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MAKE WAY FOR PERIPHERAL $V(\lambda)$

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Abstract

In the vision and lighting field, there are currently several attempts to model the mesopic luminous efficiency function. The models are commonly combined functions of the photopic and scotopic luminous efficiency functions, where the photopic part is usually described by the $V(\lambda)$ or $V_{10}(\lambda)$ functions. Reaction time measurements made in the present work indicate that this may be an inaccurate basis. The results imply that the $V(\lambda)$ and $V_{10}(\lambda)$ functions underestimate the short wavelengths in peripheral vision at photopic levels. A new luminous efficiency function is proposed for the peripheral vision at photopic light levels.

Introduction

Over the past four decades, several studies Palmer, 1968; Ikeda & Shimozono, 1981; Trezona, 1987; Kokoschka & Bodmann, 1975; Sagawa & Takeichi, 1992; He, Rea, Bierman, & Bullough, 1997; He, Bierman, & Rea, 1998) [1–6, 9] and the revised work of Palmer (Palmer 2nd) and the work of Nakano & Ikeda, both presented in CIE 1989 and CIE 2001 [7, 8], have been performed in order to establish a model of mesopic photometry that would correctly echo the mesopic spectral sensitivity of the human eye. The majority of the proposed models (Palmer, 1968; CIE 1989, 2001; Sagawa & Takeichi, 1992; He et al., 1997; He et al., 1998) [1, 5, 7, 9] are combined functions of the photopic and scotopic luminous efficiency functions. The mesopic region lies between the photopic and scotopic regions, and the mesopic luminous efficiency is usually thought to merge with the photopic luminous efficiency function at the upper end, and with the scotopic luminous efficiency function at the lower end of the mesopic region (CIE, 1978) [10].

In mesopic modelling, two photopic functions are mainly used, the CIE 1924 [11] $V(\lambda)$ and the CIE 1964 [12] $V_{10}(\lambda)$. The $V(\lambda)$ function for foveal 2° visual field was introduced by Gibson and Tyndall in 1923 and is based mainly on step-by-step brightness matching and flicker photometry experiments performed by several researchers at photopic light levels (Gibson & Tyndall, 1923) [13]. The CIE adopted the $V(\lambda)$ curve at its 6th Session in 1924 (CIE, 1926) [11]. The other photopic function that is generally used in mesopic modelling is the $V_{10}(\lambda)$ function, which was introduced by the CIE in 1964 for a central 10° field (CIE, 1964) [12].

The scotopic region is represented by the $V'(\lambda)$ function which was established by the CIE in 1951 (CIE, 1951) [14]. The $V'(\lambda)$ function was determined for a large central field of 20° under conditions of dark adaptation. It is based on the detection threshold data of Wald (1945a) [15] and on the direct brightness matching data of Crawford (1949) [16].

In 1951, Judd proposed a modification to the 1924 $V(\lambda)$ (Judd, 1951) [17] as the 1924 curve was realized to underestimate the spectral sensitivity at wavelengths below 460 nm. However, Judd's modification was slightly too sensitive below 410 nm and in 1978 Vos (Vos, 1978) [18] presented second-order correction to the Judd modification. The $V_M(\lambda)$ function, modified first by Judd and second by Vos, was approved as a supplement to, not a replacement of, the $V(\lambda)$ function by the CIE in 1988 (CIE, 1988) [19]. CIE recommends the use of this modified function for luminance measurements of stimuli containing appreciable amount of radiation at short wavelengths (CIE, 1990) [20]. The $V_M(\lambda)$ function has not to date established itself either in practical use or in mesopic modelling purposes.

Foveal vision is believed to be adequately well described by the $V(\lambda)$ function at mesopic light levels (He et al., 1997; Eloholma, Halonen, & Setälä, 1999) [6, 21]. This is because rods are absent from the fovea and only cones contribute to foveal vision (Forrester, Dick, McMenamin, & Lee, 1996) [22]. On the other hand, at mesopic light levels when the luminance level decreases, rods become more and more active. Therefore, in mesopic modelling, peripheral vision is usually of more importance than foveal vision.

At present, no luminous efficiency function represents peripheral vision alone at photopic light levels. However, the results of the reaction time measurements made in the work presented in this paper imply that peripheral luminous efficiency at photopic levels differs from the currently available photopic luminous efficiency functions $V(\lambda)$, $V_M(\lambda)$ and $V_{10}(\lambda)$. Thus, the use of these functions as the basis of mesopic models combining photopic and scotopic luminous efficiency functions may result in inaccurate results. Therefore, a new luminous efficiency function based on the reaction time measurements, for peripheral photopic vision is proposed for mesopic modelling.

Method

Reaction time (RT) measurements evaluate the vision process by quantifying tasks in terms of time used to perform a certain task. Reaction times can be used to compare different parameters, and let the time needed to perform the visual task be the indicator of performance level. Similar reaction times should indicate, with some limitations, that the visual tasks are similar. The scope of this work was to study whether the $V(\lambda)$ applies in both foveal and peripheral vision when small coloured stimuli are presented over a white and uniform background at photopic levels.

Pollack (1968) [23] found in her research that reaction time is inversely related to stimulus luminance. She also found that stimulus wavelength affected the reaction times only at lowest mesopic luminance levels. Lit, Young & Shaffer (1971) [24] found in their research that RT could be used as an appropriate response criterion for determining a photopic luminosity function. He, Bierman, & Rea (1998) [9] used RT as a criterion in their work of modelling mesopic luminous efficiency functions as linear combinations of the $V_{10}(\lambda)$ and $V'(\lambda)$. Lennie, Pokorny, & Smith (1993) [25] present that RT can be used as criterion when establishing spectral sensitivities that are like $V(\lambda)$. Eloholma, Liesiö, Halonen, Walkey, Goodman, Alferdinck, Freiding, Bodrogi, & Várady (2005) [26] present in their review article that additivity of reaction times has not been profoundly confirmed, but the merits of reaction time as a promising method of producing additive spectral luminous efficiency functions has been discussed. In the works of He et al. (1997) [6] and He et al. (1998) [9], the authors claim that additivity of RTs in the mesopic region holds within certain adaptation level only. Additivity is one major issue when selecting proper visual criteria for defining luminous efficiency functions.

For these reasons we have chosen reaction time as a criterion for describing visual performance at low photopic light levels and describing a spectral luminous efficiency function.

Hemispherical Background

The interior of a large hemisphere with a diameter of 1980 mm was used as the visual field background in the experiments. The surface of the hemisphere was painted white and it was illuminated uniformly with 18 W fluorescent lamps with a correlated colour temperature (CCT) of 5400 K. The lamps produced an even spectral power distribution over a wide range of wavelengths. The background luminance produced by the lamps as such was too high, as the desired luminance level was 10 cd/m^2. The luminance was first decreased with achromatic filters. The luminance level of the background was adjustable with the use of dimmable electronic ballasts. The fine adjustments were made with a DC power source. The filtering and the fine adjustment affected the spectrum of the light resulting in the CCT of 4930 K. The spectrum of the filtered and adjusted light is presented in Fig. 1. The uniformity of the background luminance was very high. The background luminance was between –7% and +3% of the desired level within a major part of the visual field.

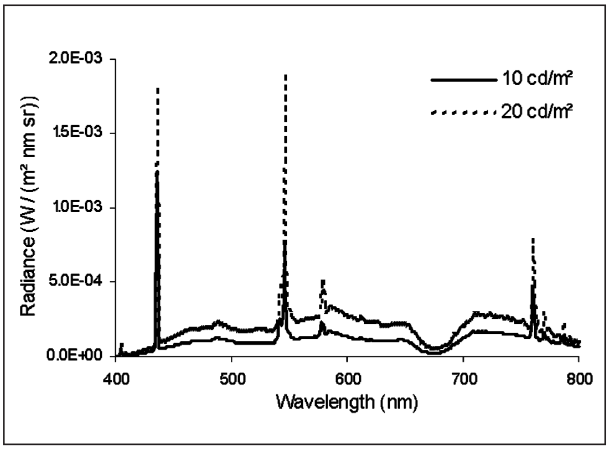

Fig. 1. The background of the hemisphere was illuminated with filtered 18 W fluorescent lamps with a CCT of 4930 K and 4610 K at 10 and 20 cd/m^2 background luminance, respectively

Stimuli

Visual stimuli of five different spectral distributions, referred to as blue, cyan, green, amber, and red, produced by light emitting diodes (LED) were used. The half-bandwidths, peak wavelengths, and S/P-ratios of the LEDs are presented in Table 1. The S/P-ratios have been calculated using the $V(\lambda)$ function. The spectral characteristics of the five LEDs are illustrated in Fig. 2. Fig. 2 illustrates that the major part of the visible spectrum, between 420 to 680 nm, was covered by these five LEDs.

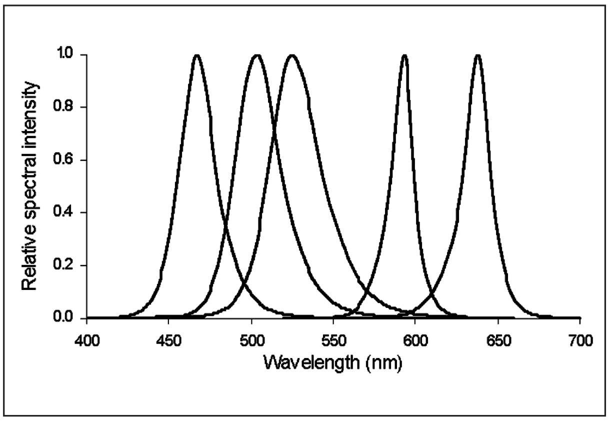

Fig. 2. Relative spectral power distributions of the stimulus spectra. The spectra from left to right: blue, cyan, green, amber, and red

Table 1

The peak wavelengths, half-bandwidths, and S/P-ratios of the LED spectra. The S/P-ratio calculations are based on the $V(\lambda)$ function

LED colour	Blue	Cyan	Green	Amber	Red
Peak wavelength (nm)	467	503	525	593	638
Half bandwidth (nm)	26	32	36	16	18
S/P-ratio	5.81	1.72	0.872	0.0988	0.0171

The S/P-ratio is the ratio between the scotopic and photopic lumens. It is used to demonstrate the effect of the used luminous efficiency functions on the calculated luminances.

Computer driven LED controllers gave the opportunity to adjust the intensity and the on- and off-set times of each LED individually. The LEDs were adjusted to produce short, rectangular shaped flash-like stimuli of 500 ms duration. The visual size of the circular stimuli was 0.29° (17.4′).

The stimuli were presented through small holes with a diameter of 5 mm. The holes were covered with a white diffuser covering the direct view to the LEDs. The immediate surrounding area of the stimuli was covered with a white self-adhesive film attached on the surface of the background. When the background illumination was turned on, the luminances of the diffusers were 10% to 12% lower than the overall luminance of the background. The luminance of the immediate surrounding was 2% to 3% higher than the overall background luminance. These differences were due to different reflectances of the materials. This characteristic caused that the contrast between the stimulus and the background could be negative (see Equation 1 for the definition of contrast). The luminance of the target was the sum of the luminance produced by the LED alone and the luminance produced by the fluorescent lamps taking into account the different reflectance of the diffuser material.

Viewing Conditions

The stimuli were presented both foveally and peripherally at an eccentricity of 10°. The chin and the forehead of the subject were static, while subject fixated to the centre of the visual field and viewed the stimuli binocularly. The viewing distance was 990 mm so binocular vision could be used without a concern of significant angular errors. The calculated angular error at 10° eccentricity is less than 0.05° taken the distance between pupils to be 70 mm. The subjects did not wear any artificial pupil, and the movement of the eyes was not monitored.

Procedure

Each measurement session started with a 10-minute adaptation period. One measurement session consisted of 15 sequences each of which lasted for 95 seconds. The subjects had a short break of about 40 seconds between the sequences to avoid fatigue of the eyes. Each subject participated in two measurement sessions on different days.

Three sequences of one stimulus colour were presented consecutively. The presentation order of the stimulus colours was randomised for each measurement session. One sequence consisted of 26 flashes of stimuli, half of which were presented foveally and the other half at the 10° eccentricity. The foveal and peripheral stimuli were presented in random order and the interval between two flashes varied from 2.25 to 4 seconds. The first two flashes of each sequence were «dummy» and were presented to arouse the attention of the subject. The reaction times were recorded with an LMT System Flash Meter SF 105 Version B with a resolution of 1 ms. The allowed time for reaction was adjusted to 1000 ms.

Reaction times were measured for three different stimulus contrasts. The used contrasts were adjusted individually for each stimulus spectrum in order to attain a common reaction time for the five stimulus spectra at each background luminance. Thus, the number of repetitions of one subject for one contrast of each stimulus colour was 24, as altogether six sequences of each stimulus spectrum were measured.

Subjects

Five experienced subjects, four males (ages 27, 31, 30, 34) and one female (age 24), participated in the reaction time measurements. The subjects had been examined by an ophthalmologist. Visual acuity was examined at a distance of 5 m (Snellen charts). None of the subjects wore glasses or contact lenses in their daily life or during the tests. The eyes were examined using a Haag-Streit slit lamp biomicroscope with and without a Volk lens and by binocular indirect ophthalmoscopy after application of mydriatics (tropicamid). The visual fields were investigated with a Goldmann kinetic perimeter. The intraocular pressures were measured by Goldmann's applanation tonometer. Colour vision was tested using pseudo-isochromatic plates (Ishihara).

Method for Modelling Constant RTs

In this work, reaction time is selected as the quantifying unit. RT is used to indicate the differences and similarities between visual tasks. The objective of the measurements was to find a common RT for five different stimulus spectra, in order to see whether the same RT requires the same photopic contrast. For modelling purposes, it was necessary that the contrasts used were low enough, so that the reaction times would not be saturated to a certain minimum level. Preliminary measurements showed that that if the contrast was too high, there was no significant difference in RT between different stimulus spectra. However, when the contrasts were close to the visibility threshold, the difference between stimulus spectra was significant. In this paper the contrast, C, is defined as

$$C = (L_t - L_b) / L_b, \quad (1)$$

where L_t is the stimulus luminance and L_b is the luminance of the immediate surrounding of the stimulus.

In the *RT* measurements, three contrasts were used and these were individual for each stimulus spectrum. The contrasts were close to the visibility threshold. In addition, another measurement was conducted using high contrast stimuli in order to achieve the asymptotic minimum *RT* for all subjects. These measurements were made with green stimulus spectra only, as the minimum *RT* is independent of stimulus colour. Pollack (1968) [23] and Lit et al. (1971) [24] found the *RT* independency of wavelength at higher intensities in their research. The contrasts were 2.13 and 2.16 for foveal and peripheral targets, respectively. The *RT* data was modelled using Equation 2.

$$RT = RT_{\min} + aC^{b}, \qquad (2)$$

where *RT* is the measured reaction time, $RT_{\min}$ is the asymptotic minimum reaction time, *C* is the photopic contrast, and *a* and *b* are coefficients. Coefficients *a* and *b* were optimised with Number Cruncher Statistical System (NCSS) 2001 statistical analysis software.

A common *RT* was selected as a basis for the contrast calculations. The contrasts for each stimulus spectra were optimised with the «Goal Seek» routine included in the Microsoft® Excel 2000 program. When the desired contrasts were known, the corresponding stimulus luminances were calculated by interpolating them from the measured values. The data consisting of the spectral power distribution (SPD) of the LEDs and the background light was converted into radiance by measuring first the photopic luminance which is based on the $V(\lambda)$ function. The SPD was measured with Optronics OL 754 Portable High Accuracy UV-Visible Spectroradiometer manufactured by Optronic Laboratories, Inc. The measured spectral power density was converted into radiance by using the measured luminance and irradiance and applying Equation 3 (CIE, 1978) [10].

$$L = K_m \int L_{e,\lambda} V(\lambda) d\lambda, \qquad (3)$$

where *L* is the measured luminance, K_m is the maximum spectral luminous efficacy (683 lm/W), $L_{e,\lambda}$ is the integrated radiance of a source and $V(\lambda)$ is the spectral luminous efficiency function of the human eye at photopic light levels. All luminances were measured with LMT L1009 luminance meter using $V(\lambda)$ weighting. The data for the luminous efficiency functions used in the calculations were extracted from the CIE Disk D001 Rel 1.2 (CIE, 1988) [19].

Results

The *RT* measurements of the first phase were conducted at 10 cd/m^2 background luminance. The results for the foveal vision show that the contrasts of the five stimulus spectra are close to each other (Fig. 3). The Fig. contains also the 2.5th and 97.5th percentiles, thus, including 95% of measurement results at each point. The contrast for the blue stimulus was slightly higher than for the other stimuli, which was expected, as the small stimulus size tends to decrease the visibility of a stimulus with high contents of short wavelengths (Abramov & Gordon, 1977) [27]. The explanation can be found from the structure of retina, which lacks cones sensitive to short wavelengths in the centre of the fovea (Curcio, Allen, Sloan, Lerea, Hurley, Klock & Milam, 1991) [28]. Curcio et al. found that S-cones were missing in a zone about 100 μm in diameter near the peak cone density. This corresponds to approximately 0.35° visual field. This visual field is slightly wider than the size of the targets of this study. However, the zone lacking S-cones was irregular in shape and it did not locate precisely centred on the site of peak density of overall cones. Therefore, it is not likely that the target had located entirely inside the zone missing the S-cones. It is also probable that the fixation of the eyes was not perfectly centred at the foveal target.

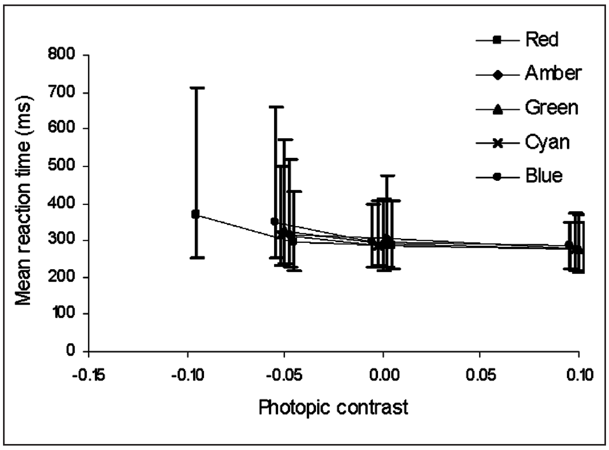

Fig. 3. RT as a function of stimulus spectra in foveal vision at 10 cd/m^2. The measurement points are the mean *RT*s of five subjects. In order to make the figure more clear, the contrasts of red and amber stimuli have been shifted by 0.005 and 0.0025 of the correct contrast, respectively, and cyan and blue stimuli by –0.0025 and –0.005, respectively

The results for the peripheral vision showed that in order to reach a common *RT*, the contrasts for all five stimulus spectra were not equal. The mean *RT*s of all subjects have been plotted in Fig. 4*a–e*. A common *RT* was selected as 315 ms. This *RT* was within the measurement range of all stimulus spectra and above the asymptotic *RT*s, which were 236 ms for foveal vision and 251 ms for peripheral vision.

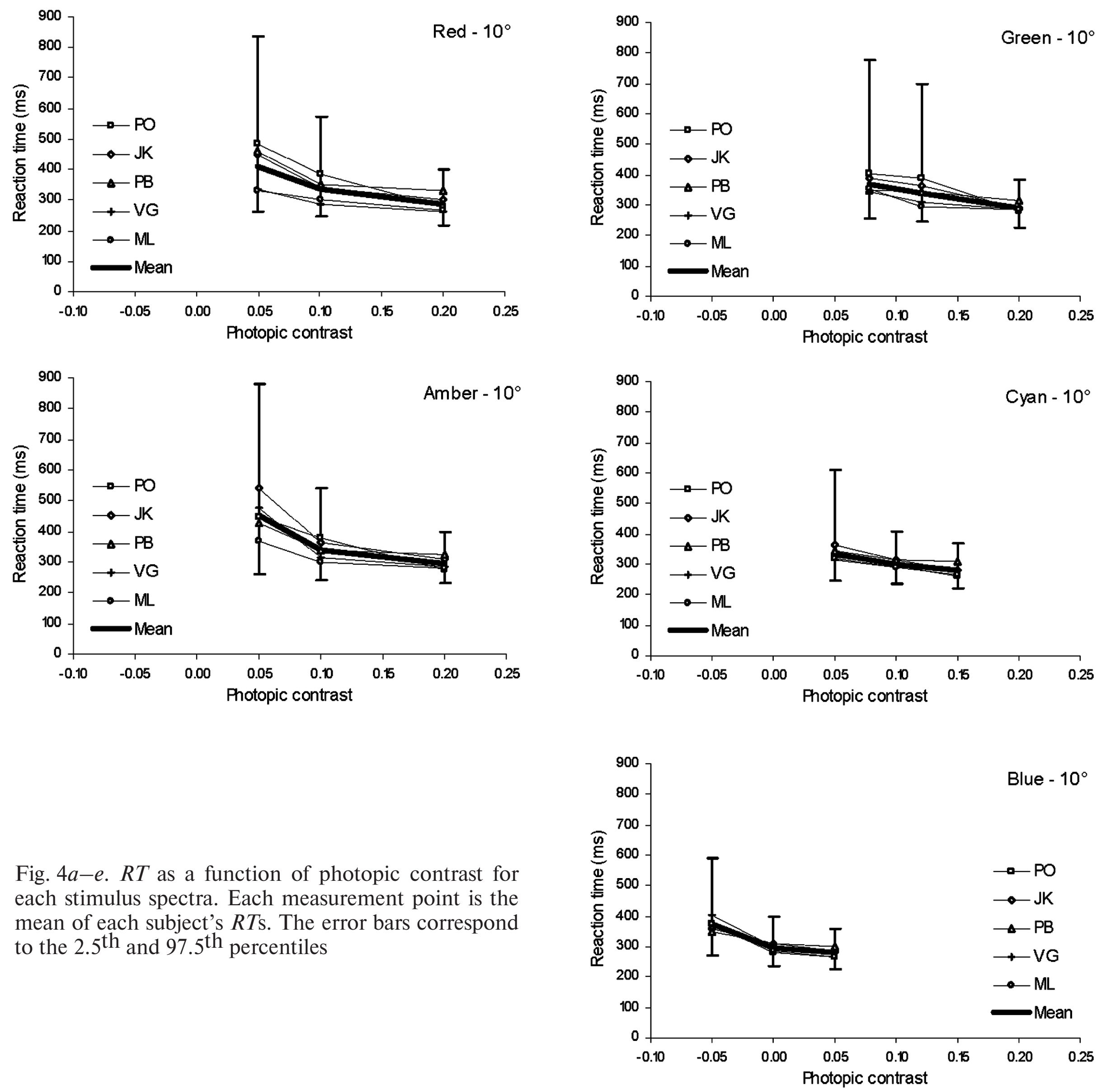

Fig. 4*a–e*. *RT* as a function of photopic contrast for each stimulus spectra. Each measurement point is the mean of each subject's *RT*s. The error bars correspond to the 2.5^{th} and 97.5^{th} percentiles

Luminance level 10 cd/m^2 is usually considered to be in the photopic region, where the luminous efficiency of the human eye is described by the $V(\lambda)$ function. If the $V(\lambda)$ function describes the photopic luminous efficiency of the human vision correctly, the expected result would be that the same *RT* for all stimulus spectra requires the same photopic contrast.

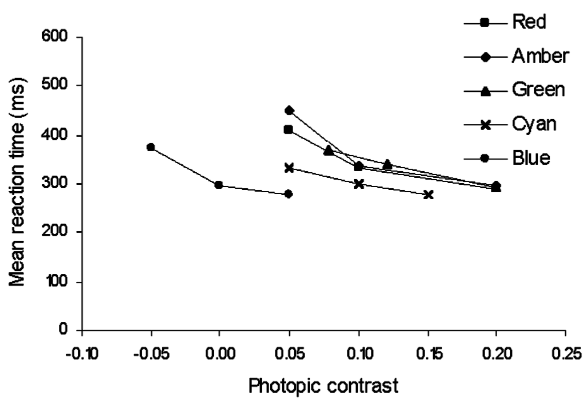

Fig. 5. *RT* as a function of stimulus spectra in peripheral vision at 10 cd/m^2. The measurement points are the mean *RT*s of five subjects. Data of individual subjects and the percentile bars are presented in fig. 4*a–e*

The results for the peripheral vision show that the stimulus spectra with the highest content in the short wavelength region (i.e. blue and cyan) required the lowest contrasts to reach the common *RT* of 315 ms. This implies that $V(\lambda)$ does not describe the luminous efficiency of the peripheral vision with sufficient accuracy. The lower contrasts of the blue and cyan stimuli imply that the bluish region of the $V(\lambda)$ function underestimates the luminous efficiency of the human eye in the peripheral vision at photopic light levels.

The measured *RT* data was modelled using Equation 2 yielding coefficients *a* and *b* for each stimulus spectra separately. For the blue stimulus, contrast C was replaced with $(1+C)$ because of the negative contrasts and negative exponent. Coefficients a and b and the contrast C, to yield 315 ms *RT* are presented in Table 2. The contrasts were used to calculate the stimulus luminance. The SPDs of the LEDs were measured using several currents ranging from 1.7 mA up to 28.1 mA with an interval of 2.2 mA. 28.1 mA was the highest available current. These measurements were made in an earlier stage in order to model the changes in SPD as a function of LED current. Due to the relatively modest difference between two consecutively measured SPDs, the closest SPD or the mean of two closest SPDs was used to calculate the radiance produced by the stimulus. Equation 3 was used to calculate the radiance of the stimulus and the background.

Table 2

Optimised coefficients *a* and *b*, and contrast *C*, that yields *RT* of 315 ms for the peripheral vision. Calculations are based on Equation 2. For the blue stimulus, the equation is modified by replacing *C* with (1+*C*). RT_{min} is 251 ms

Stimulus	*a*	*b*	*C*
Blue	50.989	–16.6823	–0.0135
Cyan	6.246	–0,86486	0.0678
Green	10.013	–0.97695	0.1497
Amber	6.454	–1.14401	0.1346
Red	8.242	–0.98397	0.1246

The radiance data was used to calculate to see whether the $V(\lambda)$ function with the Judd modification (i.e. $V_M(\lambda)$) or the $V_{10}(\lambda)$ could compensate for the difference and yield the same contrasts for all stimulus spectra. The results are presented in Table 3. It turned out that neither the $V_M(\lambda)$ nor the $V_{10}(\lambda)$ could explain the difference in the measured *RT*s of the different stimulus spectra. The contrasts of the cyan and blue stimuli remained lower than the contrasts of the other stimuli. The contrasts calculated with the $V_M(\lambda)$ function showed very little difference compared to the calculations made with the $V(\lambda)$ function. The contrasts calculated with the $V_{10}(\lambda)$ function were closer to each other, but the difference in contrasts between the stimulus spectra was still too large to be explained by this function alone. The contrasts were also calculated using the scotopic $V'(\lambda)$ function, but as expected, the difference is then reversed, the red stimulus having lower contrast than the blue stimulus.

A Proposal for a New Luminous Efficiency Function

A new luminous efficiency function for peripheral photopic vision is proposed. The new function, here designated as $V_{per}(\lambda)$, is based on the use of $V_{10}(\lambda)$. The use of $V_{10}(\lambda)$ yielded the smallest standard deviation of the contrasts among the luminous efficiency functions that were used for calculations. The weighted difference between $V_{10}(\lambda)$ and $V(\lambda)$ is added to the $V_{10}(\lambda)$ in order to enhance the short wavelength part of the luminous efficiency function. The new luminous efficiency function was built this way, so that it would be easy to reproduce, and that the transition from the $V_{10}(\lambda)$ function to the new part of the function would be smooth. The new function is presented in Equation 4.

$$V_{per}(\lambda) = V_{10}(\lambda) + k\,(V_{10}(\lambda) - V(\lambda)),\ \lambda = 380 \ldots 556\ \text{nm}$$
$$V_{per}(\lambda) = V_{10}(\lambda),\ \lambda = 557 \ldots 800\ \text{nm}, \quad (4)$$

where k is the weighting coefficient. Wavelength 557 nm was selected as a transition point, because it is the peak wavelength of the $V_{10}(\lambda)$ function. Wald (1945b) [29] noticed in his research that the peripheral cones are relatively more sensitive than the foveal cones between wavelengths 380 and 550 nm. This supports the selection of the transition point at 557 nm.

Table 3

Contrasts and standard deviations of the five different stimulus spectra calculated by using various luminous efficiency functions. The results are based on *RT* measurements made at 10 cd/m^2 background luminance. Coefficient $k = 0.8215$ (Equation 4)

	LED colour					
	Blue	Cyan	Green	Amber	Red	Standard deviation
$V(\lambda)$	–0.0135	–0.0679	0.1498	0.1346	0.1246	0.0670
$V_M(\lambda)$	–0.0124	0.0670	0.1486	0.1335	0.1235	0.0660
$V_{10}(\lambda)$	0.0614	0.0854	0.1402	0.1224	0.1163	0.0315
$V'(\lambda)$	0.7437	0.3047	0.1792	–0.0991	–0.1270	0.3547
$V_{per}(\lambda)$	**0.1177**	**0.0998**	**0.1351**	**0.1107**	**0.1048**	**0.0137**

The weighting coefficient, k, was optimised with the «Goal seek» routine, which is supplied with the Microsoft® Excel 2000 program. The standard deviation of the contrasts of the five stimulus spectra was minimised. The best solution was found at $k = 0.8215$ yielding a standard deviation of 0.0137. The calculated contrasts of the five stimulus spectra are presented in Table 3. The results presented in Table 3 have been calculated using five different luminous efficiency functions including the new $V_{per}(\lambda)$.

The contrasts of the cyan and especially the blue stimuli deviate from the contrasts of the other stimulus spectra when the $V(\lambda)$ function is used. The contrast of the stimulus consisting of short wavelengths is lower than the contrasts of the other stimulus spectra yielding to a common *RT*. This applies also for the $V_M(\lambda)$ luminous efficiency function used in the calculations. When the calculations are based on the $V_{10}(\lambda)$, the contrasts of the five stimulus spectra are closer to each other, but for the cyan and blue stimuli the contrasts are still lower. The $V'(\lambda)$ function emphasizes the short wavelengths, which can be seen in Table 3. Using the $V'(\lambda)$ function the contrast of the blue stimulus increases radically while the contrast of the red decreases. When the presented $V_{per}(\lambda)$ with the optimised coefficient k is used as the luminous efficiency function, the standard deviation of the contrasts is smaller than in the other cases.

When the $V_{per}(\lambda)$ function is applied, the contrast of the green stimulus is higher than those of the other stimuli. This implies that the green part of the visible spectrum is overestimated, when using the $V_{per}(\lambda)$ function. Consequently, the luminous efficiency function may in fact have two peaks, which locate on both sides of the peak wavelength of the colour green. Similar multi-peak effects have been reported in other studies conducted with other methods as well (e.g. Weale,

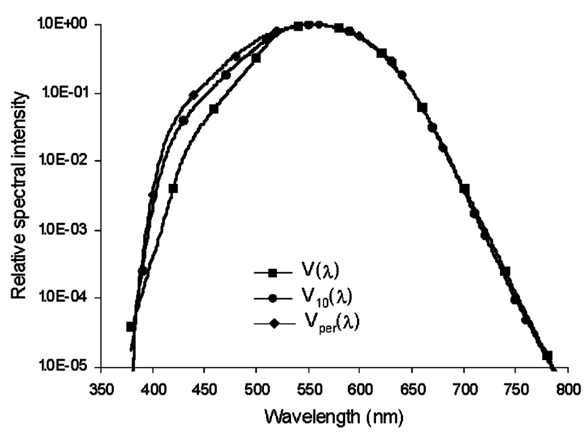

Fig. 6. Relative spectral luminous efficiency functions: $V(\lambda)$, $V_{10}(\lambda)$, and $V_{per}(\lambda)$. $V_{per}(\lambda)$ function was calculated with the weighting coefficient $k = 0.8215$, which was achieved in the optimisation process

Table 4

Contrasts of the five different stimulus spectra calculated by using various luminous efficiency functions. These results are based on *RT* measurements made at 20 cd/m^2 background luminance. Coefficient *k* = 0.7684 (Equation 4)

	LED colour					
	Blue	Cyan	Green	Amber	Red	Standard deviation
$V(\lambda)$	–0.0348	0.0626	0.0580	0.1128	0.0609	0.0535
$V_M(\lambda)$	–0.0344	0.0619	0.0573	0.1120	0.0602	0.0530
$V_{10}(\lambda)$	0.0245	0.0812	0.0516	0.1027	0.0556	0.0299
$V'(\lambda)$	0.5835	0.3218	0.0809	–0.0998	–0.1277	0.3007
$\mathbf{V_{per}(\lambda)}$	**0.0668**	**0.0955**	**0.0484**	**0.0933**	**0.0480**	**0.0232**

Table 5

Contrasts of the five different stimulus spectra calculated with $V_{per}(\lambda)$ luminous efficiency function. These results are based on RT measurements made at 10 cd/m^2 background luminance. Coefficient *k* = 0.7684 (Equation 4)

	LED colour					
	Blue	Cyan	Green	Amber	Red	Standard deviation
$\mathbf{V_{per}(\lambda)}$	**0.1143**	**0.0989**	**0.1354**	**0.1114**	**0.1056**	**0.0138**

1953; Wooten, Fuld, & Spillman, 1975; van Esch, Koldenhof, van Doorn, & Koenderink, 1984) [30–32].

In the first phase measurements, it was only once that the number of missed flashes increased above 5% of the total amount of flashes. The amber stimulus was missed 21 times out of 120 in the peripheral vision at the lowest contrast. This yields a 17.5% missing rate. These flashes were not considered in the modelling.

Second Phase Measurements

In order to improve the reliability of the results, another test was conducted at 20 cd/m^2 background luminance. In the second phase measurements, the CCT of the background illumination was 4610 K. The same subjects participated in this phase as in the first phase measurements at 10 cd/m^2. In the second phase, the number of contrasts was increased to four in order to get an improved impression on the variation of *RT* close the threshold of visibility. The measurements for asymptotic *RT* were included in the measurement sessions as the last measurement. The results of the second phase are presented in Fig. 7 and Table 4. The main difference is that the contrasts for the green and cyan stimuli do not deviate from each other. Similar calculations as those for the first phase results were conducted for the second phase results. The coefficient *k* was optimised for both background luminance levels simultaneously yielding the results presented in Tables 4 and 5. The optimal value for the coefficient *k* was 0.7684 yielding the standard deviations of 0.0232 and 0.0138 for 20 and 10 cd/m^2, respectively.

The results presented in Tables 3, 4, and 5 show that calculations made with the $V_{per}(\lambda)$ function yield the lowest standard deviations for the measured *RT* data for both the first and the second phase measurements. The calculations for 20 cd/m^2 do not show similar increase in contrast for the green spectra as it did for 10 cd/m^2.

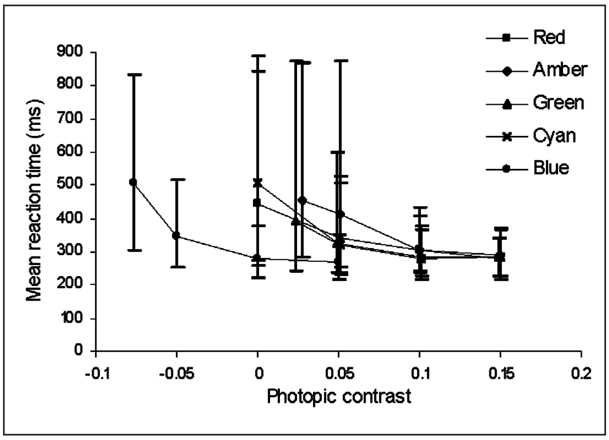

Fig. 7. Reaction time as a function of stimulus spectra in peripheral vision at 20 cd/m^2. The measurement points are the mean *RT*s of five subjects

In the second phase measurements, the number of missed flashes increased above 5% of the total amount of flashes only at the lowest contrast of all five stimulus spectra. The number of missed flashes was between 10 and 32 out of 120 in these cases. These flashes were left out from the modelling phase.

Discussion

RT measurements were made to find out whether the $V(\lambda)$ function would apply for five different stimulus spectra when they were presented on a uniform white background light having a CCT of 4930 K and 4610 K at 10 and 20 cd/m^2 background luminances, respectively. The results of the foveal vision showed that the small blue stimuli required higher contrast in order to be seen equally fast than the other stimuli of other spectra. This result was expected, as this kind of behaviour has been reported before (Abramov & Gordon, 1977) [27].

The results of Tables 3, 4, and 5, imply that the currently used $V(\lambda)$ function underestimates the short wavelength region of the visible spectrum in describing the luminous efficiency of the visual system in photopic peripheral vision. In order to correct this, a new luminous efficiency function should be established. In this paper, a first estimate for the new photopic luminous efficiency function for peripheral vision is presented. This new function is a linear combination of the two well-known functions $V_{10}(\lambda)$ and $V(\lambda)$. The $V_{10}(\lambda)$ function describes the spectral sensitivity of a 10° visual field surrounding the fovea. In the measurements of this work the stimulus located at 10° eccentricity, thus to a double radius. The $V_{10}(\lambda)$ is, however, the only photopic CIE luminous efficiency function that includes a part of the peripheral vision, and thus we consider it to be the best candidate function for the basis of the new function.

There are at least four possible explanations for the enhanced spectral sensitivity to short wavelengths in peripheral vision in the photopic region. The first explanation is that rods do contribute to visual performance even at photopic light levels (Abramov & Gordon, 1977; Stabell & Stabell, 1980, 1981) [27, 33, 34]. The second explanation is that the distribution of cones is different in the fovea and in peripheral parts of the retina (De Valois & De Valois, 1988) [35]. It is known that the central fovea does not have any cones sensitive to short wavelengths. The third explanation is that macular pigmentation affects the spectral sensitivity in foveal vision by absorbing short wavelengths (Weale, 1953) [30]. The peripheral vision is not affected by this absorption. The fourth explanation is that the cones sensitive to short wavelengths are more sensitive in the peripheral vision than in the foveal vision (Weale, 1953) [30]. The enhanced spectral sensitivity to wavelengths in peripheral vision could also be explained by the combined effect of some or even all of these presented explanations.

The measurements to describe a new peripheral $V_{per}(\lambda)$ have been made using five subjects, two luminance levels, five stimulus spectra, and a stimulus size of 0.29°. In order to confirm the results presented in this paper, additional measurements will be done with a larger number of subjects. The accuracy of the modelling would improve if monochromatic or near-monochromatic stimulus spectra were used. In this study, one peripheral eccentricity for target location was studied. Expanding the measurements to far peripheral vision will improve our understanding about the visual performance of the eye.

The proposed peripheral $V_{per}(\lambda)$ shows that the current attempts to establish the mesopic luminous efficiency functions may actually be based on inaccurate assumptions. It is not possible to establish accurate mesopic functions for the mesopic light levels if the starting point is imprecise. At low mesopic light levels, the situation is less severe as the $V'(\lambda)$ is much more dominating and it has higher relative sensitivity in the blue part of the spectrum.

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References

1. *Palmer, D.A.* (1968). Standard observer for large-field photometry at any level. Journal of the Optical Society of America, 58, 1296-99.

2. *Ikeda, M.*, & Shimozono, H. (1981). Mesopic luminous efficiency functions. Journal of the Optical Society of America, 71, 280-84.

3. *Trezona, P.W.* (1987). A system of general photometry designed to avoid assumptions. Proceedings of the CIE 21st Session Venice 1987. Vienna, Austria. Central Bureau of the CIE. 1, 30-33.

4. *Kokoschka, S.*, *Bodmann, H.W.* (1975). Ein konsistentes System zur photometrischen Stralungsbewertung im gesamten Adaptationsbereich. Proceedings of the CIE 18th Session, London, 1975. Vienna, Austria. Central Bureau of the CIE. 217-25.

5. *Sagawa, K., Takeichi, K.* (1992). System of mesopic photometry for evaluating lights in terms of comparative brightness relationships. Journal of the Optical Society of America A, 9, 1240-46.

6. *He, Y., Rea, M., Bierman, A., Bullough, J.* (1997). Evaluating light source efficacy under mesopic conditions using reaction times. Journal of the Illuminating Engineering Society, 26, 125-138.

7. Commission Internationale de l'Éclairage. (1989). Mesopic photometry: History, special problems and practical solutions. Publication CIE No. 81. CIE Central Bureau.

8. Commission Internationale de l'Éclairage. (2001). Testing of supplementary systems of photometry. CIE 141-2001. CIE.

9. *He, Y., Bierman, A., Rea, M.* (1998). A system of mesopic photometry. Lighting Research & Technology, 30, 175-81.

10. Commission Internationale de l'Éclairage. (1978). Light as a true visual quantity: Principles of measurement. Publication CIE No. 41. Paris, France. CIE Central Bureau.

11. Commission Internationale de l'Éclairage. (1926). Principales decisions (6e Session, 1924), CIE Sixième Session, Genève, Juillet, 1924. Recueil des Travaux et Compte Rendu de Séances. Cambridge: Cambridge University Press. 67-69.

12. Commission Internationale de l'Éclairage. (1964). Revue des progrès du comité secrétariat, E1.4.1. CIE Compte Rendu, 15th Session. Central Bureau of the CIE.

13. *Gibson, K.S., Tyndall, E.P.T.* (1923). Visibility of radiant energy. Scientific Papers of the Bureau of Standards, 19, 131-91.

14. Commission Internationale de l'Éclairage. (1951). Compte Rendu, 12th Session, Stockholm 1951, Vol. III, 32-40.

15. *Wald, G.* (1945a). The spectral sensitivity of the human eye; A spectral adaptometer. Journal of the Optical Society of America, 35, 187-196.

16. *Crawford, B.H.* (1949). The scotopic visibility function. Proceedings of the Physical Society. B62, 321-34.

17. *Judd, D.P.* (1951). Report of U.S. Secretariat Committee on Colorimetry and Artificial Daylight. Proceedings of the CIE 12th Session Stockholm 1951. Central Bureau of the CIE. 7, 11.

18. *Vos, J.J.* (1978). Colorimetric and photometric properties of a 2° fundamental observer. Color Research and Application, 3, 125-128.

19. Commission Internationale de l'Éclairage. (1988). CIE Disk D001 Rel 1.2 «CIE Photometric and Colorimetric Tables». Vienna, Austria. CIE Central Bureau.

20. Commission Internationale de l'Éclairage. (1990). CIE 1988 2° Spectral Luminous Efficiency Function for Photopic Vision. Publication CIE No. 86. Vienna, Austria. CIE Central Bureau.

21. *Eloholma, M., Halonen, L., Setälä, K.* (1999). The effects of light spectrum on visual acuity in mesopic lighting levels. EPRI/LRO Fourth International Lighting Research Symposium. Proceedings: Vision at Low Light Levels. EPRI. 149-161.

22. *Forrester, J., Dick, A., McMenamin, P., Lee, W.* (1996). The eye. Basic sciences in practice. London, UK. W.B. Saunders Company Ltd. 409 p.

23. *Pollack, J.D.* (1968). Reaction time to different wavelengths at various luminances. Perception & Psychophysics, 3, 17-24.

24. *Lit, A., Young, R.H., Shaffer, M.* (1971). Simple time reaction as a function of luminance for various wavelengths. Perception & Psychophysics, 10, 397-399.

25. *Lennie, P., Pokorny, J., Smith, V.C.* (1993). Luminance. Journal of the Optical Society of America A, 10, 1283-1293.

26. *Eloholma, M., Liesiö, M., Halonen, L., Walkey, H., Goodman, T., Alferdinck, J., Freiding, A., Bodrogi, P., Várady, G.* (2005). Mesopic models — from brightness matching to visual performance in night-time driving: a review. Lighting Research & Technology. (In press)

27. *Abramov, I., Gordon, J.* (1977). Color Vision in the peripheral retina. I. Spectral sensitivity. Journal of the Optical Society of America, 67, 195-202.

28. *Curcio, C.A., Allen, K.A., Sloan, K.R., Lerea, C.L., Hurley, J.B., Klock, I.B., Milam, A.H.* (1991). Distribution and morphology of human cone photoreceptors stained with anti-blue opsin. The Journal of Comparative Neurology, 312, 610-624.

29. *Wald, G.* (1945b). Human vision and the spectrum. Science, 101, 653-658.

30. Weale, R.A. (1953). Spectral sensitivity and wavelength discrimination of the peripheral retina. Journal of Physiology, 119, 170-190.

31. *Wooten, B.R., Fuld, K., Spillman, L.* (1975). Photopic spectral sensitivity of the peripheral retina. Journal of the Optical Society of America, 65, 334-342.

32. *van Esch, J.A., Koldenhof, E.E., van Doorn, A.J., Koenderink, J.J.* (1984). Spectral sensitivity and wavelength discrimination of the human peripheral visual field. Journal of the Optical Society of America A, 1, 443-450.

33. *Stabell, B., Stabell, U.* (1980). Spectral sensitivity in the far peripheral retina. Journal of the Optical Society of America, 70, 959-963.

34. *Stabell, U., Stabell, B.* (1981). Spectral sensitivity of the dark-adapted extrafoveal retina at photopic intensities. Journal of the Optical Society of America, 71, 841-844.

35. *De Valois, R.L., De Valois, K.K.* (1988). Spatial vision. New York, USA. Oxford University Press, Inc. 381 p.

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