Luminous efficiency function for small stimulus size

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Luminous efficiencies obtained for a small test field of 2.3′ showed a simple and narrow type of curve regardless of experimental methods, flicker photometry and heterochromatic brightness matching. Past available data of luminous efficiencies for small fields were collected from published papers and plotted together on one graph, from which a single curve was derived to represent the luminous efficiency function for point sources. The function resembled the CIE $V(\lambda)$.

Need for establishing the luminous efficiency function for point sources was emphasized by Kinney[1], the last chairperson for the CIE Technical Committee TC 1.4 Vision. We are equipped with the photopic luminous efficiency function for 2° field, $V(\lambda)$, but it is uncertain whether this function is also valid for stimuli much smaller than 2° since the visual system may function differently for different sizes.

In a previous report[2] we determined luminous efficiency functions at fovea for various sizes, 68.7′, 22.9′, 11.5′, and 2.3′ are of visual angle from two male subjects of 24 and 26 years old with two different methods, flicker photometry and heterochromatic brightness matching, and found that the luminous efficiency functions became very alike in their shape when the stimulus size was made very small, regardless of the experimental methods. The evidence is summarized in **Fig. 1** where luminous efficiencies for 2.3′ are plotted together for the two methods and for the two subjects. At each wavelength except at 400 nm there are four experimental points corresponding to different conditions. Points are normalized relative to 560 nm. It seems not too unreasonable to represent all points by one smooth curve. The difference in experimental methods does not matter in determining the luminous efficiency function for point source.

The above fact suggests us that we can plot all the available data of luminous efficiencies on a same one graph regardless of different conditions if they were obtained for small test fields. We collected the past available data from published papers which concerned with luminous efficiencies for small test sizes, smaller than 10′, presented at fovea, and plotted them together in **Fig. 2.** Experimental methods differed among authors: Abramov et al.[3] (open circles) employed the flicker

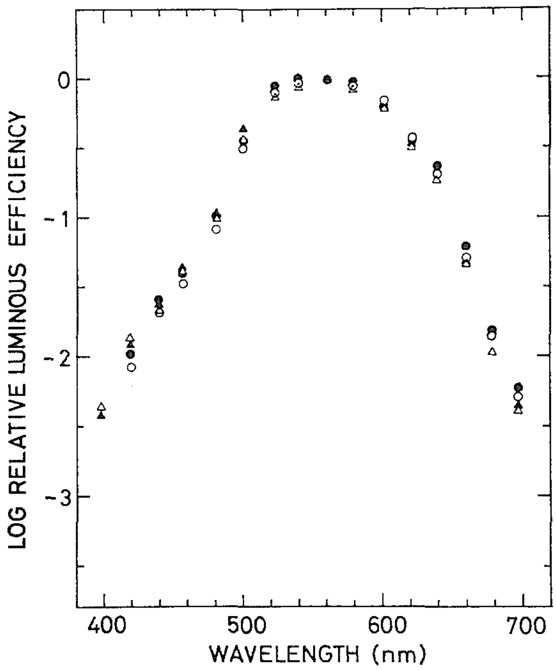

Fig. 1 *Luminous efficiencies for 2.3′ stimulus size obtained with heterochromatic brightness matching (filled) and flicker photometry (opened) from two subjects (triangles and squares). Paints are normalized relative to 560 nm.*

photometry for a 5′ test size with a reference light of 560 nm at 1,200 td, Bedford et al.[4] (open triangles) employed the heterochromatic brightness matching for a 1.5′ test size with a white reference light at 150, 1,500, and 11,000 td, and we[2] employed both flicker photometry (filled circles) and heterochromatic brightness matching (filled triangles) for 2.3′ test size with a white reference light at 100 td. Data obtained by another method, namely the absolute threshold, are also included from Sperling et al.[5] (filled squares) who used a stimulus of 3′ and from Wald[6] (open squares) who

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used 8.5′. Different authors employed different numbers of subjects and only averaged values are presented in the figure. Data are normalized for 560 nm.

In spite of a variety in the experimental conditions all points except at short wavelengths come together to construct one smooth and narrow luminous efficiency curve. This convergence is contrasted to varieties found in luminous efficiencies obtained for test sizes at a neighborhood of 2° arc. **Fig.** 3 shows such efficiency curves taken from the CIE TC-1.4 Technical Report[7], corresponding to three different methods, the heterochromatic brightness matching (triangles), the absolute threshold (filled squares), and the flicker photometry (circles). The curve of the flicker photometry is represented by the Judd's modification of $V(\lambda)$ which was further modified by Vos[8]. Points are normalized relative to 570 nm. The difference among curves is quite evident, in particular at long and middle wavelengths.

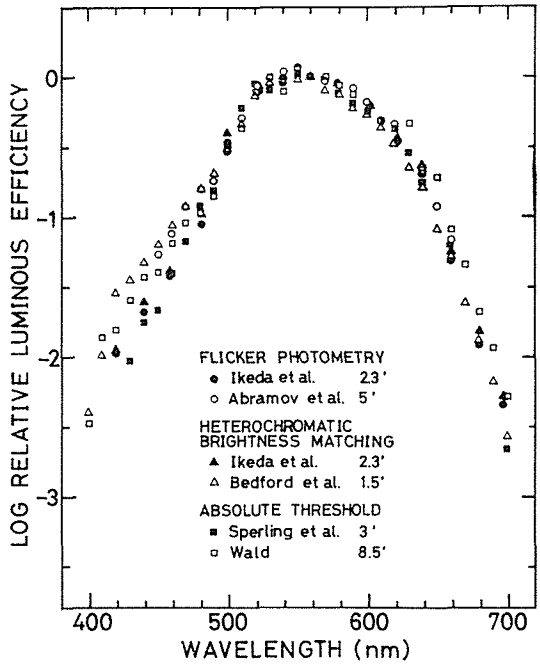

Fig. 2 *Luminous efficiencies for small stimulus size determined by various authors. Points are normalized relative to 560 nm.*

Returning to Fig. 2, such difference is no longer present and only one and narrow type of curve is exhibited. The variance at short wavelengths is not a new phenomenon and is commonly found in spectral sensitivities of any type. It is normally interpreted as the effect of individual differences in densities of pre-receptoral substances such as yellow pigments and crystalline lenses.

To derive a standard luminous efficiency function for point sources, a weighted mean was calculated at each wavelength according to the number of subjects employed in each author of Fig. 2; six in Abramov et al., four in Bedford et al., three in Sperling et al., and two in Wald. Our data were collected for two subjects at 20 nm steps and the intermediate values were interpolated by the visual inspection. Results are shown by circles in **Fig. 4.** Some authors did not cover all the wavelengths

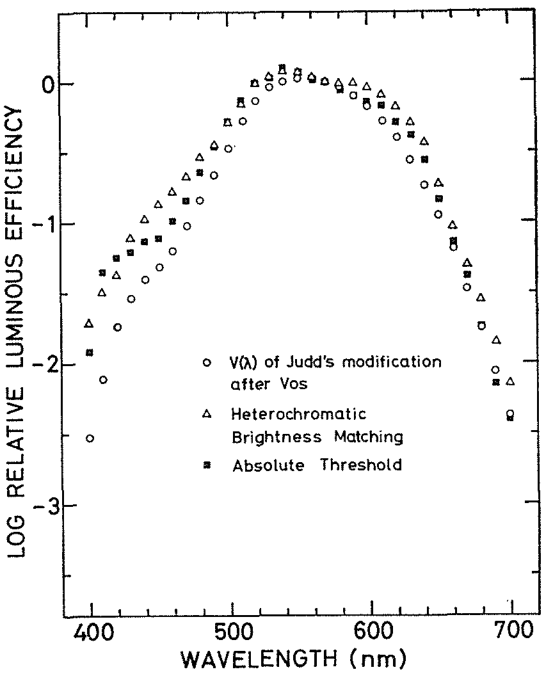

Fig. 3 *Luminous efficiencies for 2° or a little less sizes obtained with three different methods, heterochromatic brightness (triangles), absolute threshold (squares), and flicker phtometry (circles).*

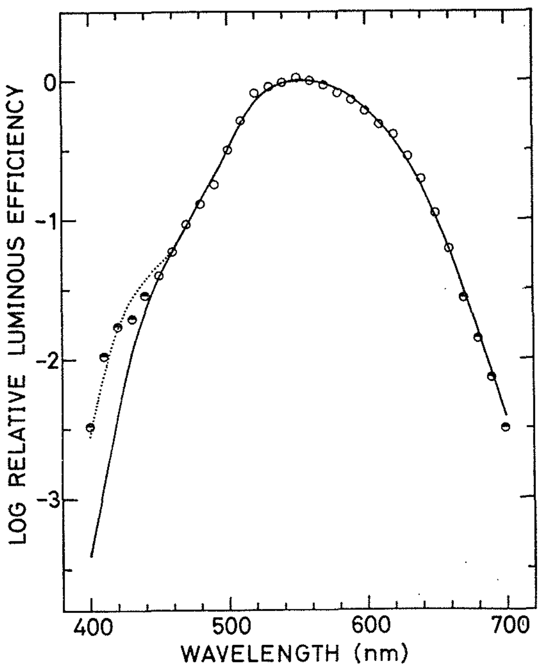

Fig. 4 *Mean luminous efficiencies of six investigations appearing in Fig. 2. Half-filled circles indicate incomplete data compared to others shown by open circles. Solid line: CIE V(λ), dotted line: Judd,s modification after Vos.*

from 400 nm through 700 nm as seen in Fig. 2, and means were obtained from reduced number of subjects in the incomplete regions, which are indicated by half-filled circles. The solid curve represents the CIE $V(\lambda)$ and the dotted curve the Judd's modification of $V(\lambda)$, same as circles of Fig. 3. Both curves are normalized for 560 nm in accordance to the experimental points.

It is clearly seen in Fig. 4 that the luminous efficiencies for small test fields less than 10′ of arc are nicely fitted by the CIE $V(\lambda)$ except at the blue region. The situation is quite fortunate for us as we are freed from establishing yet another luminous efficiency function for point sources. We can utilize the already existing photopic luminous efficiency function for them. It is uncertain, however, which of the two, $V(\lambda)$ or its modification according to Judd, should be finally adopted at the blue region, although the present incomplete data at the region look to favor the Judd's modification.

The narrow feature of the luminous efficiency function which does not have double peaks at around 620 nm and 540 nm common in large test fields with the heterochromatic brightness matching, suggests an advantage of the function in that the additivity holds. The additivity failure between two or more spectral lights is often observed in the brightness matching, and it causes a great complication in photometry where the luminous efficiency function is used. The additivity failure is related to the cancellation among responses within the opponent-colors channels of the visual system[9)-11)]. The disappearance of the double peaks in the luminous efficiency function, therefore, suggests the disappearance of the contribution of the opponent-colors channels to the function when the stimulus size is decreased. Consequently the additivity failure should also disappeare and a simple integration of the luminous responses due to the compound spectral lights will represent the resultant luminous response, which is quite advantageous in photometry.

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