Luminous Efficiency and the Measurement of Daytime Displays, Signals, and Visors

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Purpose: Measurements concerning the usability or safety of optical equipment are based on assumptions regarding luminous efficiency. The current luminous efficiency functions are derived from human sensitivity experiments taken at low light levels compared with the outdoor daytime environment. The amount of error induced by extrapolating from low light level data to high light level applications is not known. We sought to determine whether standard luminous efficiency curves CIE V(λ) and CIE Heterochromatic Brightness Matching are appropriate for measuring day-use optical equipment such as display phosphors, lasers, LEDs, and laser eye protection, which are becoming more common in aviation. **Methods:** Flicker photometry and successive heterochromatic brightness matching were used to measure changes in luminance efficiency functions with increasing levels (1, 10, 100, and 1000 fL) of light adaptation. **Results:** Luminous efficiency was found to depend on both the method and the reference intensity with which the measurements were taken. For heterochromatic brightness matching, luminous efficiency increased for longer wavelengths as reference intensity increased. Peak luminous efficiency shifted from approximately 540 nm to greater than 600 nm with increasing intensity. Peak luminous efficiency was constant for flicker photometry across all intensities, but the function narrowed slightly at 100 fL. **Conclusion:** Luminous efficiency curves measured at high reference intensities are substantially different from the standard luminous efficiency functions. Caution should be used when measuring spectrally narrow and bright sources such as lasers and LEDs with a V(λ) corrected photometer because the measured luminance may correlate poorly with perceived brightness.
Keywords: heterochromatic brightness matching, flicker photometry, psychophysical measurement.

MEASUREMENTS OF LIGHT sources including cockpit displays, beacons, and signals require assumptions about the luminous efficiency of the human visual system. Likewise the transmission measurements of windscreens, HUD/HMD combiners, visors, sunglasses, and laser eye protection are based on a luminous efficiency function. The most frequently used function for these purposes is the International Commission on Illumination (CIE) Spectral Luminous Efficiency Function for Photopic Vision (V(λ)). Because of its widespread use and convenience, V(λ) is often used in measurements when other luminous efficiency functions would be more accurate. Use of V(λ) is widely accepted because it is assumed that the errors introduced are small. For example, in the photometric comparisons of two incandescent lamps with spectrally broad outputs, any error induced by the luminous efficiency function used in the measurement of the first lamp will be cancelled by a similar error in the mea-

surement of the second. However, cancellation of errors will not occur if the light sources compared are spectrally narrow and dissimilar, such as with phosphors, diodes, and lasers (8). Recent non-lethal technologies research regarding laser illuminators has revealed situations in which photometry based on V(λ) has been poor at predicting device performance.

Laser illuminators are designed to protect military assets through visual glare and discomfort without causing injury. Initial work on laser illuminators, conducted using a deep red (650 nm) diode laser, found that these devices were only useful under low light conditions. An attempt to improve illuminator performance by switching to a 532-nm laser, a green wavelength that is more luminously efficient according to V(λ), was disappointing. It is unclear whether the poor performance of the 532-nm system was due to an overestimate of the luminous efficiency of 532-nm light under these viewing conditions or a result of limitations of the illuminator's optical design (3).

It is possible to measure luminous efficiency functions with a variety of psychophysical measurement techniques, including heterochromatic brightness matching, increment threshold detection, or flicker photometry. To derive a luminous efficiency function we typically adjust the energy output of a narrow wavelength band (monochromatic) light source in order to accomplish a perceptual tie (brightness match, just noticeable brightness difference, minimal flicker) to a standard light stimulus. The more energy required to meet the perceptual requirement, the less efficient that wavelength of light is at producing visual sensation. If this process is repeated across many different wavelengths, the efficiencies of the different wavelengths can be compared, thereby defining a luminous efficiency function. The resulting luminous efficiency functions are known to be dependent on both the psychophysical technique

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and characteristics of the standard stimulus used (6,7,10). The exploration of technique/stimulus dependence has been a fruitful area of research over many decades, contributing greatly to our understanding of human vision.

Only minimal psychophysical explorations of luminous efficiency have been conducted at high photopic stimulus levels. The major reason for this void was the absence of high intensity spectrally narrow light sources. Without high intensity spectrally narrow light sources, it is very difficult to create the test stimuli required for the psychophysical measurements. However, the increasing importance of day-use display phosphors, lasers, and LEDs as light sources has created a need to evaluate luminous efficiency functions at high photopic intensities.

CIE Technical Committee 1.4 encourages the use of their CIE Luminous Efficiency Curve for Centrally-Viewed, Two Degree Field by Heterochromatic Brightness Matching (CIE-HBM) as an alternative to V(λ) for photometric measurement of spectrally narrow sources such as phosphors, LEDs, and lasers (11). These newer light sources can produce intensities several orders of magnitude higher than those used to generate most of the published heterochromatic brightness matching luminance efficiency curves on which the CIE-HBM is based (1,2,4,9,13,15,16).

Because of the importance of this issue in lighting design and engineering, we decided to investigate luminous efficiency functions at high intensities using two psychophysical techniques: flicker photometry, which was fundamental in the development of V(λ), and successive heterochromatic brightness matching. Successive heterochromatic brightness matching is felt to produce results similar to the traditional heterochromatic brightness matching advocated by CIE Technical Committee 1.4 and has the advantage of using the same apparatus as flicker photometry (5). The major goal of this study was to compare results of the two methods to their related CIE standard functions and to each other directly, using the same optical system and subjects, in order to explore how luminance efficiency functions change with increasing intensity so that we can better predict the visual perception of spectrally narrow and bright light sources.

METHODS

Apparatus

Light from a 1000-W xenon arc lamp was split 99/1 using an antireflective window to produce two illumination channels, a spectrally broad (white) reference channel and a monochromatic test channel. The test channel could be varied in intensity and monochromatic spectral content using an iris aperture, a remotely controlled, motor driven, dual, counter rotating set of variable density filters (variable density filter system) and a motorized filter wheel which contained 17 narrow (10-mm full width-half maximum) bandpass interference filters. Nominal wavelengths for the monochromatic filters were 420, 450, 480, 500, 510, 520, 532, 540, 550, 560, 568, 580, 589, 600, 620, 650, and 676 nm.

The reference channel was modulated in intensity using a circular variable density filter and an iris aperture. A rotating mirrored, variable frequency optical chopper was used to merge the two channels spatially while maintaining temporal separation. The reference and test channels alternately illuminated the end of a 19 mm diameter acrylic cylinder that served both as a diffusing optic to dampen the variation in beam intensity and as a backlit viewing screen to produce the stimulus field. A chin rest was used to position the subject 53 cm from the viewing end of the diffusing optic. The stimulus subtended 2° of visual angle.

Calibration

After each trial, the test stimulus radiance was calculated from the system output at the given wavelength multiplied by the subject's transmission setting from the variable density filter system. Measurement of the system output at each wavelength and calibration of the variable density filter system was accomplished using a NIST traceable Photo Research PR 650 spectroradiometer. Calibration for the variable density filter system was accomplished for each of the 17 wavelengths. For each test wavelength, the transmission of the variable density system was sampled at 22° intervals. The transmission values were imported into Sigma Plot 5.0 and a non-linear regression was performed to model the angular rotation vs. filter transmission function. The resulting regression equations fit the data points very well ($r^2 > 0.98$ across all wavelengths).

Spectral calibration for the test stimulus channel was verified by comparing the manufacturer's nominal filter transmission peaks and band widths for each of the narrow bandpass filters against the measured transmission peaks using the PR 650 Spectrascan spectroradiometer. Nominal specifications and measured characteristics were found to be in agreement for all 17 filters.

The measurement of the relative spectral output was conducted both before and after the experiment to verify that expected changes in spectral output (due to aging of the lamp and other factors) were small compared with the measured effect size. The lamp output shifted slightly toward longer wavelengths, suggesting that we have slightly underestimated short wavelength sensitivity in the luminous efficiency curves.

Procedure

After allowing the xenon lamp to warm up for a minimum of 30 min to reach equilibrium, the reference channel was adjusted to one of four luminance levels (1, 10, 100, or 1000 fL). The test channel's interference filter wheel was then rotated to the open (achromatic) position, and the test channel's luminance was adjusted to match the luminance of the reference channel. The chopper was started at either 2 Hz for the heterochromatic brightness matching trials or 20–30 Hz for the flicker photometry trials. The alternating achromatic, equal luminance, reference, and test fields served as an adapting source, viewed by the subject, before each set of trials. After the subject viewed the adapting field for 30 s, one of the wavelength interference filters, selected

randomly without replacement, was rotated into the test channel. The subject then adjusted the test field brightness to match the reference field using the variable density filter system. Once the match was made, the experimenter recorded the variable density filter system setting in a spreadsheet. The experimenter then decreased the test channel intensity by at least 2 log units and the subject made another match. Four trials (matches) were made in immediate succession. Each trial began with the test channel intensity set at least 2 log units below the match intensity.

After completing the four trials for a given wavelength, the subject viewed the adapting source for 30 s and a set of trials was started at the next wavelength in the random sequence. This process was repeated until all 17 test field wavelengths had been completed.

Subjects

The institutional review board of the University of Missouri–St. Louis approved all of the experimental procedures used in this study including the informed consent form signed by each subject. Seven subjects, four women and three men, ranging in age between 22 and 41 yr, were selected to participate in this study. Subjects were screened for normal color vision using pseudoisochromatic plates and were paid for their participation. All seven subjects completed all of the measurements. Prior to data collection, each subject practiced between 2 and 6 h, an average of 3.1 h, on the tasks. Most of the practice was dedicated to the more difficult task, heterochromatic brightness matching. Practice was divided over several days.

Data Reduction

The variable density filter system settings from each trial were converted to system transmission values using the regression equations derived from the filter calibration and then the four transmission values for each wavelength were averaged. These average transmissions were multiplied by the respective test channel radiance value to produce an averaged test stimulus radiance value for each wavelength. The reciprocal of these "equal brightness" radiance values produced the relative sensitivity values.

In order to compare relative sensitivity data across methods and intensities, it was necessary to normalize the data. In order to compare this study's results directly with V(λ), the measured sensitivity values were divided by the peak value for each individual curve and the maximum relative sensitivity for each curve was set at 1. This transformation was conducted on all 56 individual curves (7 subjects in each of 8 conditions), the between-subject mean curves for each experimental condition, and also for the CIE-HBM. Once the transformations were performed, the individual and between-subject mean curves could be compared with one another and to the CIE standard luminous efficiency curves. A Method (Flicker Photometry, Heterochromatic Brightness Match) × Level (1 fL, 10 fL, 100 fL, 1000 fl) × Wavelength analysis of variance (ANOVA) was performed. Data from wavelengths less than 500

nm or greater than 600 nm were excluded because there was insufficient radiance in the monochromatic channel for at least one subject to make the match at these wavelengths.

RESULTS

The only physical difference between the flicker photometry task and the heterochromatic brightness matching task was the rate at which the reference and the test stimuli alternated. Still, this small change in physical parameter had a profound impact on the subjects' performance. Subjects found the flicker photometry task relatively easy to perform and were able to make rapid and repeatable flicker matches with no more than 15 min of practice. All subjects found the heterochromatic brightness matching task to be considerably more difficult than the flicker photometry task, required more practice on brightness matching, and exhibited greater variability in their settings at each wavelength. Each data collection session lasted approximately 60 min for flicker photometry and approximately 90 min for brightness matching.

Fig. 1 shows the normalized between-subject mean flicker photometry curves for each reference intensity along with V(λ). At the 1-fL and 10-fL intensities, the flicker photometry curves are complete between 420 nm and 676 nm. At 100 fL and 1000 fL, the curves are truncated on both the short wavelength and long wavelength portions because there was not enough radiance in the monochromatic channel for at least one subject to make the match at these wavelengths. The flicker photometry curves are narrow and unimodal with peaks around 560 nm. Overall, the shapes of the curves are nearly identical to V(λ). The sole exception is the curve for the 100-fL flicker, which appears to be slightly narrower. Between-subject variability in curve shape was also low on the flicker task. Each subject's luminous efficiency curve had a similar shape and peak to V(λ) at 1 fL, 10 fL, and 1000 fL, and each subject's luminous efficiency curve was narrower than V(λ) at 100 fL.

In contrast to the flicker data, the normalized between-subject mean heterochromatic brightness matching curves are broad and show multiple peaks, as plotted in Fig. 2 along with the CIE-HBM for each reference intensity. At each of the four intensities, the data show a middle wavelength peak near 550 nm, a notch between 550 nm and 600 nm, and a long wavelength peak at 600 nm or higher. With increasing intensity, the size of the longer wavelength peak grows relative to the middle peak and the wavelength of maximum sensitivity shifts from 560 nm to approximately 620 nm. The breadth of the curves increases with increasing intensity, particularly in the long wavelength portion of the spectrum.

At the 1-fL reference intensity, the between-subject mean curve is similar to the CIE-HBM. The peak sensitivities for both curves are near 550 nm and the luminous efficiency values in the long wavelength portion of the spectrum are nearly identical. However, the between-subject mean curve shows greater sensitivity at short wavelengths and the 580-nm notch in the between-subject mean curve is not found
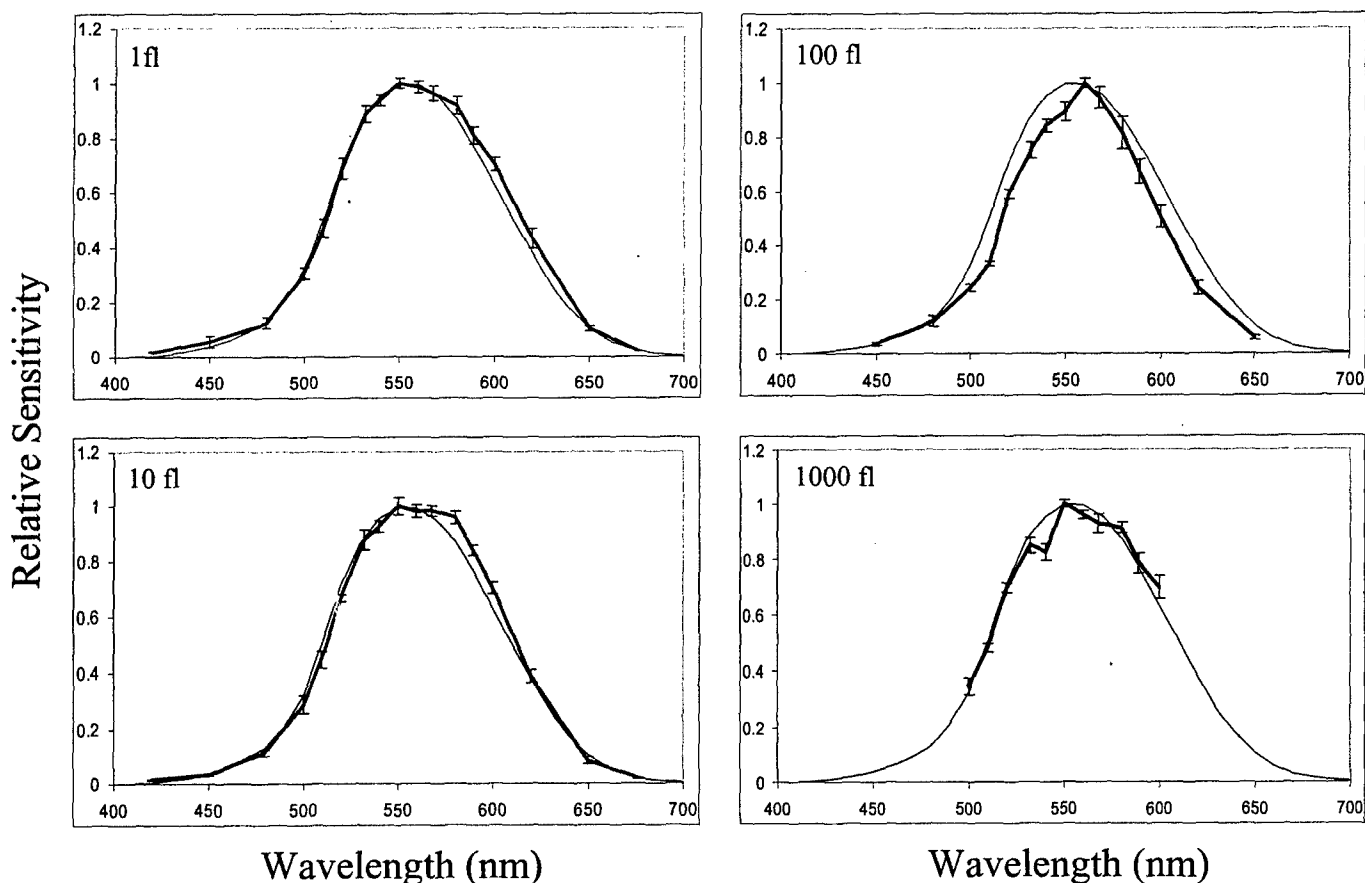
Fig. 1. Mean luminous efficiency for the seven subjects by flicker photometry (thick line) compared with the CIE V(λ) (thin line) at each of the four reference intensities. Error bars show SEM at each wavelength.

in the CIE-HBM. At the 10-fL intensity, the two curves are similar at wavelengths up to 600 nm but, at the longer wavelengths, the between-subject mean curve shows substantially higher relative sensitivity. At the 100- and 1000-fL intensities, there are substantial differences between our measured luminous efficiencies and the CIE-HBM. Despite the fact that between-subject variability was higher on the heterochromatic brightness matching task than for flicker photometry, the major changes found in the averaged curves were also apparent in each individual's curves. For example, every subject had an absolute maximum sensitivity above 600 nm and a notch between 550 nm and 600 nm at either the 100-fL or 1000-fL intensity.

A direct comparison between the two psychophysical methods across reference intensities is shown in **Fig. 3**. The heterochromatic brightness matching curves are broader than the flicker curves at all intensities and the peak of the curve is shifted toward 620 nm with increasing intensity while the flicker peak remains constant. Peak sensitivity for heterochromatic brightness matching at the 100-fL and 1000-fL levels is outside of the 500- to 600-nm range over which it was possible to obtain complete matches by flicker photometry. Consequently the normalized 100-fL and the 1000-fL heterochromatic brightness matching curves are lower in that spectral range than for the conditions where the curve peaks

remain around 550 nm. In addition, the 100-fL flicker photometry curve appears to be narrower than the flicker curves at the other intensities, as also seen in Fig. 1.

In the three-variable repeated measures ANOVA, the main effects of Method (p = 0.004), Level (p = 0.008), and Wavelength (p < 0.001) were all significant. More importantly, the interactions Method × Wavelength, Level × Wavelength, and the three-way Method × Level × Wavelength were highly significant (each with p < 0.001). The significant interactions of Method × Wavelength and Level × Wavelength support the conclusion that the shape of the sensitivity curve changes with the method for measuring sensitivity and the intensity of the reference.

Since the main effect for Method was significant, we analyzed the Level factor separately for the flicker and heterochromatic brightness matching conditions. Under both conditions, the effect of Level was found to be significant (for flicker p = 0.002 and for heterochromatic brightness matching p = 0.037). The pairwise comparison for the flicker data showed that the relative sensitivity was lower for the 100-fL level than for 1 fL (p = 0.008), 10 fL (p = 0.025) and 1000 fL (p = 0.007). Pairwise comparisons for heterochromatic brightness matching found that relative sensitivity was lower at the 100-fL level than at the 10-fL level (p = 0.013).
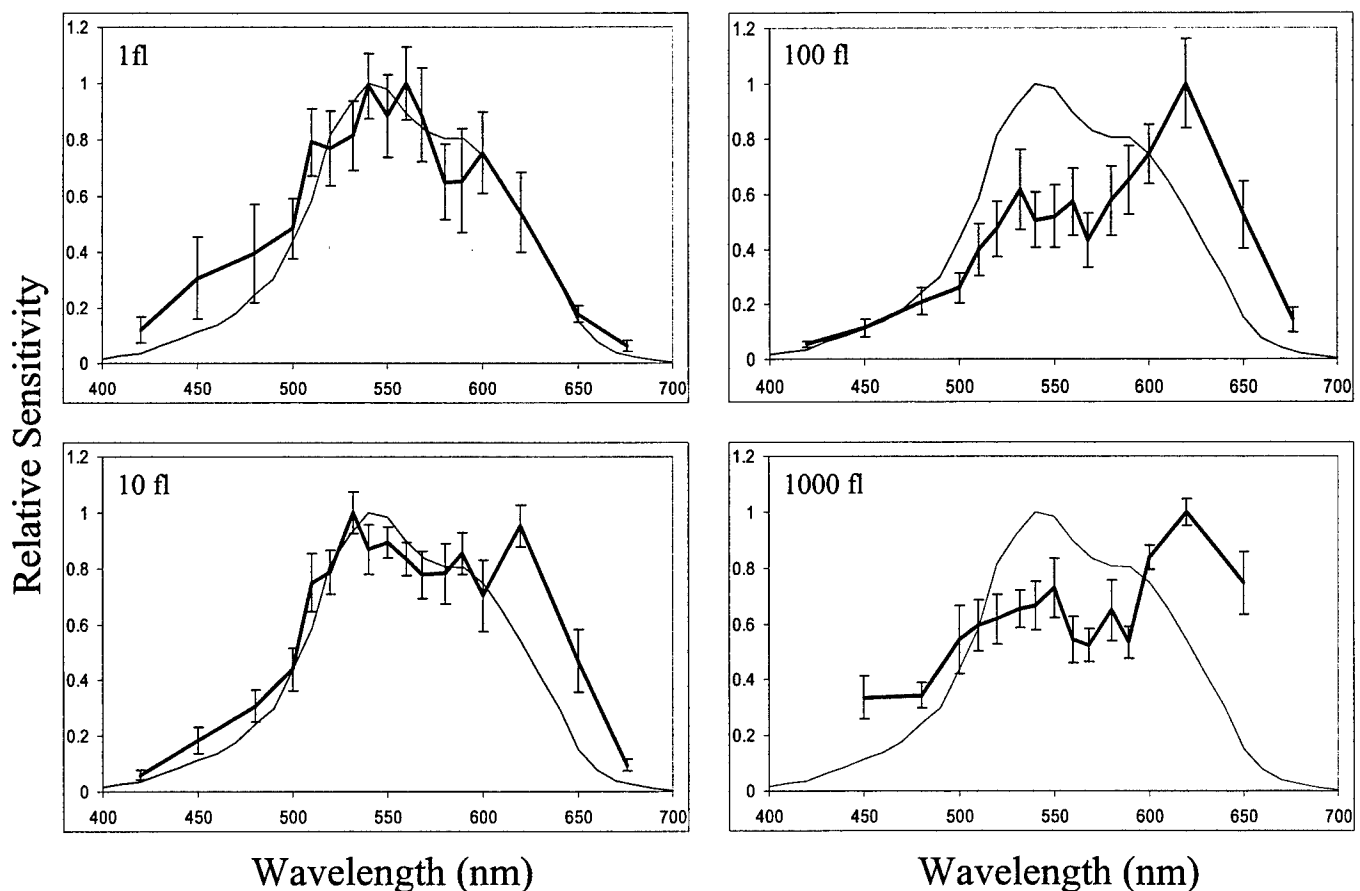
Fig. 2. Mean luminous efficiency for the seven subjects by heterochromatic brightness matching (thick line) compared with the CIE-HBM (thin line) at each of the four reference intensities. Error bars show SEM at each wavelength.

DISCUSSION

We conducted psychophysical measurements of luminous efficiency at intensities one order of magnitude greater than previously published in English literature. To accomplish this task we had to build a high intensity flicker photometer whose performance approached the practical limits of a system based on notch filtering of a spectrally broad light source. We then calibrated the system over 3 orders of magnitude in intensity. With this system we demonstrated that we could replicate earlier research conducted at lower intensities and then collected new data at intensities rarely achieved previously.

The major conclusion that can be drawn from this study is that perceived brightness of light sources across the spectrum varies with the intensity of the light. This was shown by changes in the shape of the heterochromatic brightness matching relative sensitivity curves as reference stimulus intensity increased: the relative sensitivity in the long wavelength region of the visible spectrum increased, and the peak sensitivity of the curve shifted from approximately 540 nm at 1 fL to over 600 nm at 100 and 1000 fL. The shapes of the flicker photometry curves were also found to be dependent on reference intensity, although this effect was much less dramatic than for the curves obtained with the heterochromatic brightness matching method. The flicker curve was found to be slightly narrower for the 100-fL

intensity. In contrast to the changes in peak sensitivity obtained with brightness matching, with flicker photometry the wavelength of peak sensitivity remained constant at approximately 550 nm for all intensity levels.

The similarity of the flicker photometry curves to $V(\lambda)$ and the relative stability of the curves across the different reference intensities provides reassurance that our apparatus, subjects, calibration processes, and testing procedures were appropriate. The consistency of the peaks in the flicker data at the different intensities also argues against adaptation or saturation at the photoreceptor level as a viable explanation of our heterochromatic brightness matching results. The flicker data do not rule out adaptation or saturation in some location in the visual pathways that is relatively isolated from luminance (flicker) processing.

Of the studies that can be compared with the current experiment, that of Sagawa et al. (12) is the most recent and directly relevant. Sagawa et al. conducted both flicker photometry and heterochromatic brightness matching experiments across three log units (seven levels) of reference intensity. Their brightest level was slightly more intense than the highest level in this study. The flicker photometry results of Sagawa et al. were similar to those of the present study in that they found a small decrease in relative sensitivity with increasing retinal illuminance; however, this reduced sen-
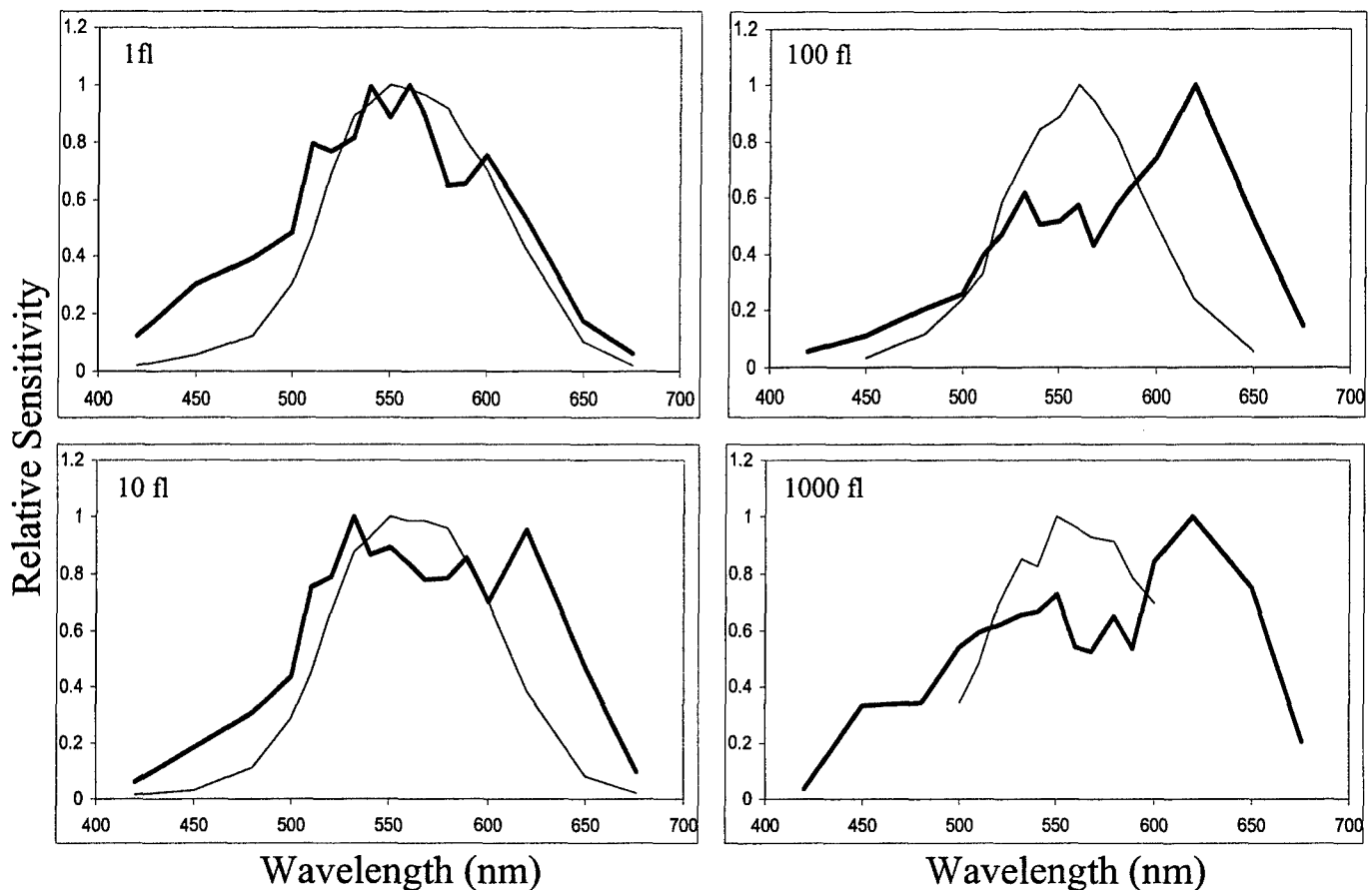
Fig. 3. Mean luminous efficiency for the seven subjects by heterochromatic brightness matching (thick line) and flicker photometry (thin line).

sitivity was obtained only at longer wavelengths. We found a small decrease in sensitivity at both long and short wavelengths, creating a measurable narrowing of the luminous efficiency curve at 100 fL. Despite this slight narrowing at 100 fL, the similarities between the flicker photometry curves in the present study, the Sagawa et al. study, and V(λ) are striking. However, this pattern of consistency across experiments and reference intensities in the flicker photometry condition does not hold for heterochromatic brightness matching.

In their heterochromatic brightness matching experiments, Sagawa and colleagues found that the relative sensitivity to both the longer and shorter wavelengths increased with increasing reference intensity between 100 trolands (~1 fL) and 3000 trolands (~50 fL). Sagawa et al. considered this increased relative sensitivity in the short and long wavelengths to be evidence of increasing chromatic contributions to brightness perception. Between 3000 and 100,000 trolands, they found that relative sensitivities were stable across wavelengths, and interpreted these results as evidence for saturation of the chromatic channel. In contrast, our heterochromatic brightness matching curves showed evidence for changes in sensitivity at higher intensities. The 1000-fL curve was broader than the 100-fL curve and the relative sensitivity at longer wavelengths was improved, particularly at 650 nm. Although this change was smaller than those that occurred between 10 fL and 100 fL, it suggests that luminous efficiency changes over a greater range than previously demonstrated.

At all reference intensities, the heterochromatic brightness matching curves of Sagawa et al. were unimodal with definite peaks near 540 nm and a small plateau between 580 and 620 nm. They were similar in appearance to CIE-HBM shown in Fig. 2. Their data are similar to those from the current study in that, for the longer wavelengths, the sensitivities from heterochromatic brightness matching increased with increasing reference intensity at least up to ~50 fL (3000 trolands). The magnitude of this increase was less in the subjects studied by Sagawa et al. than in the current study and a "notch" was not present between 550 and 600 nm as was found in this study. Additionally, while Sagawa et al. found peaks of the heterochromatic brightness matching curves at approximately 540 nm at all levels of reference intensity, in the present data, the peak sensitivities shifted into the low 600-nm region as reference intensity increased.

Other studies have also shown comparable but less dramatic changes in heterochromatic brightness matching curves than were found in this study. Yaguchi and Ikeda (18) found substantial between-subject differences in heterochromatic brightness matching data over three log units of reference intensity in which their brightest level was approximately equal to our 10-fL condition. Only one of four subjects showed a dramatic change in relative sensitivity, most notably the development of a second peak at 600 nm, one subject showed no change at all, and two subjects showed intermediate changes. Overall, they concluded that: "There are two

extreme types among observers at high illuminance levels. One type shows a change in the relative luminous efficiency curve with the change of the retinal illuminance level, and another type shows no change." In contrast, all of our subjects showed changes in relative sensitivity with increasing reference intensities. The most likely reason for this difference is that our reference levels were considerably higher.

Differences in reference intensity are also the likely explanation for the differences between the heterochromatic brightness matching curves in the present study and CIE-HBM. The CIE function is an average taken from 31 subjects across 7 different studies (1,2,4,9,11,15,16). Reference intensities for these studies were 500 trolands (~10 fL) or less. As shown in Fig. 2, our measured heterochromatic brightness matching curves agreed well with the CIE-HBM only at 1 fL. At the 10-fL level, differences between the CIE-HBM and our measurements are apparent in the long wavelength portion of the spectrum. At 100 fL and 1000 fL, the present measurements are clearly disparate from the CIE-HBM. This disparity suggests that the CIE-HBM may seriously underestimate the relative sensitivity of the eye in the long wavelength region of the visible spectrum at higher intensities.

A potential explanation for the multi-peaked appearance of our heterochromatic brightness matching data may be found in models of changes in visual sensitivity as a function of adaptation level. Sperling and Harwerth (14) have found that the locations of longer wavelength peaks in increment threshold relative sensitivity curves (at 540 nm and 610 nm) are best described by a linear subtractive model, with the middle and long wavelength photoreceptors having a mutually inhibitory relationship. Moreover, Sperling and Harwerth found that the amount of interaction or inhibition between the middle and long wavelength cone responses increased with increasing background luminance, as shown by a deepening notch at 580 nm in relative sensitivity as the background luminance increased. The mean curves from our current study produced middle and long wavelength peaks similar to those of Sperling and Harwerth at 1000 trolands. We also found a clear notch around 580 nm. However, we did not find evidence of the short wavelength peak near 445 nm, as Sperling and Harwerth did.

It is generally assumed that data obtained by flicker photometry reflect processing by an achromatic or luminance channel. The luminance channel is assumed to be very predictable, supporting the brightness matching laws of symmetry, transitivity, proportionality, and additivity (11,17). It is also assumed that the luminance channel is derived from straightforward processing of the output of retinal cones. The statistically significant effect of Level on the flicker data suggests that these assumptions do not strictly hold. Even though the size of the effect is small and may not have substantial practical influence on brightness perception, the possible failure of brightness matching laws at 100 fL is important: a relatively simple luminance channel model, using the summation of middle and long wavelength cone outputs, can be used to fit the data only if

flicker curves are consistent across intensities. If the relative sensitivity by flicker photometry changes with intensity, a more complicated model is needed to fit even flicker photometry data.

CONCLUSIONS

We demonstrated that luminous efficiency, measured by flicker photometry and heterochromatic brightness matching, is dependent on reference intensity in the high photopic range. This dependence is most evident for heterochromatic brightness matching, which has the stronger tie to real world brightness perception.

It is clear from our data that the effective illuminations created by simultaneously bright and spectrally narrow light sources such as phosphors, lasers, and LEDs can differ greatly from predictions based on the most widely used luminous efficiency function, V(λ). Currently, the preferred function for photometry of narrow sources is the CIE Luminous Efficiency Curve for Centrally-Viewed, Two Degree Field by Heterochromatic Brightness Matching (CIE-HBM) (11). The present study agrees well with the CIE-HBM at the 1-fL reference intensity. However at 10 fL or greater, our results suggest that the CIE curve may substantially underestimate the luminous efficiency of long wavelengths, which may explain why recent work on 532-nm green laser illuminators have failed to demonstrate the predicted performance improvement over older 650-nm laser systems.

Our results create some ambiguity as to how photometric measurements should be made at higher intensities. A practical solution, consistent with most of the available data on brightness matching at higher intensities, is to consider the luminous efficiency curve at high intensities to be flat over most of the spectrum, from about 480 nm to 620 nm for the average subject, and to acknowledge that prediction of individual performance is difficult because of variability across subjects. This study also reinforces the need to have human testing of any equipment, such as head-up displays, aviation signals, and laser eye protection, under representative field conditions when perceived brightness is critical to optimal performance.

Additional psychophysical measurements at somewhat higher intensities could be conducted using multiple laser or diode light sources, although there are substantial engineering challenges to overcome with this approach. Ultimately, the eye hazard radiation exposure safety standards will limit the psychophysical measurement of low efficiency light at high reference intensities.

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14. ABSTRACT Purpose: Measurements concerning the usability or safety of optical equipment are based on assumptions regarding luminous efficiency. The current luminous efficiency functions are derived from human sensitivity experiments taken at low light levels compared to the outdoor daytime environment. The amount of error induced by extrapolating from low light level data to high light level applications is not known. We sought to determine whether standard luminous efficiency curves CIE V(γ) and CIE Heterochromatic Brightness Matching are appropriate for measuring day-use optical equipment such as display phosphors, lasers, LEDs and laser eye protection, which are becoming more common in aviation. Methods: Flicker photometry and successive heterochromatic brightness matching were used to measure changes in luminance efficiency functions with increasing levels (1, 10, 100 and 1000 foot-lamberts) of light adaptation. Results: Luminous efficiency increased for longer wavelengths as reference intensity increased. Peak luminous efficiency shifted from approximately 540nm to greater than 600 nm with increasing intensity. Peak luminous efficiency was constant for flicker photometry across all intensities but the function narrowed slightly at 100 foot-lamberts. Conclusion: Luminous efficiency curves measured at high reference intensities are substantially different from the standard luminous efficiency functions. Caution should be used when measuring spectrally narrow and bright sources such as lasers and LEDs with a V (λ) corrected photometer because the measured luminance may correlate poorly with perceived brightness.

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