at six adapting levels from subject HY and at five adaptation levels from subject SS are shown in Figs. 1 and 2, respectively. The ordinate is directly proportional to the logarithm of the reciprocal of the energy of the test stimulus that matched the reference in brightness, so the luminous-efficiency curves are comparable with each other. But the curves of the 0.1-Td reference are shifted upward by 0.5 log unit to avoid overlapping the curves of the 1-Td reference in the long-wavelength region. Experiments in which there were conditions of adapting levels lower than the reference levels were not carried out because the luminous-efficiency functions under these conditions were not expected to differ from the function obtained for the same retinal illuminance of adapting light as the retinal illuminance of reference light. This expectation was derived from the fact that the luminous-efficiency functions under a no-adapting condition were not different from the functions obtained for the same retinal illuminance of adapting as that of the reference light; for example, the curve for 10-Td reference without adapting was similar to the curve for 10-Td reference at 10-Td adapting.

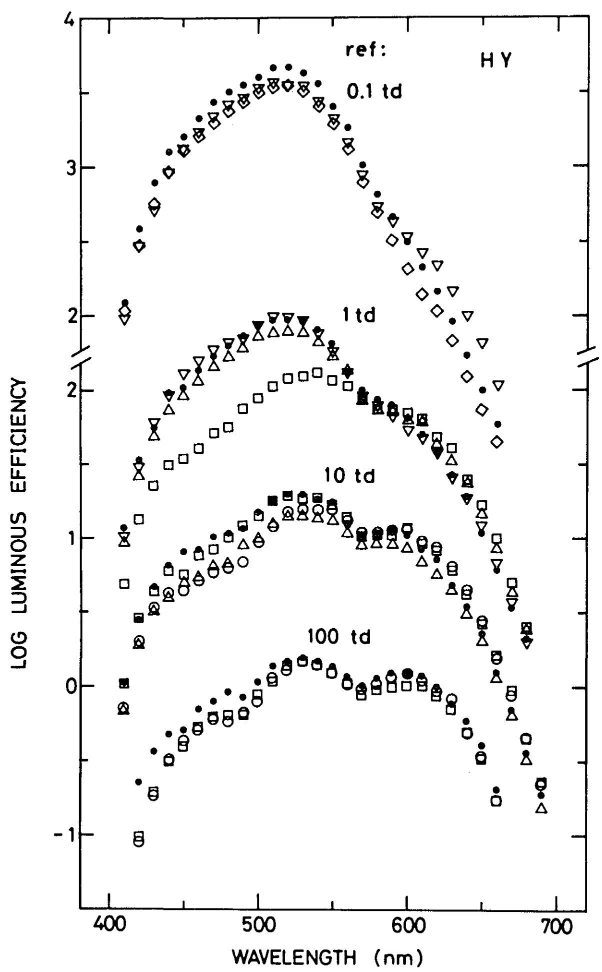

Fig. 1. Luminous functions at four retinal illuminances of reference field: 0.1, 1, 10, 100, and 1000 Td, from top to bottom. Each symbol corresponds to the adapting level: filled circles, no-adapting; open diamonds, 0.1 Td; open inverse triangles, 1 Td; open triangles, 10 Td; open squares, 100 Td; and open circles, 1000 Td. These functions were obtained from subject HY.

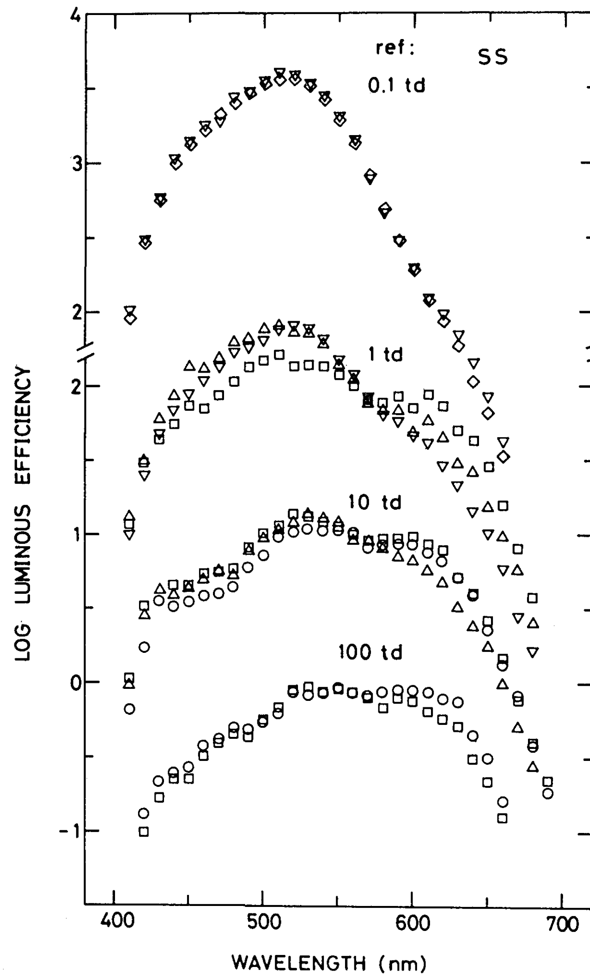

Fig. 2. Same as Fig. 1 but for subject SS. The data of no-adapting were not obtained for this subject.

When the highest adapting level of 1000 Td was presented to the subject, he could not see the reference light below 10 Td. For the same reason, the reference levels of 0.1 Td under 10- and 100-Td adapting could not be obtained. Although deviations of each datum point are not shown in Figs. 1 and 2, some of the same data in Fig. 1 are shown in Fig. 3, in which error bars indicate ±1 standard deviation for four sessions from subject HY.

The luminous-efficiency functions without adapting that are shown as filled circles in Fig. 1 are similar to the mesopic luminous-efficiency functions reported previously by Kinney[3] and Ikeda *et al.*[4] The curve for the 0.1-Td reference level without adapting is almost the same as the CIE scotopic $V'(\lambda)$ in the region of short and middle wavelengths. As the retinal illuminance of the reference light increases, the luminous-efficiency curve broadens, and some humps appear in the curve.

Because the curves for the 0.1-Td reference are similar to the scotopic function except for the long-wavelength region, the brightness at this intensity level is determined mostly by rods, but also by cones from 600 nm on. In the long-wavelength regions about 590 nm, the curve at 1-Td adapting shows significantly higher sensitivity than in a no-adapting condition (α = 0.05 by t test); furthermore, the subject perceived red here. The brightness in these regions therefore seems to be determined at least in part by cones.

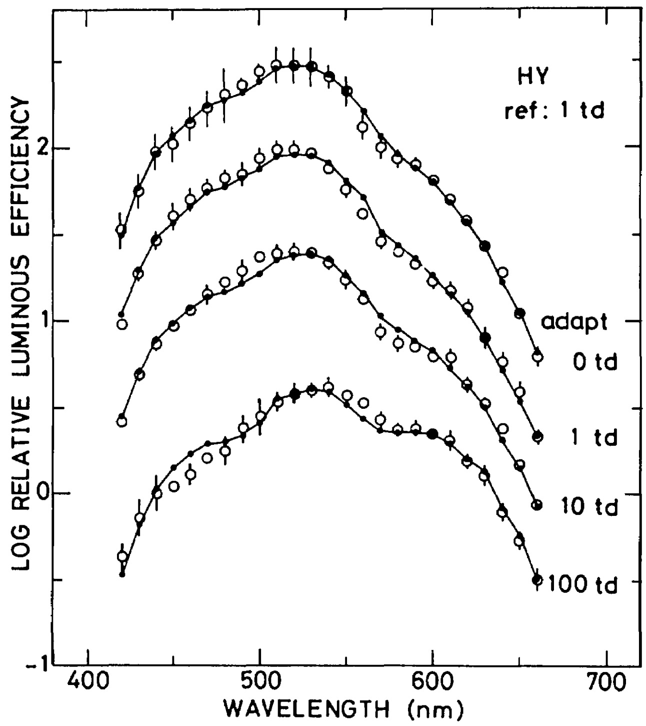

Fig. 3. Comparisons between the theoretical (filled circles) and experimental (open circles) luminous-efficiency functions for 1-Td reference at various adapting level. From top to bottom: no-adapting, 1, 10, and 100 Td for subject HY. Error bars indicate ±1 standard deviation for four sessions.

In the typical mesopic range of reference light of 1 and 10 Td, the shapes of the curves depend on the adapting level in greater or lesser degree. In particular, the luminous-efficiency curve of the 1-Td reference at a 100-Td adapting level differs from that of other adapting levels. For subject HY, the luminous efficiency of the 1-Td reference becomes significantly higher as the adapting level is increased in the red region above 600 nm ($\alpha = 0.05$). A similar result was obtained for subject SS. The luminous-efficiency curve for the 10-Td reference, however, does not depend so much on the adapting level as does that of the 1-Td reference.

The curves for the highest retinal illuminance of 100-Td reference light does not depend much on the adapting levels. The no-adapting curve is similar to the curve at 1000-Td adapting except for the short-wavelength region.

DISCUSSION

In Figs. 1 and 2 we showed that the luminous-efficiency function depends not only on the retinal illuminance level of the reference light but also on the adapting level. In order to analyze this dependence, the luminous-efficiency curves were analyzed by the Ikeda–Shimozono formula.

In that model the theoretical luminous-efficiency function $S_T(\lambda)$ is expressed as follows:

$$\log S_T(\lambda) = a \log S_R(\lambda) + b \log S_C(\lambda) + c,$$

where c is a constant and a and b are called adapting coefficients. $S_R(\lambda)$ is the luminous-efficiency function obtained by using the lowest adapting level at the lowest retinal illuminance level of the reference light; therefore this function closely represents the scotopic function. $S_C(\lambda)$ is the luminous-efficiency function obtained from the highest adapting at the highest reference level, so this function corresponds to the photopic luminous-efficiency function for brightness. The adapting coefficients a and b therefore relate to the contributions of rods and cones, respectively, to brightness. The constant factor c is only a bias component that does not influence the shape of $S_T(\lambda)$, which is not discussed further. We applied this formula to the luminous-efficiency curves obtained in Figs. 1 and 2 to find how the luminous-efficiency curves change according to the intensity level of reference and adapting.

$S_R(\lambda)$ and $S_C(\lambda)$ were derived from individual experimental data. Both the 0.1-Td curves from two subjects showed higher sensitivity than the CIE $V'(\lambda)$ in the red region. This discrepancy is due to the contribution from cones. Ikeda *et al.* mentioned that this red-cone contribution never disappeared, even at still lower illuminance levels, as long as the stimulus was presented foveally. Our 0.1-Td curves at the lowest adapting level were similar to the 0.01-Td curves of Ikeda *et al.*; therefore the luminous-efficiency function for the 0.1-Td reference and no-adapting for subject HY, and that for the 0.1-Td reference at 0.1-Td adapting for the subject SS, were chosen as $S_R(\lambda)$. For $S_C(\lambda)$, the luminous-efficiency function for the 100-Td reference at 1000-Td adapting from both subjects was chosen. The coefficients a, b, and c were obtained so that $\log S_T(\lambda)$ optimally fits the experimental luminous-efficiency function shown in Figs. 1 and 2 by the least-squares method.

Figures 4 and 5 show the coefficients a and b for subject HY and SS, respectively. Crosses mean that the reference light was invisible. Examples of curve fits are shown in Figs. 3 and

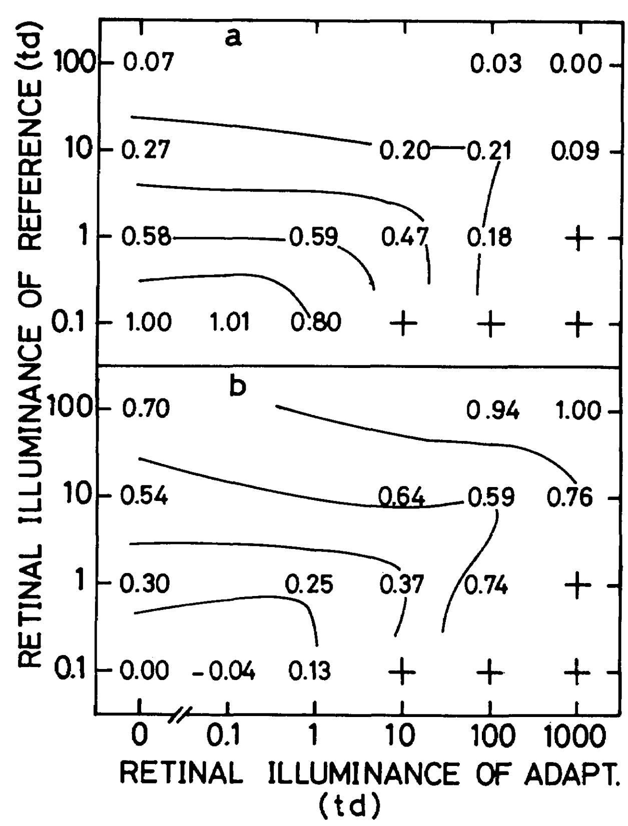

Fig. 4. The adapting coefficients a at the top and b at the bottom are from subject HY. Each continuous curve means equal values, which were drawn by the visual inspection.

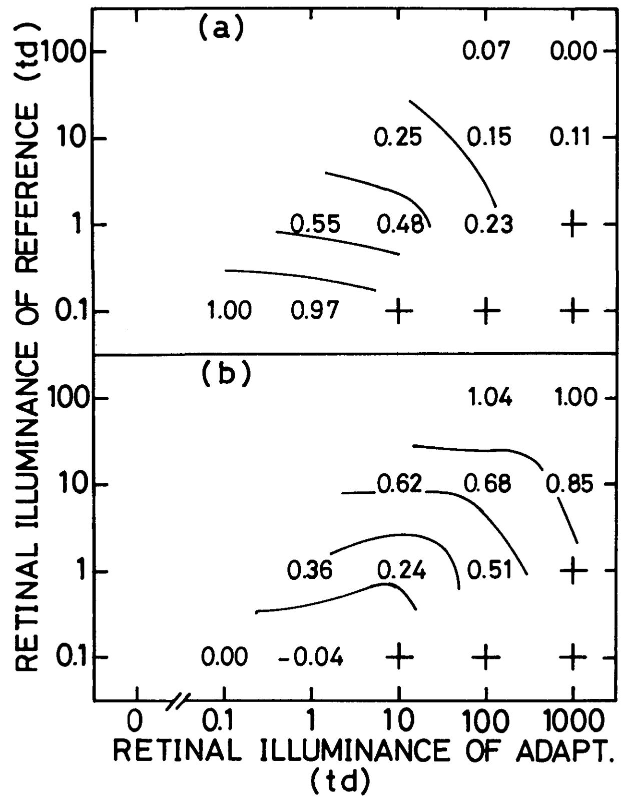

Fig. 5. Same as Fig. 4 but for subject SS.

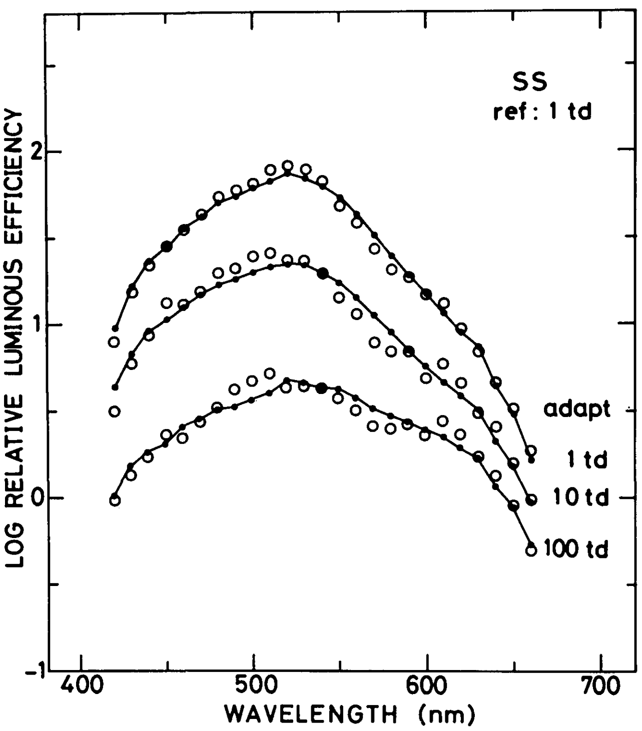

Fig. 6. Same as Fig. 3 but for subject SS. The data for no-adapting were not obtained here.

6. Figure 3 shows the theoretical curves (expressed as filled circles connecting solid lines) and the experimental data (expressed as open circles) for 1-Td reference light at various adapting levels: no-adapting, 1, 10, and 100 Td, from top to bottom, from subject HY. Figure 6 is the same as Fig. 3 but for subject SS. The curve fits agree well for both subjects.

At the highest level of 100 Td of reference light, the coefficients a and b are close to 0.0 and 1.0, respectively; therefore the brightness is determined by cones at any adapting level. Conversely, at the lowest level the coefficients are close to $a = 1.0$ and $b = 0.0$, so the brightness is determined by rods provided that the reference light is visible. But at intermediate levels of 1 and 10 Td, the brightness seems to be influenced by both the intensity level of the reference light and the adapting level. The adapting coefficient a of a 10-Td reference from HY (Fig. 4) varies slightly from 0.20 to 0.27 with the adapting levels of 0, 10, and 100 Td. On the other hand, that of the 1000-Td adapting level, 0.09, is apparently lower than that of other levels. For the 1-Td reference level, although the adapting coefficient a does not vary greatly from 0.47 to 0.59 with the adapting levels of 0, 1, and 10 Td, that of 100-Td adapting, 0.18, is apparently low. Therefore, if the adapting level is 2 log units lower than the reference level, the luminous-efficiency function is influenced by the adapting level. Similar results was obtained with subject SS.

In conclusion, the luminous-efficiency function for brightness at mesopic levels depends not only on the intensity level of the test stimulus but also on the adaptation level of the subject's eye. When the subject is in a brightly illuminated environment, the luminous-efficiency function becomes photopic at any intensity level of a test stimulus that can be seen. In other words, even if the test stimulus is low, the luminous-efficiency function obtained by the highly adapted eye is always photopic. This is because dark adaptation proceeds slowly.[6,7] Similarly, the luminous-efficiency function for a high-intensity level of the test stimulus becomes photopic, independently of the adapting level. Presumably, this is because light adaptation proceeded rapidly[8,9] and the subject's eye was adapted by the test stimulus under the present experimental condition.

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