A Luminous Efficiency Function, $V^*_{D65}(\lambda)$, for Daylight Adaptation: A Correction

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Abstract: We recently proposed a 2° photopic luminosity function, $V^*_{D65}(\lambda)$ *[J Vis 2005;5:948–968], which improves upon the original CIE 1924* $V(\lambda)$ *function and its modifications, while being consistent with a linear combination of the Stockman and Sharpe [Vis Res 2000;40:1711–1737] long- and middle-wavelength-sensitive cone fundamentals [*$L(\lambda)$ *and* $M(\lambda)$*, respectively]. Its derivation was based on 25-Hz heterochromatic flicker photometric (HFP) data obtained from 40 observers of known genotype on a 1000 troland white (D65) background. However, as a result of an analysis of new luminous efficiency data obtained on an series of chromatic backgrounds [J Vis 2008;8:1–26], we now recognize that the 25-Hz flickering targets, though near-flicker-threshold, altered the mean chromaticity of the adapting background. Consequently, we have revised the original analysis, taking into account the changes in mean adapting chromaticity with target wavelength. Our reanalysis of the individual and mean data shows that the* $V^*_{D65}(\lambda)$ *function for a D65 background should be redefined as* $1.89L(\lambda) + M(\lambda)$ *in quantal terms and as* $1.98L(\lambda) + M(\lambda)$ *in energy terms. The change in the L-cone weighting factor represents a change in luminous efficiency across the spectrum of* $\sim$*0.04 log unit.* © 2010 Wiley Periodicals, Inc. Col Res Appl, 36, 42–46, 2011; Published online 29 April 2010 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/col.20602

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INTRODUCTION

Spectral luminous efficiency functions are relative weighting functions that are used to convert physical or radiometric measures, such as radiance, to visually relevant or photometric ones, such as luminance. Recently, we proposed a revised photopic luminous efficiency function, $V^*_{D65}(\lambda)$, which was based on heterochromatic flicker photometry (HFP) measurements made in 40 genotyped observers[1] under 3 log troland neutral adaptation that corresponded to CIE standard daylight illuminant D65. The function was defined as a linear combination of the Stockman and Sharpe[2] L- and M-cone fundamentals [$\bar{l}(\lambda)$ and $\overline{m}(\lambda)$, respectively].

More recently, we have completed a series of experiments investigating how the relative contribution of the L- and M-cones to luminous efficiency depends upon chromatic adaptation.[3] While analyzing the new 25 Hz HFP data, however, it became apparent that the mean adapting chromaticity depends not only on the adapting background (μ), but also on the variable-wavelength test light (λ) and on the 560 nm reference light.[3] The influence of the test and reference lights on the adapting chromaticity also applies to the 25 Hz FPS measurements originally made on the D65 background to determine $V^*_{D65}(\lambda)$.[1] Consequently, as described in detail later, we have reanalyzed the original data, based on which we find that the initially determined L-cone weight of 1.55 is an underestimate. Instead, we find that the quantal $V^*_{D65}(\lambda)$ function with quantal cone fundamentals normalized to unity peak should be [Eq. (1a)]:

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$$V^*_{\text{D65}}(\lambda) = [1.89\bar{l}(\lambda) + \bar{m}(\lambda)]/2.80361, \qquad (1a)$$

where 1.89 is the relative L-cone weight (which is specific to the D65 background) and 2.476985 is a constant that rescales the luminous efficiency function so that it peaks at one. After applying the rescaling factor, this equation simplifies to [Eq. (1b)]:

$$V^*_{\text{D65}}(\lambda) = 0.67413\bar{l}(\lambda) + 0.35668\bar{m}(\lambda), \qquad (1b)$$

Alternatively, with all functions in relative energy units (as denoted by the subscript e), and with $\bar{l}_e(\lambda)$ and $\bar{m}_e(\lambda)$ normalized to unity energy peak, and $V^*_{\text{D65}e}(\lambda)$ rescaled to peak at one, Eq. (1a) becomes [Eq. (2a)]:

$$V^*_{\text{D65}e}(\lambda) = [1.98065\bar{l}_e(\lambda) + \bar{m}_e(\lambda)]/2.87091, \qquad (2a)$$

and the rescaled equation becomes [Eq. (2b)]:

$$V^*_{\text{D65}e}(\lambda) = 0.68990\bar{l}_e(\lambda) + 0.34832\bar{m}_e(\lambda), \qquad (2b)$$

The change in the weights between the quantal and energy forms of the equation reflects the different unity-peak normalizations of the cone fundamentals.

METHODS

Details of the experimental methods and subjects are given in the earlier paper.[1] In brief, corneal spectral sensitivities were measured by 25 Hz HFP. The measurements were confined to the central 2° of the fovea. A reference light of 560 nm was alternated with a superimposed test light, which varied in wavelength from 425 to 675 nm in 5 nm steps. Flicker was square-wave. The flickering stimuli were superimposed on a 16° diameter white adapting field (xenon arc white) with an intensity of 3.0 log trolands, which was tritanopically metameric with the CIE D65 standard daylight. The 560 nm reference flicker was set to 0.2 log unit above flicker threshold.

Mean Adapting Chromaticities

In our previous analysis of HFP data obtained under neutral white (CIE D65 standard daylight) adaptation, we implicitly assumed that the reference and test lights did not affect the mean state of L- and M-cone adaptation.[1] However, this assumption is no longer tenable (see Stockman *et al.*[3]). The 25 Hz reference and test lights, even though the reference was set to only 0.2 log unit above flicker threshold, altered the mean adapting chromaticity away from that of the D65 field.

The adapting chromaticity is defined as the relative quantal M:L cone excitation produced by the combined variable test, constant reference (560 nm) and constant D65 background lights [$M_{\text{D65},\lambda}$/$L_{\text{D65},\lambda}$ in Eq. (3)]. These values can be calculated for each subject using the calibration data for each HFP setting, and by using the Stockman and Sharpe M-cone fundamental,[2] and the appropriate variant of the L-cone fundamental optimized for either alanine or serine at position 180 in the L-cone opsin molecule see for details.[1,3]

In the absence of any test or reference lights, the chromaticity of the D65 background, expressed as the ratio of *M*:*L* cone excitation, is 0.82. The calculations show that averaged across subjects this ratio varies from as high as 0.96 when short-wavelength test lights are used to as low as 0.64 when long-wavelength ones are used These changes are large enough that they must be taken into account in the derivation of $V^*_{\text{D65}}(\lambda)$, as described later.

Reanalysis of the 25-Hz Flicker Photometric Data

We approximated each individual HFP curve (or spectral luminous efficiency function) by linear combinations of the Stockman and Sharpe L- and M-cone spectral sensitivities.[2] The linear combinations were found by simultaneously fitting the luminous efficiency data for each subject with the best-fitting versions of Eq. (3):

$$\begin{aligned}\log_{10} V^*_{\text{D65}}(\lambda) = {} & \log_{10}\left(\beta_{\text{D65}}\frac{M_{\text{D65},\lambda}}{L_{\text{D65},\lambda}}\bar{l}(\lambda) + \bar{m}(\lambda)\right) \\ & + k_{\text{lens}}d_{\text{lens}}(\lambda) + k_{\text{mac}}d_{\text{mac}}(\lambda) - \log_{10} \\ & \times \left(\beta_{\text{D65}}\frac{M_{\text{D65},\lambda}}{L_{\text{D65},\lambda}}\bar{l}(560) + \bar{m}(560)\right) \\ & - k_{\text{lens}}d_{\text{lens}}(560) + k_{\text{mac}}d_{\text{mac}}(560), \qquad (3)\end{aligned}$$

where $V^*_{\text{D65}}(\lambda)$ is the predicted spectral sensitivity (luminous efficiency) function for the D65 adapting field, $\bar{l}(\lambda)$ is either the L(ser180), or the L(ala180) variant of the Stockman and Sharpe[2] quantized L-cone fundamentals, and $\bar{m}(\lambda)$ is the Stockman and Sharpe[2] quantized M-cone spectral sensitivity. The function $d_{\text{lens}}(\lambda)$ is the lens pigment density spectrum of van Norren and Vos (1974), slightly modified by Stockman *et al.*,[4] and k_{lens} is the lens pigment density multiplier or weight applied to $d_{\text{lens}}(\lambda)$ to adjust each subject's HFP curve so that it is consistent with the mean lens pigment density spectrum implied by the Stockman and Sharpe standard observer. The function $d_{\text{mac}}(\lambda)$ is the mean macular density spectrum based on measurements by Bone *et al.*[5] proposed by Stockman *et al.*,[4] and k_{mac} is the macular pigment density multiplier applied to $d_{\text{mac}}(\lambda)$ to adjust each subject's HFP curve so that it is consistent with the mean macular pigment density spectrum implied by the Stockman and Sharpe standard observer. For further details about these functions, see our previous papers.[1–3] All of the functions in Eq. (3) can be downloaded from the website: http://www.cvrl.org. The development of the model embodied by Eq. (3) is described in Stockman *et al.*[3]

The values of $M_{\text{D65},\lambda}/L_{\text{D65},\lambda}$ are the M:L cone excitation ratios produced by each combination of test, reference and D65 adapting light at the flicker null threshold, as noted earlier. Note that $\beta_{\text{D65}} \times M_{\text{D65},\lambda}/L_{\text{D65},\lambda}$ is different from the L-cone weighting factor, a_{D65}, which has a value of 1.89 in Eq. (1a). In general, scaling the L-cone weight by $M_{\text{D65},\lambda}/L_{\text{D65},\lambda}$ has the effect of increasing the L-cone contribution

TABLE I. Standard errors and root mean squared residuals of β_{D65}, k_{lens}, and k_{mac}.[a]

Subject ID	Gender	Age	L-cone Polymorphism(codon 180)	a_{D65}	SE	k_{lens}	SE	k_{mac}	SE	rms
AN	M	18	Ala	3.17	0.46	0.30	0.07	0.02	0.07	0.04
CF	M	40	Ala	0.56	0.04	0.08	0.06	−0.76	0.06	0.03
CH	F	32	Ala	6.48	0.65	0.08	0.03	0.18	0.03	0.01
CP	M	33	Ala	1.90	0.13	0.13	0.04	0.05	0.04	0.02
FG	M	30	Ala	3.01	0.24	0.02	0.04	0.53	0.04	0.02
HJ	M	39	Ala	1.19	0.10	−0.07	0.07	−0.72	0.07	0.04
HM	M	32	Ala	2.07	0.22	−0.07	0.07	0.46	0.07	0.04
HS	M	30	Ala	8.68	4.15	0.01	0.09	0.35	0.10	0.05
JK	M	40	Ala	1.63	0.12	0.07	0.05	0.02	0.05	0.03
MJ	M	27	Ala	1.73	0.09	0.05	0.03	0.23	0.03	0.02
MS	M	37	Ala	2.24	0.42	−0.04	0.10	−0.17	0.10	0.05
OB	M	28	Ala	1.47	0.12	−0.11	0.06	−0.08	0.06	0.03
RL	M	32	Ala	2.44	0.32	0.15	0.07	0.47	0.07	0.04
RT	M	42	Ala	1.54	0.27	0.08	0.12	0.11	0.12	0.07
SK	M	31	Ala	1.32	0.13	0.19	0.07	−0.43	0.07	0.04
SW	M	34	Ala	1.50	0.18	−0.31	0.08	−0.37	0.08	0.04
ED	F	38	Ala/Ser	1.20	0.09	0.39	0.07	−0.13	0.06	0.04
SWI	F	27	Ala/Ser	2.38	0.31	0.38	0.10	0.03	0.08	0.04
AC	M	30	Ser	1.43	0.18	0.04	0.09	0.34	0.09	0.05
AS	M	44	Ser	2.04	0.21	−0.01	0.07	0.15	0.07	0.04
AT	M	31	Ser	1.65	0.15	−0.08	0.07	−0.44	0.07	0.04
CFR	M	31	Ser	3.19	0.35	−0.02	0.05	−0.09	0.05	0.03
CK	M	36	Ser	1.66	0.19	0.43	0.08	0.35	0.08	0.04
DR	M	26	Ser	2.53	0.29	0.08	0.06	0.59	0.07	0.03
EA	M	39	Ser	1.54	0.13	−0.14	0.06	−0.46	0.06	0.03
HJS	M	29	Ser	2.13	0.23	−0.01	0.06	0.37	0.07	0.03
HK	M	35	Ser	1.37	0.08	0.33	0.05	0.42	0.05	0.02
HSC	M	32	Ser	17.75	14.30	0.18	0.08	0.23	0.09	0.05
JA	M	33	Ser	1.94	0.17	0.02	0.05	0.07	0.06	0.03
KK	M	47	Ser	2.21	0.24	0.06	0.07	0.58	0.07	0.04
LS	M	29	Ser	2.23	0.19	0.27	0.05	−0.01	0.05	0.03
LTS	M	48	Ser	1.65	0.11	−0.10	0.04	−0.38	0.04	0.02
MK	F	27	Ser	3.15	0.49	0.74	0.15	0.30	0.09	0.04
MR	M	33	Ser	1.16	0.14	−0.23	0.09	0.14	0.09	0.05
TB	F	29	Ser	1.55	0.11	0.31	0.05	0.33	0.05	0.03
TD	M	38	Ser	0.88	0.07	0.12	0.14	−0.59	0.08	0.04
TE	M	25	Ser	2.47	0.29	0.23	0.07	−0.06	0.07	0.04
UW	M	31	Ser	1.66	0.13	0.01	0.06	−0.11	0.06	0.03
WJ	M	33	Ser	5.59	1.13	−0.03	0.06	0.07	0.06	0.03
WL	M	27	Ser	2.40	0.41	0.12	0.10	0.04	0.10	0.05

Age, gender and L-cone polymorphism of the 40 observers of known genotype [L(ser^{180}) or L(ala^{180})], whose 25-Hz HFP sensitivities, measured on a white (xenon) 3.0 log td adapting field, were best-fitted by a linear combination [Eq. (3)] of the Stockman and Sharpe (2000) L- and M-cone fundamentals: a_{D65} (L-cone weight for the D65 background alone), k_{lens} (lens pigment density weighting factor) and k_{mac} (macular pigment density weighting factor). The best-fitting parameters are shown for the spectral range 425–675 nm. Standard errors (SE) for each fitting parameter are given as well as the root mean square error (rms) of the entire fit.

[a] Corrected version of Table 1 of Sharpe et al. (2005).

to luminance efficiency for effectively shorter wavelength adaptation (when $M_{D65,\lambda} > L_{D65,\lambda}$), and decreasing it for longer wavelength adaptation (when $M_{D65,\lambda} < L_{D65,\lambda}$). The scaling by $M_{D65,\lambda}/L_{D65,\lambda}$ in Eq. (3) is equivalent to a reciprocal sensitivity adjustment of each cone contribution in accordance with Weber's Law (the L-cone weight is scaled by $1/L_{D65,\lambda}$, and the M-cone weight by $1/M_{D65,\lambda}$). Changes in $M_{D65,\lambda}/L_{D65,\lambda}$ can be caused by changes in the reference and test lights.

In applying Eq. (3), we are assuming that changes in $M_{D65,\lambda}/L_{D65,\lambda}$ around the mean for the D65 condition can be accounted for by Weber's Law applied independently to the outputs of the M- and L-cones e.g.,[6,7] Weber's Law holds approximately for 25 Hz flicker detection above 3 log td e.g.[8,9] See Stockman *et al.*[3] The second part of Eq. (3), in which $\lambda = 560$ nm, simply renormalizes each luminous efficiency relative to the efficiency at 560 nm, the reference wavelength.

Curve Fitting

All curve-fitting was carried out with the standard Marquardt-Levenberg algorithm implemented in SigmaPlot (SPSS, Chicago), which was used to find the coefficients (parameters) of the independent variable or variables that gave the "best fit" between our model and the data. This algorithm seeks the values of the parameters that minimize the sum of the squared differences between the values of the observed and predicted values of the dependent variable or variables. Fits were made to log quantal spectral sensitivity data.

RESULTS

Individual Data

Using Eq. (3), we found the best-fitting values of β_{D65}, k_{lens} and k_{mac} for each individual subject. The values,

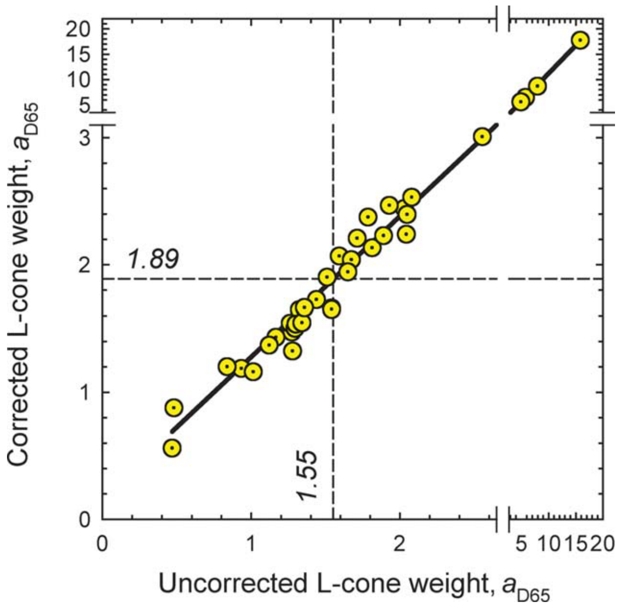

FIG. 1. The corrected L-cone weights for each subject plotted against their uncorrected L-cone weights (yellow dotted circles). The solid line is a regression line with a slope of 1.11 and intercept of 0.17. For details, see text.

their standard errors, the root mean squared (rms) residuals, and other subject details are given in Table I, below. In general, the rms values are good.

For the D65 field alone, $M_{D65}/L_{D65} = 0.824$, thus $a_{D65} = \beta_{D65} \times 0.824$ for the D65 background alone. Figure 1 shows as yellow dotted circles the best-fitting adjusted values of a_{D65}, the L-cone weight for each subject, plotted against the previously published values of a_{D65},[1] in which the effects of the test and reference lights upon chromatic adaptation were ignored. Taking into account the adapting effects of the test and reference lights consistently increases the L-cone weight for all subjects. As indicated by the regression line fitted to the yellow dotted circles, the increase can be characterized by increasing the old weight by 1.11 and adding an offset of 0.17. Thus, as indicated by the intersection of the horizontal and vertical dashed lines in Fig. 1, according to this reanalysis, the proposed standard L-cone weight should be 1.89.

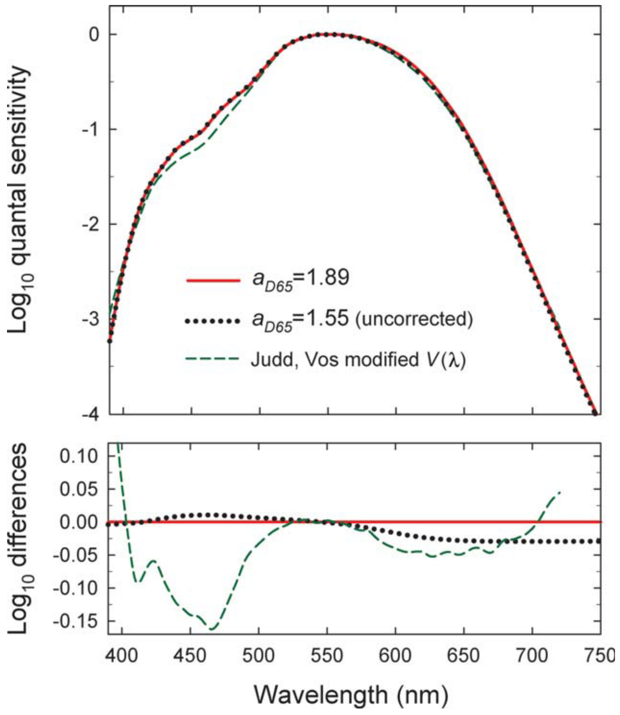

FIG. 2. Corrected version of $V^*_{D65}(\lambda)$ (continuous red line) compared with uncorrected version (dots) and with the Judd-Vos modified $V(\lambda)$ (dashed green line). The differences between the corrected $V^*(\lambda)$ and the other functions are shown in the bottom panel.

TABLE II. New values of V^*_{D65} (λ).[a]

(λ) nm	V*(λ)	(λ) nm	V*(λ)	(λ) nm	V*(λ)
390	*−3.2291*				
395	*−2.8271*				
400	*−2.4682*	600	−0.1938	800	*−5.5343*
405	*−2.1666*	605	−0.2401	805	*−5.6692*
410	*−1.9104*	610	−0.2941	810	*−5.8049*
415	*−1.7186*	615	−0.3547	815	*−5.9381*
420	*−1.5720*	620	−0.4217	820	*−6.0682*
425	−1.4671	625	−0.4941	825	*−6.1979*
430	−1.3681	630	−0.5807	830	*−6.3263*
435	−1.2753	635	−0.6752		
440	−1.1972	640	−0.7733		
445	−1.1448	645	−0.8756		
450	−1.0978	650	−0.9919		
455	−1.0540	655	−1.1186		
460	−0.9882	660	−1.2510		
465	−0.8977	665	−1.3883		
470	−0.8142	670	−1.5303		
475	−0.7462	675	−1.6777		
480	−0.6845	680	*−1.8310*		
485	−0.6265	685	*−1.9904*		
490	−0.5694	690	*−2.1569*		
495	−0.4953	695	*−2.3175*		
500	−0.4126	700	*−2.4779*		
505	−0.3277	705	*−2.6398*		
510	−0.2468	710	*−2.8068*		
515	−0.1746	715	*−2.9742*		
520	−0.1155	720	*−3.1377*		
525	−0.0756	725	*−3.3006*		
530	−0.0467	730	*−3.4604*		
535	−0.0263	735	*−3.6196*		
540	−0.0083	740	*−3.7790*		
545	−0.0002	745	*−3.9331*		
550	−0.0008	750	*−4.0878*		
555	−0.0002	755	*−4.2400*		
560	−0.0052	760	*−4.3899*		
565	−0.0120	765	*−4.5392*		
570	−0.0233	770	*−4.6858*		
575	−0.0411	775	*−4.8329*		
580	−0.0666	780	*−4.9754*		
585	−0.0890	785	*−5.1171*		
590	−0.1172	790	*−5.2576*		
595	−0.1525	795	*−5.3973*		

Quantal photopic luminosity function V^*_{D65} (λ), for 2° viewing conditions, in logarithmic units, tabulated in 5-nm steps from 390 to 830 nm. V^*_{D65} (λ) is scaled to unity peak at 546.1 nm (not tabulated). The data contained in this table are available in 0.1, 1, and 5 nm steps and also in energy units, on the Web site: http://www.cvrl.org. The data given in italics are extrapolated using the Stockman and Sharpe (2000) cone fundamentals.

[a] Corrected version of Table 1 of Sharpe *et al*. (2005).

Mean (Standard Observer) Data

The mean luminous efficiency function cannot be reliably estimated from the average of the 40 corrected individual L-cone weights shown in Fig. 1 because luminous efficiency changes with L-cone weight in a highly nonlinear fashion (see Ref. 1). In short, large L-cone weights tend to disproportionately bias the mean relative to small weights. This difficulty can be highlighted by the fact that the mean of the individual L-cone weights (a_{D65}) for our 40 subjects is 2.67; whereas the L-cone weight derived from their mean luminous efficiency function, as we show below, is considerably less.

A more secure method of estimating the mean L-cone weight is to fit Eq. (3) directly to the mean luminous efficiency data for the 40 subjects, using the mean values of $M_{D65,\lambda}/L_{D65,\lambda}$. The coefficient of determination of the fit, R^2, is 99.96%. The best-fitting L-cone bias, β_{D65} is 2.29 ± 0.07, while the best-fitting value of k_{lens} is 0.08 ± 0.02 and that of k_{mac} is 0.04 ± 0.02. For the D65 field alone, $M_{D65}/L_{D65} = 0.824$, thus a_{D65} is 1.89. The lens and macular density adjustments required in the fit imply that the mean or standard observer for the 25 Hz HFP data has slightly lower macular and lens pigment densities than the Stockman and Sharpe[2] standard observer, as we found in our original analysis.[1] Such small differences between populations are to be expected.

DISCUSSIONS

Importantly, the derivations of the new value of a_{D65} obtained from the individual analyses and from the mean analysis agree exactly. We therefore feel justified in concluding that the appropriate L-cone weight for the standard mean observer should be 1.89 [see Eq. (1a)].

The revised value of 1.89 for a_{D65} has also been integrated into the generalized function for the standard observer, $V^*_{\mu}(\lambda)$.[3] Using this function, luminous efficiency can be predicted for the standard observer for most conditions of chromatic adaptation.

The change in $V^*_{D65}(\lambda)$ that results from the change in the L-cone weight from 1.55 (dots) to 1.89 (red line) is illustrated in Fig. 2. For comparison, the Judd-Vos modified $V(\lambda)$ or $V_M(\lambda)$ (dashed green line) is also shown. The change in spectral sensitivity caused by the correction represents a change in spectral sensitivity across the spectrum of ~0.04 log unit, which is typically less than the difference between $V^*_{D65}(\lambda)$ and $V_M(\lambda)$.

The new values of $V^*_{D65}(\lambda)$ are tabulated in logarithmic quantal units in Table II. The function can be downloaded in energy or quantal units in 0.1, 1, or 5 nm steps from: http://www.cvrl.org.

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Publications Briefly Mentioned

CIE 191:2010 Recommended System for Mesopic Photometry Based on Visual Performance: 79 pages, ISBN 978 3 901906 88 6, €146

This report deals with visual task performance-based approaches to mesopic photometry, with a major aim to establish appropriate mesopic spectral sensitivity functions to serve as the foundation of a system of mesopic photometry. A review of the most important visual tasks and the range of visual conditions typically encountered in the context of night-time driving is given.

The existing visual performance-based systems for mesopic photometry were reviewed and tested with new independent data sources. The outcome of the analysis and testing is a recommended system for mesopic photometry based on visual performance. The report summarises the justifications for the recommended system and gives general guidelines for its use and application.

This article is available at the National Committees of the CIE or via the website of the Central Bureau of the CIE (www.cie.co.at).