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MODELS FOR SPECTRAL LUMINOUS EFFICIENCY IN PERIPHERAL VISION AT MESOPIC AND LOW PHOTOPIC LUMINANCE LEVELS

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Abstract

The aim of this work was to find out how the spectral sensitivity of the human eye varies in peripheral vision at mesopic and low photopic luminance levels. Two different measurement methods were employed for this purpose. Reaction time and contrast threshold measurements were conducted at various mesopic and low photopic luminance levels in foveal and peripheral vision. Luminance levels between 0.1 cd/m² and 20 cd/m² and visual target eccentricities of 0°, 10°, 30° and 60° were investigated in the measurements. Both measurement methods revealed the same observations: at low photopic luminance levels, the currently used $V(\lambda)$ function is not the best descriptive spectral luminous efficiency function for peripheral vision. The short wavelengths were underestimated by the $V(\lambda)$ function. A new spectral luminous efficiency function $V_{per}(\lambda)$ was developed for peripheral vision at photopic light levels. This function is a linear combination of $V(\lambda)$ and $V_{10}(\lambda)$ functions and takes into account the higher spectral sensitivity to short wavelengths as compared to the $V(\lambda)$ function. Both measurement methods show that this function describes the spectral sensitivity of the eye better than $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ functions at low photopic luminance levels (≤ 20 cd/m²). At mesopic luminance levels (≥ 0.1 cd/m²), it was investigated how a linear combination of photopic and scotopic spectral luminous efficiency functions describes the spectral sensitivity of the eye in peripheral vision. A model for the mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ was developed for peripheral vision. The results showed that this function describes the peripheral spectral sensitivity with best accuracy at mesopic luminance levels. The new function was compared with the proposed unified system of photometry by Rea, Bullough, Freyssinier-Nova and Bierman (2004). The function developed in this work described the measurement results with much higher accuracy. A sigmoid function was developed to describe the mesopic spectral luminous efficiency function as a combination of photopic and scotopic spectral luminous efficiency functions. This function can be used to calculate the weighting coefficient from 0.1 cd/m² upwards.

Keywords	peripheral vision, mesopic vision, reaction time, contrast threshold, spectral luminous efficiency function		
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Preface

This study was carried out in the Lighting Laboratory of the Department of Electrical and Communication Engineering at Helsinki University of Technology. Most of the work was conducted as a part of the Mesopic Optimisation of Visual Efficiency (MOVE) project during the period 2002-2004. MOVE was funded by the European Commission in the Fifth Framework Programme (G6RD-CT-2001-00598). The Academy of Finland funded this research in part (decision no: 78093). I acknowledge both institutions for their support.

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Espoo, September 2005

Pasi Orreveteläinen

List of symbols and abbreviations

a	optimised coefficient
b	optimised coefficient
C	(photopically weighted) contrast
C_{mes}	mesopically weighted contrast
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
f_1 (also f_1')	deviation of relative spectral responsivity from the V(λ) function
k	coefficient used in the calculation of $V_{per}(\lambda)$
k	normalisation coefficient
K_m	maximum luminous efficacy of radiation, 683 lm/W for V(λ)
L	luminance
L'	luminance based on V'(λ)
$L_{e,\lambda}$	integrated radiance of the source, spectral power distribution
L_b	luminance of the background
L_t	luminance of the target
L_{10}	luminance based on $V_{10}(\lambda)$
LED	light emitting diode
LMT	Lichtmesstechnik GmbH Berlin
M	coefficient used in the calculation of $V_{mes}(\lambda)$
p	significance level
R^2	coefficient of determination
S/P-ratio	ratio between scotopically and photopically weighted luminance
T_{10}	retinal illuminance
Td	troland
V(λ)	photopic spectral luminous efficiency function, 2° field
V'(λ)	scotopic spectral luminous efficiency function
$V_M(\lambda)$	photopic spectral luminous efficiency function with Judd-Vos modification
$V_{mes}(\lambda)$	mesopic spectral luminous efficiency function
$V_{per}(\lambda)$	photopic spectral luminous efficiency function for peripheral vision
$V_{10}(\lambda)$	photopic spectral luminous efficiency function, 10° field
x	coefficient used in the calculation of $V_{mes}(\lambda)$
x_{10}	CIE 1964* chromaticity coordinate
x_{max}	maximum value for coefficient x
x_{min}	minimum value for coefficient x
X	coefficient used in the calculation of $V_{mes}(\lambda)$ in Rea et al. (2004) model
X_{10}	CIE 1964* tri-stimulus value
y_{10}	CIE 1964* chromaticity coordinate
Y_{10}	CIE 1964* tri-stimulus value
Z_{10}	CIE 1964* tri-stimulus value
λ	wavelength

*CIE 1964 supplementary standard colorimetric system, 10° field

Contents

1 Introduction

1.1 Background

Mesopic light levels fall in the region between photopic and scotopic light levels. In photopic vision, cone photoreceptors are active in the visual process. In scotopic vision, the visual process is dominated by rod photoreceptors. Mesopic vision is, however, different, as both cones and rods are simultaneously active. The different spectral sensitivities and dependency on the light level of the photoreceptors make the modelling of mesopic vision difficult. It appears that the modelling of the mesopic vision is strongly dependent on the visual task under consideration.

Since the mesopic light level is between the photopic and scotopic light levels, the current models of mesopic vision tend to be combinations of the photopic spectral luminous efficiency function $V(\lambda)$ and the scotopic spectral luminous efficiency function $V'(\lambda)$. There are no rods in the central fovea. This region is fully occupied by cones, which become inactive at scotopic light levels. As the fovea is occupied by cones only, the relative foveal spectral sensitivity does not change during the transition from photopic to scotopic vision, where they become inactive. Therefore, the most interesting region of mesopic vision is in the peripheral vision that occupies the rest of the visual field beyond the fovea.

In this work, "peripheral vision" is used to describe extra-foveal vision. The foveal vision participates in, for instance, the adaptation process and is active in the visual process, but the target or stimulus is presented extra-foveally to the subject (off-axis target). "Foveal vision" is used to describe situations where the target locates at least partially in the fovea (on-axis target).

It has been noticed with respect to peripheral vision that the $V(\lambda)$ function does not describe it perfectly at photopic light levels. In fact, even in foveal vision, it has been noticed that the $V(\lambda)$ function underestimates the short wavelengths of the visible spectrum. This phenomenon was already known when the $V(\lambda)$ function was established in 1924 (Gibson and Tyndall, 1923). Eventually, further research conducted after the establishment of the $V(\lambda)$ function led to another function presented by Judd (1951). This function enhanced the spectral sensitivity of short wavelengths. Vos (1978) revised later the function presented by Judd. The CIE (Commission Internationale de l'Éclairage, International Commission on Illumination) adopted the results and established a new function, $V_M(\lambda)$ (CIE, 1990). This function has been accepted as a supplementary function to $V(\lambda)$, but even today it has not been adopted in practical photometry.

$V(\lambda)$ describes the spectral sensitivity of foveal vision. An additional function, $V_{10}(\lambda)$, was established in 1964; this consists of a 10° centrally-viewed field around the fovea (CIE, 1963). Thus, the field of view of this function includes the fovea also. The $V_{10}(\lambda)$ function

has higher sensitivity at short wavelengths than the V(λ) function. The difference in spectral sensitivities between these two functions implies that the spectral luminous efficiency of peripheral vision may not, however, be well described by either V(λ) or $V_{10}(\lambda)$, even at photopic light levels.

1.2 Aim of the study

The aim of this study was to investigate the spectral sensitivity of the human eye in peripheral vision at mesopic and low photopic luminance levels. The work was restricted to small visual targets (0.29°) at an eccentricity of 10°. Additional target eccentricities of 30° and 60° were included in some of the measurements. The spectral sensitivity of foveal vision was also examined in the tests. The light levels covered luminances between 0.01 cd/m² and 20 cd/m², although the main part of the research was performed at luminance levels between 0.1 cd/m² and 10 cd/m².

1.3 Research methods and scope of the research

Spectral sensitivity was studied using two methods. Reaction time tests were conducted in order to see how the spectral power distribution of the target affects its visibility; contrast threshold measurements were performed to investigate spectral sensitivity using another visual criterion. The method of limits (Forrester et al., 1996) was used in the contrast threshold measurements. It was assumed in the reaction time measurements that if a spectral luminous efficiency function describes the spectral sensitivity correctly, the targets with the same contrasts would yield the same reaction times at the same luminance level. In the contrast threshold measurements, it was assumed that the correct spectral luminous efficiency function would yield the same threshold contrasts for all colours at the same luminance level.

2 State of the art

2.1 Introduction

Several studies have been performed to investigate the spectral sensitivity of the human eye. Gibson and Tyndall (1923) combined the results of several investigations, including their own, and, as a result, the photopic spectral luminous efficiency function V(λ) was established by the CIE in 1924. In 2004, the V(λ) function was standardized by the CIE (2004). All practical current photometry is based on this function.

Weale (1953) noticed in his measurements using brightness matching of two fields subtending 50' that spectral sensitivity of short wavelengths was greatly enhanced in peripheral vision as compared to foveal vision. In the measurements, the two fields were vertically above each other and their angular separation was between 3° and 4°. Later, Wooten et al. (1975) suggested that this enhancement was greatly affected by the colour of the background, which affected the spectral sensitivity. Wooten et al. concluded from

their own experiments (increment threshold and dark-adaptation curve measurements), and those performed by others, that the chromatic surroundings of the target (Stiles and Crawford, 1934), adaptation to different background colours (Wald, 1964) and bright or chromatic adaptation fields (Brindley, 1953) alter the photopic spectral sensitivity functions selectively. According to them, the spectral composition of the background may depress two of the three cone systems.

Abramov and Gordon (1977) found in their investigations that spectral sensitivity of short wavelengths is enhanced in peripheral vision. For foveal vision they found that a target of 5' had reduced sensitivity to short wavelengths. They interpreted this as small-field tritanopia, which is caused by a lack of S-cones in the central fovea. Curcio et al. (1991) found in their retinal investigations of the fovea that there is a zone with a diameter of approximately 100 μm (0.35° visual angle) which lacks S-cones entirely. This area is not located perfectly symmetrically around the peak density of cones.

Stabell and Stabell (1980a) investigated relative spectral sensitivity at different eccentricities during the cone-plateau period of the long-term dark-adaptation curve. They employed the absolute threshold and flicker techniques, which both showed an increase in spectral sensitivity to short wavelengths with increasing eccentricity. They suggested that the variation in the density of macular pigmentation and the sensitivity of the S-cones affected the results of the threshold techniques, while the results of the flicker techniques were affected only by the density of macular pigmentation. In later research, Stabell and Stabell (1980b) found results that contradicted their earlier results. The later investigations employed three different methods – heterochromatic brightness matching, flicker photometry and threshold measurement – in order to investigate the relative spectral sensitivity of a 1°-by-2° target at 45° eccentricity during the cone-plateau period and in a dark-adapted state. They found that the relative contribution of the receptor mechanism of the S-cones stays essentially constant between eccentricities 7° and 45° temporally. The contradiction of the two experiments became evident as the spectral sensitivity functions were apparently either photopic in nature at 10 Td[1] (1980a) or scotopic at 1000 Td (1980b). This suggested that, in the far periphery, the rods may dominate spectral sensitivity at a higher intensity than in the near-peripheral retina.

Stabell and Stabell (1981a) measured spectral equal-brightness functions by matching the brightness of two 50' by 100' test fields. The test fields were presented as successive 0.5 second flashes with an interval of 1 second. Temporal target eccentricities between 6° and 65° were used in the tests. They found that the equal-brightness functions were basically scotopic in form in the short and middle wavelength region at a retinal illumination up to

[1] Troland (Td) is a unit used to express a quantity proportional to retinal illuminance produced by a light stimulus. When the eye is viewing a surface of uniform luminance, the number of trolands is equal to the product of the area in mm² of the limiting pupil, natural or artificial, by the luminance of the surface in cd/m² (SFS-IEC 50(845), 1992). In several references presented in Section 2, the terminology when using trolands has been inconsistent with this definition. As it cannot always be certain in what purpose the author of the original text has used the unit troland, the terminology of the original text has been applied.

1000 Td. They concluded that rods may function and dominate spectral sensitivity, even at this light level. The test and comparison fields were presented in succession, not simultaneously. This had the effect that the luminance range affected by the Purkinje shift (increased sensitivity to short wavelengths at low light levels) was far more extensive in successive presentation than in simultaneous presentation. In another test, Stabell and Stabell (1981b) showed that, as absolute spectral threshold functions were measured during the cone-plateau period and dark-adapted state, the relative spectral sensitivity of the M- and L-cone photopigments remained unchanged across the retina. However, the absolute sensitivity decreased from the fovea to 65° eccentricity. For the S-cones, the sensitivity increased between the fovea and 17°, remained constant between 17° and 28° and decreased between 28° and 65°. These conclusions were derived by comparing the gained relative photopic spectral-threshold functions. The functions closely resembled each other in the region between 520 nm and 700 nm at every investigated peripheral eccentricity.

Eisner and MacLeod (1980) investigated the sensitivity of S-cones by using violet backgrounds (range between 0.1 Td and 30 Td) and altering the S-cone sensitivity using flicker photometry. According to Eisner and MacLeod, the S-cone contribution to luminance varies according to the flicker frequency. They concluded that S-cones make no significant contribution to luminance as defined by flicker photometry.

The investigations cited above show that measuring spectral sensitivity at mesopic and photopic light levels is at least challenging. Several factors affect the outcome: the method used, spectral characteristics of the background, intensity of the background, eccentricity of the visual target, the size of the visual target, etc. Nevertheless, several researchers have endeavoured to describe the spectral sensitivity of human vision at mesopic light levels. In the next chapter, several of those methods are introduced in chronological order; the most modern performance-based methods are introduced in Section 2.3.

2.2 Models for mesopic vision

Several methods have been employed with the aim of modelling mesopic vision. Certain methods that work well at photopic or scotopic luminance levels have, however, failed because, for instance, the critical flicker fusion is different for rods and cones (Forrester et al., 1996). Brightness matching has been another method for establishing mesopic spectral luminous efficiency curves.

Walters and Wright (1943) measured the energy (the range of investigated background intensities varied between $0.015 \cdot 10^{-4}$ ergs/deg²/sec and $45 \cdot 10^{-4}$ ergs/deg²/sec; 1 erg/sec = 10^{-7} W) required to match the brightness of a 2° test field of various wavelengths with a fixed comparison field. The colour of the comparison field was red (630 nm), which yielded the best accuracy for long-wavelength test fields. The measurements were performed for two subjects in foveal vision, and at eccentricities of 3° and 10° from the fovea. They found both a small shift in the foveal luminous efficiency curve towards the

shorter wavelengths as the intensity decreased and a hump on the red side of the curve. For peripheral vision they found the Purkinje shift. Walters and Wright were surprised by the high intensities required to achieve a pure photopic curve. They assumed that the rods were interacting at higher levels than generally accepted. They deduced that the sensitivity to wavelengths above 600 nm was mainly due to cone sensitivity. The measurements at 10° were easiest to reproduce. Foveal targets suffered from fixation problems. At 3° eccentricity, when the eye was sensitive to small intensity differences, the rapidly changing sensitivity of the retina caused problems as the fixation of the eyes wandered.

Bridgman (1953) analysed and summarised earlier measurements by other authors and concluded that an assumption of summation between rod and cone mechanisms is required when the sensitivity of rods and cones is near-equal in order to explain the residual discrepancies between predicted and empirical curves. According to Bridgman, the mesopic luminous efficiency functions are, in fact, products of the method employed, rather than fundamental functions, as pure cone and pure rod functions are. Photometry at mesopic light levels requires the determination of the transition range over which transition occurs from cone to rod function and the contribution of cones and rods at various intensities.

Kinney (1958) measured the spectral sensitivity curves of the eye by matching a bipartite 2° stimulus in 10° peripheral vision at scotopic and mesopic light levels. She noticed that when the luminance was increased to 3.5 to 4.0 log units above the absolute scotopic threshold, the spectral sensitivity curves started to shift towards longer wavelengths. At higher luminance levels, the curves started to become irregular in shape, yielding, for instance, a region of increased sensitivity at around 610 nm to 620 nm. She found that illuminated surrounding which covered over 100° visual field yielded increased sensitivity to red but not to other colours at lower light levels. An illuminated surrounding also reduced the variability of the results, compared to those gained with a dark surrounding. A major difference was found between foveal and peripheral vision, as the peak wavelengths of the foveal curves remained near 550 nm, while the peak wavelengths of the peripheral curves were between 510 nm and 520 nm. In another experiment conducted by Kinney (1964) using direct brightness matching, she found that, in contrast to the case of pure foveal vision, increasing the size of a visual stimulus above the size of the fovea at 0.3426 cd/m² increases sensitivity to short wavelengths as well as to those near 600 nm, as compared to pure foveal vision. In the same experiment, she found that sensitivity to short wavelengths at 0.03426 cd/m² increases in near peripheral vision (2° and 4° eccentricity).

Palmer (1967) found that, at medium mesopic levels (0.316 cd/m²), spectral sensitivity in the violet region of the spectrum is enhanced compared to the (at that time) proposed CIE standard observer ($V_{10}(\lambda)$, today). In his test, he used a 15° bipartite central field surrounded by a 21° field. The task of the subject was to match a test colour against a standard test field. As this luminance level is currently considered to be in the mesopic

range, such enhancement in the violet region is, in fact, expected. Palmer (1968) derived an empirical formula for equivalent luminance. This formula was designed for large-field photometry (5° or larger) at any light level. He used the scotopic and photopic luminances to describe the equivalent luminance (*Luminance of a comparison field in which the radiation has the same relative spectral distribution as that of a Planckian radiator at the temperature of freezing platinum and which has the same brightness as the field considered under the specified photometric conditions of measurement* SFS-IEC 50(845), 1992). This formula used the $V_{10}(\lambda)$ function of the CIE 1964 supplementary standard colorimetric system. Palmer revised his first formula (CIE, 2001) to improve the fit of his own data based on heterochromatic brightness matching. The change to his first system is that the system equivalent luminance becomes a non-linear function between L_{10} and L'. A later analysis of the results by Palmer (1976) showed that a simple rod-cone mechanism was responsible for the brightness sensation. Palmer suggested a simple photometer for mesopic vision, where the square root of the scotopic input is added to the photopic input of the two photocells calibrated for scotopic and photopic spectral luminous efficiency functions, respectively. Palmer also suggested modifications to the $V'(\lambda)$ spectral luminous efficiency function in order to make the representation of the long wavelength radiation more accurate.

Hough (1968) made brightness matches with 55' circular fields using the flicker technique at retinal illumination levels of 10 Td, 2.5 Td and 0.6 Td. In the tests, near-monochromatic (2 nm to 7 nm bandwidths) targets were matched against a white reference source. From the results it was concluded that the differences between the foveal and extra-foveal (7° eccentricity) brightness match at higher levels of illumination were caused almost exclusively by absorption in the lens and the difference in absorption by the macular pigment, as well as any change in cone sensitivity. Furthermore, at lower light levels, the spectral sensitivity curves shifted towards shorter wavelengths. This was interpreted as increasing the rod intrusion of the extra-fovea as compared to the fovea. On the other hand, the results suggested a possible enhancement of the S-cones in the extra-foveal retina. A possible combination of rods and S-cones affecting the Purkinje shift led to a four-variable function describing the spectral sensitivity of the eye. By comparing the results of a tritanope and a normal observer, Hough and Ruddock (1969) suggested that the Purkinje shift is facilitated by the functioning of the S-cone mechanism. They could not say whether it was due to the S-cones blocking or taking over from the rods, or to any more complex form of interaction.

In 1975, Kokoschka and Bodmann (CIE, 2001) developed a mesopic photometric system based on heterochromatic brightness matching that in turn is based on a linear weighted sum of four components (four-variable system). The four components are the CIE 1964 tristimulus values for a 10° field and its scotopic luminance. These components reflect the activity of the three types of cones and of the rods.

Ikeda and Shimozono (1981) used the direct heterochromatic brightness matching method to derive an empirical formula for a 10° field mesopic spectral luminous efficiency function, which is presented foveally. They noticed that the spectral luminous efficiency curve undergoes a continuous and complex transition pattern when the retinal illuminance level varies from 0.01 Td to 100 Td. They concluded that mesopic vision can be expressed by simple formulae that represent the sensitivities of the cones and rods. They also concluded that $V(\lambda)$ does not represent the sensitivity of the cones in mesopic vision, whereas the sensitivity of the rods can be described by the $V'(\lambda)$ function, except above 620 nm. They also predicted additivity failures resulting from the contribution of opponent chromatic channels to the mesopic spectral luminous efficiency function. The formula gained was based on the logarithmic relation between the $V(\lambda)$ and $V'(\lambda)$ spectral luminous efficiency functions. Yaguchi and Ikeda (1984) performed a heterochromatic brightness matching test for a 10° centrally viewed field. Two subjects participated in the tests. The results were modelled with the Ikeda-Shimozono formula and it was found that at high adaptation levels (100 Td) the coefficients indicated pure cone activity and at low adaptation levels (0.1 Td) the coefficients indicated rod activity. At intermediate levels (between 1 Td and 10 Td), the brightness was affected by the intensity level of the reference light and the adaptation level. They concluded that the spectral luminous efficiency function for brightness at mesopic levels depends on the intensity level of the test stimulus and also the adaptation level of the eye. If the intensity level of the test stimulus is high enough (100 Td), the spectral luminous efficiency function becomes photopic ($V(\lambda)$) at any adaptation level. They assumed that this is because the light adaptation proceeds rapidly.

Kokoschka and Adrian (1985) employed a bipartite field for direct brightness matching when they investigated the spectral sensitivity of the eye in the mesopic region. They used central field sizes between 3° and 64° and noticed increasing deviation from $V(\lambda)$ in the blue part of the spectrum when the size of the field was increased. The luminance levels in the measurements varied between 10 cd/m² and 0.001 cd/m². Their results with a 9.5° central field showed good fit with the $V_{10}(\lambda)$ function at 30 Td (10 cd/m²). They assumed that differences in sensitivity in the blue part of the spectrum between small and large fields can be explained by absorption resulting from the macular pigmentation. They disagree with the linear model of Bridgman (1953), as they assume that the interactions of all four photoreceptor types take place in mesopic vision. They found that the influence of the field size on the relative spectral sensitivity had a dependency on the intensity level in the far red region (660 nm). As $V_{10}(\lambda)$ showed a rather good fit with their 64° field data, they concluded that the field size is the determining factor, and not the location in the extra-foveal region. This conclusion became evident as the data of Kinney (1958) gained from 10° extra-foveal measurements resembled their results of 64° field data.

Sagawa and Takeichi (1986) measured several spectral luminous efficiency curves in the mesopic range, using twelve subjects. They used the direct brightness matching method for a bipartite 10° central field. They noticed that each of the measured retinal

illuminance levels (range 100 Td to 0.01 Td) required a mesopic function of its own. They concluded that a function based on the logarithms of the scotopic and photopic spectral luminous efficiency functions would yield the desired mesopic function if the logarithms of the photopic (based on the 100 Td data) and scotopic (based on the 0.01 Td data) base functions were weighted properly. The difference between the methods of Ikeda and Shimozono (1981) and Sagawa and Takeichi (1986) is that the latter require the sum of the weighting factors to be unity, which is not required by the former method. Sagawa and Takeichi concluded that, since the mesopic functions were determined by brightness matching, the use of the brightness matching function to express the mesopic functions seems reasonable.

Trezona (1987) introduced a four-variable system (rods and three types of cones) for general photometry (including mesopic vision) based on heterochromatic brightness matching. The measurements were conducted with a 10° centrally-viewed bipartite field using a 588-nm yellow test field on one half and the test stimulus on the other half. The advantage of this model is that it does not assume additivity, while allowing independent and interactive behaviour for all four receptor types. The model uses the hyperbolic tangent function with polynomial functions, based on the CIE 1964 tri-stimulus values X_{10}, Y_{10}, Z_{10} and $V'(\lambda)$. Later on, Trezona (1991) updated her system and used a 10° central field to produce a system of photometry for the photopic, mesopic and scotopic regions. The measurements were based on brightness matching, and both spectral and non-spectral stimuli were used. Trezona claims that the treatment of the mesopic problem as a two-variable – $V(\lambda)$ and $V'(\lambda)$ – system is an oversimplification. She goes on to state that four variables – one for each receptor type – are required. The data gained showed again that the hyberbolic tangent function described the measured data with best accuracy. In the scotopic range, the data points were close to the line representing the $V'(\lambda)$ function, which validated the use of the $V'(\lambda)$ function. The photopic measurement data for the test stimulus with the same chromaticity as D65 (daylight illuminant) located close to a line that was based on the luminance derived from flicker photometry. The blue data points that were plotted were more displaced. On the other hand, for the red data points, it was noticed that they did not reach the line representing the $V'(\lambda)$ function within the measurement range.

Vienot and Chiron (1992) used heterochromatic flicker photometry and direct comparison brightness matching to evaluate the spectral sensitivity in the mesopic range. Three subjects made visual matches from 0.03 Td to 100 Td on a 10° central field. For short wavelengths (445 nm), they found that brightness matches underwent smooth changes in a relative sensitivity-versus-illuminance plots, producing a sigmoid-shaped curve between 0.03 Td and 10 Td, while the flicker curve exhibited a step-like transition around 1 Td to 3 Td. A slight reverse Purkinje shift (relative sensitivity to short wavelengths increases as luminance level increases) was recorded in the photopic and scotopic regions. In the high mesopic range (approximately above 2 Td to 3 Td), the flicker photometry was found to yield lower spectral sensitivities than the brightness

matching method. For the 560-nm test light, the differences between the two methods were smaller. The step-like transition in the flicker method occurred between 0.3 Td and 1 Td. With the 630-nm test light, the Purkinje shift started at over 100 Td and the shift was not completed at 0.03 Td. A significant difference between the two methods was found, implying that the rods and cones do not interact smoothly in the mesopic range when flicker photometry is applied. On the basis of their experiments, Vienot and Chiron (1991) suggested possible problems for mesopic photometries. Direct brightness matching shows additivity failures at photopic levels; the situation is likely to be more complex in the mesopic range, where both cones and rods contribute to the visual process. Discontinuities were found for flicker photometry at mesopic levels (around 1 Td), although it works well at photopic levels. Vienot and Chiron (1995) concluded that the differences between heterochromatic flicker photometry and direct-comparison brightness matching cannot be explained by any extra S-cone activity alone. Vienot et al. (1997) added heterochromatic spatial structure photometry to the test methods. In this method, the reference (5500 K white) and spectral test lights are respectively displayed on an adjustable two-colour grating. In the peripheral retina, the heterochromatic spatial structure photometry matches followed the direct comparison brightness matches, but, in the fovea, they clearly departed from each other. As a conclusion, they supposed that no mesopic system of universal value exists.

2.3 Performance-based methods

The previously mentioned methods are based on a comparison of two fields that have different spectral properties. Berman and Clear (2001) comment that the use of wide-field (they refer to several investigations made with field sizes of approximately 10° and above) brightness matching is not a very successful method in the mesopic region, because it does not work properly even at photopic levels. Kaiser and Wyszecki (1978) found both enhancement and cancellation type of additivity failures in their study based on calculations of brightness matching data. Heterochromatic flicker photometry works well at photopic levels, but fails to do so in the mesopic range (Vienot and Chiron, 1991). The critical flicker fusion frequency depends on the adaptation level and is different for rods and cones (Forrester et al., 1996), which makes the applicability of the flicker photometry an unsuitable method for defining the spectral sensitivity of the eye in peripheral vision at mesopic luminance levels. The problems associated with these methods have led to investigations of other types of methods. Current interest in performance-based methods has emerged because they imitate many real-world tasks such as speed of response (He et al., 1997). In the performance-based approach adopted by Eloholma et al. (2005b), the criteria are the ability to detect the target at threshold, the time it takes to react to the onset of the target, and the ability to recognise details of the target.

Reaction time as a criterion has also been investigated by He et al. (1997), He et al. (1998) and Rea et al. (2004). Those models are mainly based on the assumption that the spectral sensitivity in the photopic and scotopic regions are described by the spectral luminous efficiency functions $V(\lambda)$ or $V_{10}(\lambda)$, and $V'(\lambda)$. The intermediate mesopic region is then

modelled as a linear transition between the two functions representing the photopic and scotopic luminous efficiencies. Eloholma et al. (2005b) have adopted a multi-technique method where reaction time is one of the three visual tasks investigated.

Plainis et al. (1997) noticed in their investigations that the maximal sensitivities under night-time driving conditions were reduced by at least 2 log units compared to complete darkness. Their findings implied that the rate of adaptation for cones is slower under mesopic than scotopic conditions. They found that, for the peripheral retina (30° eccentricity), there was a roughly linear relationship between the size of the stimulus and retinal sensitivity. For foveally fixated targets, retinal sensitivity increased up to a target size of 2°, but no significant differences were found for larger target sizes. Foveal vision was found to be more sensitive than peripheral vision. Plainis and Murray (1999) investigated retinal adaptation at mesopic light levels using reaction time as a criterion. A circular test field with achromatic vertical gratings that subtended an angle of 7.13° was presented foveally in the tests. The mean luminance range of the test screen varied between 0.005 cd/m² and 20 cd/m². They found that, as the target contrast reduced, the reaction time increased. They also found that targets of low spatial frequency were perceived faster than targets of high spatial frequency, and that the reaction times increased as the luminance decreased. Plainis and Murray (2000) continued with a setup and criterion similar to Plainis et al. (1999). Again, the contrast and spatial frequency had a similar effect on the reaction time. Reduction of contrast yields longer reaction times as well as the increment of the spatial frequency. Also, decreasing the luminance level increased the reaction times. This was most pronounced at the lowest spatial frequencies, which were best detected at the highest luminance levels. They found that the product of reaction time and contrast had a linear relationship when plotted against the reciprocal of contrast. An equation was derived for the reaction time as a function of target contrast, spatial frequency and luminance.

Recognition thresholds were investigated by Hurden et al. (1999), who used visual search time to characterise visual performance at mesopic light levels. The task of the subjects was to find the correct target (modified Landolt C) among 48 distracting elements (rings) on a computer screen; the search time was recorded. An equation was derived from the results employing eleven constants, photopic and scotopic contrasts and background luminance. The results showed that, at high near-photopic luminance levels, the search time was mainly determined by the photopic contrast, but the importance of the scotopic contrast increased with decreasing luminance levels. The authors concluded that the sign of the photopic contrast was not significant, but for scotopic contrast it turned out that search times for negative scotopic contrasts were shorter than for positive contrasts.

2.3.1 Contrast threshold

A visual task starts with the detection of an object. In order for the object to be visible, a certain contrast is required between the target and its background. The contrast threshold has been investigated with several methods. Blackwell (1946) noticed in his extensive

research that, given a free choice in detecting the target, the visual search process shifted from foveally-based detection to peripherally-based detection. This transition was detected when the luminance level decreased below approximately 0.0024 cd/m². Another basic finding was that the product of the area and the stimulus brightness was constant below a critical visual angle, above which the equation did not apply any more. This critical visual angle is affected by the adaptation luminance. Currently, no mesopic spectral luminous efficiency function based on contrast threshold exists. The contrast threshold is one of the measurement methods used in the work of Eloholma et al. (2005b).

Sperling and Lewis (1959) used the absolute contrast threshold method, along with flicker photometry and heterochromatic brightness matching to investigate the spectral sensitivity of the fovea. These measurements were made in the photopic range (500 Td and 1 mm² artificial pupil). Their results implied clear scotopic effects with a 2° centrally viewed target, despite the fact that the luminance level was well within the photopic range. They could only speculate about the reasons for such behaviour: the possible existence of rods in the fovea, possible fixation problems of the subjects and changes in the responses of several groups of photopic foveal receptors, which combine to determine luminance and which have maximum sensitivity at different locations in the visible spectrum. The smaller target of 45' yielded a lesser scotopic effect than the 2° target. The absolute threshold measurements also revealed a significant dip in the spectral sensitivity curve at 530 nm that was not recorded by the other methods.

Patel and Jones (1968) conducted an investigation on increment and decrement visual thresholds at 7° eccentricity with target sizes between 15' and 4.3°. The scotopic luminances varied approximately between 0.0022 Td and 2200 Td. Their results showed that increment thresholds (target brighter than background) were greater than decrement thresholds (target dimmer than background). In their experiment, the target had the same colour as the background.

2.3.2 Reaction time and binocular simultaneity methods

Reaction time is a rather novel method used in the modelling of mesopic vision. Reaction time measurements have been used to investigate spectral sensitivity to coloured targets, for instance by Pollack (1968), who found that when the luminance level is reduced enough, the spectral properties of the targets start to affect the reaction time. The research of Lit et al. (1971) also demonstrated this effect. This observation can be interpreted vice versa; if the contrast is high enough, the spectral properties do not affect the reaction time any more. This effect was also recorded by the author when measuring the reaction times of high-contrast targets (Section 5.2).

The investigated models for describing the spectral sensitivity of the eye at mesopic luminance levels using reaction times were developed in the late 1990s and early 2000s. The first model was developed by He et al. (1997). Their investigation concentrated on how the spectral differences between two commonly-used lamp types in road and outdoor

lighting – high-pressure sodium lamp and metal halide lamp – affect the reaction time. These measurements were conducted with targets having the relatively high contrast of 0.7, while the colour of the target was the same as the colour of the background. The target was superimposed on the background. They found that, in the foveal, on-axis vision, the reaction times were not affected by the spectral power distribution of the two light sources at constant luminance levels. In the peripheral, off-axis vision, a difference in reaction times was found between 0.3 cd/m² and 1 cd/m². The use of a high-pressure sodium lamp yielded longer reaction times at lower luminance levels, but no differences could be found at 1 cd/m² and above. They concluded that, at luminance levels above 0.6 cd/m², there is no rod contribution to the detection of a 2°, off-axis target. Increased rod activity was detected by decreasing the luminance level below 0.6 cd/m². An iteration method to calculate the mesopic luminance of a given source was presented. The $V_{10}(\lambda)$ function was applied in this method. The binocular simultaneity method was used by He et al. (1998). The method was based on the comparison of two light sources, which were viewed simultaneously. The background illuminated with a low-pressure sodium lamp was viewed with the right eye and the background illuminated with a xenon-lamp was viewed with the left eye. Monochromatic flashes were presented for both eyes simultaneously. The radiance of the left field was adjusted, so that the targets appeared to flash simultaneously. The ratio of the radiances of the two sources was used to determine the spectral luminous efficiency of the test wavelength at the reference field radiance. The model for mesopic luminous efficiency developed by He et al. (1998) had the form presented in Equation 1. He et al. presented again an iterative process to calculate the mesopic luminance. The results of He et al. (1997) were compared to the new results (He et al., 1998). Both studies show a similar relationship between the weighting coefficient x (Equation 1) and the photopic retinal illuminance.

$$V_{mes}(\lambda, T_{10}) = k(T_{10})\{x(T_{10})V_{10}(\lambda) + [1 - x(T_{10})]V'(\lambda)\} \quad (1)$$

where $V_{mes}(\lambda,T_{10})$ represents the mesopic spectral luminous efficiency as a function of the wavelength λ, T_{10} represents the retinal illuminance, $V_{10}(\lambda)$ is the photopic spectral luminous efficiency function for a 10° field, x is the adaptation coefficient (value between 0 and 1), and k is the normalisation constant.

Rea et al. (2004) simplified the model of He et al. (1998). This time, instead of the $V_{10}(\lambda)$ function, the $V(\lambda)$ function was used to describe the spectral luminous efficiency in the photopic region. The reason for such a change was to promote the practical photometry based on $V(\lambda)$, which has been used since its adoption in 1924; on the other hand, it was estimated that the differences between the $V(\lambda)$ and $V_{10}(\lambda)$ functions are relatively small for most conventional white light sources. This proposed unified system of mesopic photometry covers a luminance region between 0.001 cd/m² and 0.6 cd/m². CIE (1978) defines the mesopic luminance range to be approximately between 0.001 cd/m² and 3 cd/m² (also expressed as several cd/m²). Thus, the lower limit is accepted as the limit below which the pure scotopic luminance region starts. The upper limit is, however,

much lower than the defined threshold between the photopic and mesopic regions. The definition of CIE mentions that the upper limit of the mesopic luminance level is at least several cd/m², which is well above 0.6 cd/m². The region above 0.6 cd/m² is treated in the model of Rea et al. as "photopic"; that is, the V(λ) function describes the spectral luminous efficiency. Rea et al. gave a set of X-values (X is a weighting coefficient similar to x in Equation 1) as a function of the S/P-ratio and photopic luminance level to calculate the corresponding mesopic spectral luminous efficiency functions and eventually mesopic luminances. The advantage of this simplified model is that it does not any more require knowledge (or an estimate) of the size of the pupil. The spectral luminous efficiency functions V(λ) and V'(λ) are also preserved.

3 Measurement set-up and equipment

3.1 Introduction

The measurement system used in the present work consisted of a large hemispherical surface, which was painted white. Visual targets located on the surface of the hemisphere near the horizontal plane of the subject's vision. The subject positioned his head on chin and forehead rests, which positioned the eyes at the opening plane of the hemisphere (Figure 1b). The subject looked at the centre of the hemisphere and performed the desired visual task.

3.2 Hemispherical surface

3.2.1 Structure

The hemispherical surface was the other half of an integrating sphere. The diameter of the hemisphere was 1980 mm. The inner surface was painted with white paint Temadur 20 and tint MoniColor 201. Although the paint was only semi-matt, there were no noticeable specular reflections on the surface during the measurements.

The surface of the hemisphere was illuminated with eight 18 W Osram Lumilux® de luxe L-18W/12-950 fluorescent lamps (Figure 1a). The lamps were diagonally attached to the hemisphere in such a way that they were approximately 10 cm inside the hemisphere. Two lamps were attached next to each other, so that the lamps formed four pairs. The lamps were divided into two groups, which included four lamps each. Group 1 consisted of those four lamps that were closer to the hemisphere's edge, and group 2 consisted of those four lamps that were closer to the centre of the hemisphere.

Dimmable electronic ballasts Osram Quicktronic® de luxe Dimmbar HF 1×18/230-240 DIM were used with the lamps. A single ballast was used per lamp. The performance of the lamps and ballasts were measured before deciding which ballast was used with which lamp and in what position. The selection was made in order to achieve as even a

background luminance on the hemisphere's surface as possible. The lamps were dimmed with a DC power source that was connected to four lamps simultaneously.

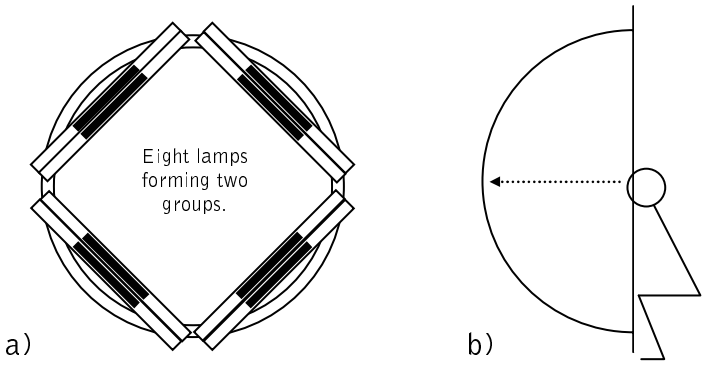


Figure 1 *Frontal and side view of the large hemispherical surface. a) Eight 18 W fluorescent lamps were attached diagonally to the hemisphere. The lamps were formed into two groups. b) The subject sat in front of the hemisphere viewing the foveal fixation point.*

When the fluorescent lamps were used this way, it was not possible to reach mesopic light levels. Therefore, several layers of filter film were attached on the surface of the lamp covering entirely its light-emitting surface. With this arrangement, the desired light levels were achieved, but due to the uneven transmittance of the filters, the achieved spectrum of the hemispherical background light was changed from the original. This altered the correlated colour temperature from the original 5400 K to 4920 K ± 100 K (Figure 2). The latter value depended on the dimming level as well.

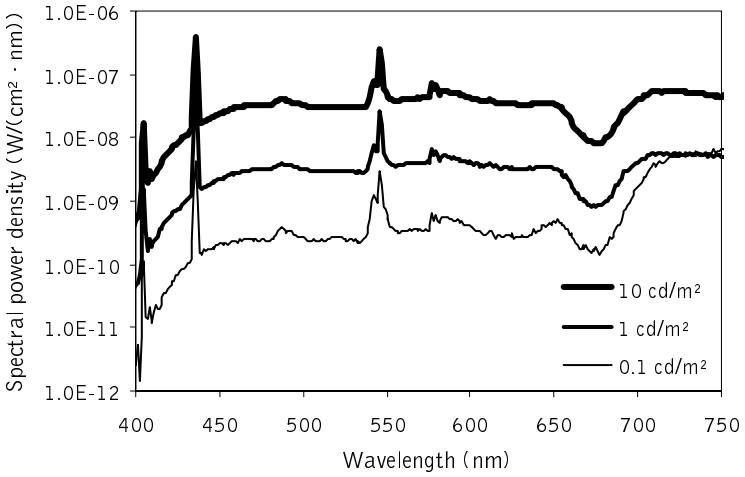


Figure 2 *Radiances of the background light at three luminance levels: 0.1 cd/m², 1 cd/m² and 10 cd/m². The correlated colour temperatures of the background lights were 4820 K, 5020 K and 4930 K, respectively.*

With the filtering, the maximum background luminance was approximately 20 cd/m² using lamp group 1 and 2 cd/m² using lamp group 2. The lamps of group 1 were used to achieve background luminances between 20 cd/m² and 1 cd/m², while the lamps of group 2 were used to achieve background luminances between 0.3 cd/m² and 0.01 cd/m². The 0.01 cd/m² luminance level required the use of light-absorbing surfaces inside the hemisphere.

In order to improve the uniformity of the background luminance, four white sheets were attached around the hemisphere's opening. The sheets were approximately 250 cm by 150 cm in size. The sheets were attached around the centre of the hemisphere's opening in such a way that two of the sheets were positioned horizontally and the other two vertically, so that an area of approximately 20 cm by 25 cm was left clear in the centre. This arrangement improved the uniformity of the background luminance. In order to prevent the subjects seeing the lamps or any other disturbing elements inside the hemisphere during the measurements, it was necessary to block a part of the far peripheral visual field with two white vertically-attached columns of paper (side-shields). In the horizontal direction, the side-shields blocked the background from approximately 65°.

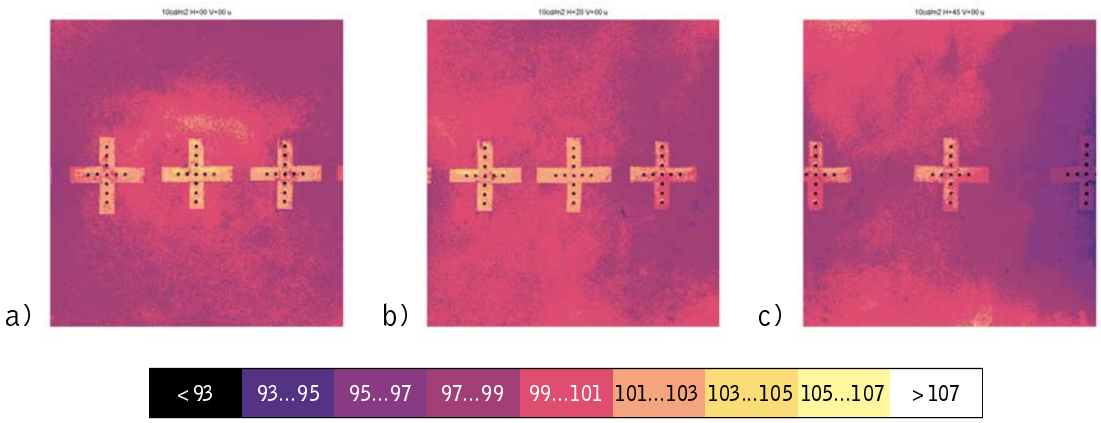


Figure 3 *Uniformity of the background luminance at 10 cd/m². The centremost cluster in the figures locates at a) 0°, b) 20° and c) 45° eccentricity. The bar below the figures shows the luminance ranges in percentages of the set value 10 cd/m².*

The uniformity of the background luminance was measured with a ProMetric™ Digital 1400 Light Measurement System by Radiant Imaging. Three luminance distributions, each of them subtending a visual angle of approximately 34° by 34°, are presented in Figure 3. The background luminance measurements were made without the side-shields. The luminance of the background was measured from -60° to +60° in the horizontal direction and from -36° to +36° in the vertical direction. The measurements revealed that the uniformity of the background luminance was between -7% and +3% of the luminance adjacent to the centremost target cluster, with two major exceptions. Higher values were attained close to the lamps that created the background illumination. This was not a problem because the visual field of the subjects did not reach those directions in the upper half of the hemisphere, while, in the lower half, the side-shields blocked the view.

The second exception was the locations near the target positions. At those points, the use of white self-adhesive film increased the luminance locally by approximately 2%.

3.2.2 Advantage of using a large hemispherical surface

The main reason for using a large hemispherical surface was that angular errors would be small when the targets in the peripheral vision were viewed binocularly. Figure 4 shows how the angle between the foveal fixation and target location changes, when the radius of the surface is 990 mm and the distance between the pupils is 70 mm.

The calculations for angular errors show that the deviation from the correct direction is at most 1° if the intended eccentricity is 60° or less. If the sphere were only 500 mm in diameter, the error would already exceed 1° at 39°. The error becomes smaller when the angular eccentricity is smaller

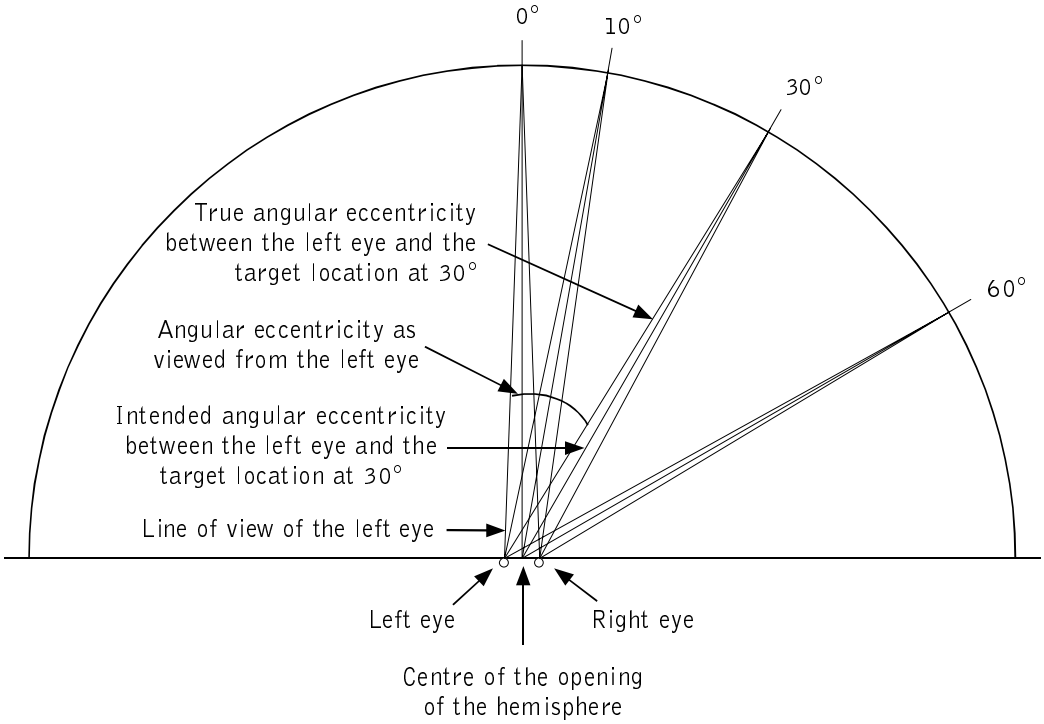


Figure 4 Angular deviation of the peripheral target is approximately 0.3° of the intended direction at 30° peripheral eccentricity for both eyes.

3.3 LED supports

LEDs were used to illuminate the targets. The LEDs were positioned outside the hemisphere using plastic tubes as supports. The inner diameter of the plastic tubes was 5 mm and the outer diameter 7 mm. The LEDs, of which the outer diameter was 5 mm, were attached firmly inside the tube. 7-mm holes were drilled through the hemisphere where the plastic tubes were attached (Figure 5).

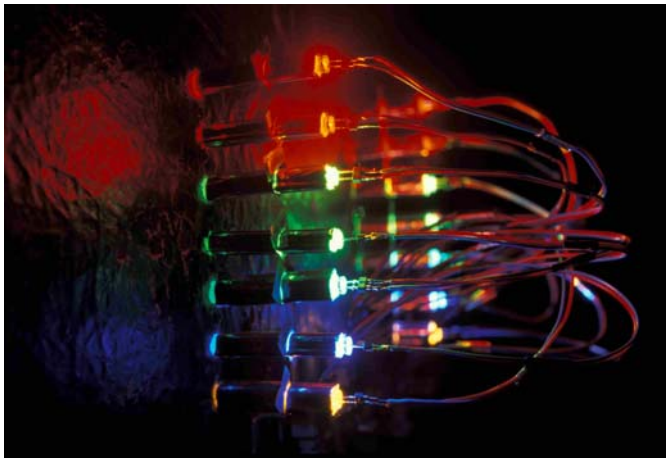


Figure 5 *LEDs were used to illuminate the targets. The LEDs were attached to plastic tubes, which were in turn attached to the holes drilled through the hemisphere.*

The diameter of the circular targets was 5 mm, which is the same as the diameter of the LEDs. As the drilled hole was 7 mm in diameter, the outer part had to be covered. The surrounding area of the holes was first covered with an aluminium adhesive tape. The purpose of the aluminium adhesive tape was to eliminate all stray light coming from the LED. 5-mm holes were made through the aluminium adhesive tape, allowing the light to come out only at desired locations. The aluminium adhesive tape was covered with a white opaque self-adhesive film. 5-mm holes were also made through this film. The reflectance of the film was slightly higher than the reflectance of the background of the hemisphere's surface. The measured luminance difference between the background and self-adhesive film was from 1.6% to 2.7%, depending on the location.

The 5-mm holes were covered with white diffusers located immediately behind the aluminium adhesive tape. The difference in the luminance between the background and the diffuser was between 10.5% and 13.3%, depending on the location. This difference was taken into account when measuring the target luminances.

The luminance produced by the LEDs on the diffuser was high, considering the need of the measurements. Although it was possible to dim the LEDs, the dimming was not continuous (see Section 3.5) and therefore it was not possible to achieve the desired luminance levels by controlling of the LED current alone. The same type of filters that were used to dim down the light produced by fluorescent lamps was used to dim down the LED light as well. A narrow gap was made in the supports in order to allow the positioning of filters and diffusers in front of the LED.

3.4 Target positions

The holes that were drilled through the hemispherical surface formed eleven clusters consisting of eleven holes each. The clusters formed a cross shape that had seven holes vertically aligned and five holes horizontally aligned. The original purpose of the holes

was to create the ability of presenting disturbing light elements around the target. This feature was not used in the measurements presented in this work. The distance between two adjacent holes was 1° as viewed from the subject's location. The shape of the clusters is presented in Figure 6.

The clusters were positioned on the hemispherical surface in such a way that the centremost holes located in a horizontal plane. The centremost cluster located directly in front of the subject. The other clusters located symmetrically on the right and left side of the centremost cluster in the following angular eccentricities: 10°, 20°, 30°, 45° and 60°.

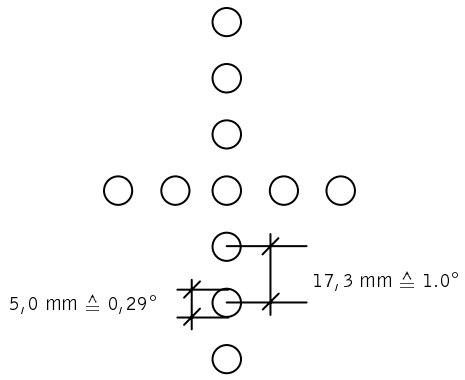


Figure 6 *A single cluster of targets. Each LED colour was presented through its own hole. The foveal and peripheral targets located on the same horizontal level. The subject fixated both eyes on the foveal target location during the measurements.*

3.5 LEDs and LED controller

The light output of the LEDs was controlled with LED controllers, which consisted of fourteen electronic controlling units. These units were attached to a laptop computer, which had a controller program. The LED controllers and the controller program was designed and manufactured by Obelux Oy, Helsinki, Finland.

The program allowed individual control of each LED. It was possible to adjust a continuous current for each LED by using a slider, which had 256 possible light levels (including zero). It was also possible to make a program for each LED that regulated the light output.

Each LED controller was designed and programmed for four LEDs. During the measurements, when a fifth colour was needed, two controllers were used to share the colours. Red, green and blue LEDs were used through one controller, and cyan and amber LEDs through the other.

The forward current produced by the LED controller was not entirely direct current. The forward current had also a 1-kHz AC-component on top of it. The amplitude of the AC-

component was approximately 6% of the intensity, except at near-peak intensity, at which it reduced and finally disappeared at maximum intensity. Rovamo and Raninen (1984, 1988) and Raninen and Rovamo (1986) showed in their experiments that critical flicker frequency is below 90 Hz at any target eccentricity. Therefore, the high frequency of the AC-component and its relatively low amplitude was estimated to have no effect on the luminous intensity. This feature, however, did make a part of the measurements more difficult. The intensity of the flash was defined as the mean intensity over a long period of time.

3.6 Filters and diffusers

Filters and diffusers were used to reduce the light level of the lamps producing the background luminance of the hemispherical surface and the LEDs producing the target luminances. The filters used had four different transmissions, approximately 75%, 50%, 25% and 12.5%. The spectral transmissions can be seen in Figure 7. From the figure, it can be seen that the transmission increases rapidly after 680 nm. The transmission of the filters was not linear throughout the visible spectrum. Therefore, the final relative spectral power distribution of the targets was calculated by multiplying the spectral power distribution of the LED with the transmissions of the applied filters and diffusers.

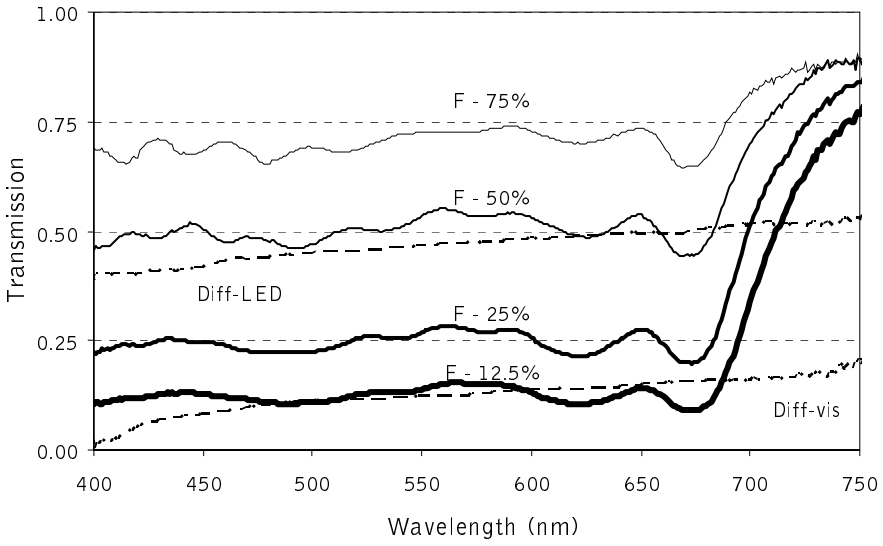


Figure 7 *Transmissions of the filters (F) and diffusers (Diff) used in the measurements. Filters were used to reduce the light output of the fluorescent lamps and LEDs. Diffusers were used to reduce the light output of the LED and to spread the light on the visible diffuser. Diff-vis is the visible diffuser and Diff-LED is the diffuser used to spread the light of the LED.*

White diffusers were used to cover the holes of the targets at the surface of the hemisphere. The diffusers were visible to the subjects during the tests. This diffuser alone was not sufficient to produce even target luminance. Therefore, another diffuser was

positioned in front of the LEDs in the same slit where the filters located. This diffuser made the luminance of the target more uniform. The uniformity of the target luminance was measured with the ProMetric™ 1400 Light Measurement System. The luminance had a peak value in the centre of the target. According to luminance distribution, it was estimated that the peak luminance was approximately 5% to 9% higher than the average luminance of the whole surface. The area of the peak luminance was less than 1.5% of the whole target area.

3.7 Characteristics of the LEDs

Five different coloured LEDs were used in the tests: red, amber, green, cyan and blue. The relative spectral power distributions of the colours are presented in Figure 8. The LEDs were manufactured by Agilent Technologies and their characteristics are presented in Table 1. The values measured by the author are presented in Table 2. Each coloured LED had different characteristics relating to the dimming of the LED and maintenance of the luminous output during a flash or in a continuous mode. Individual correction factors were needed to convert the set value of the program to the luminous output of the LED.

Table 1 Characteristics of the LEDs as presented by the manufacturer Agilent Technologies measured with 20 mA forward current.

Colour	Code	Viewing angle	Dominant wavelength	Peak wavelength	Luminous intensity	Spectral half-band width	Maximum forward current
	HLMP-	(°)	(nm)	(nm)	(mcd)	(nm)	(mA)
Blue	CB30-M0000	30	472	470	450	35	30
Cyan	CE31-QTQ00	30	505	502	1000	35	30
Green	CM30-S0000	30	526	524	1650	47	30
Amber	EL31-STK00	30	592	594	1650	17	30
Red	ED31-ST000	30	630	639	1650	17	30

Table 2 Characteristics of the coloured LEDs measured with 20.4 mA forward current.

Colour	Dominant wavelength (nm)	Peak wavelength (nm)	Spectral half-band width (nm)
Blue	469	466	27
Cyan	505	503	32
Green	529	522	37
Amber	591	594	16
Red	626	638	18

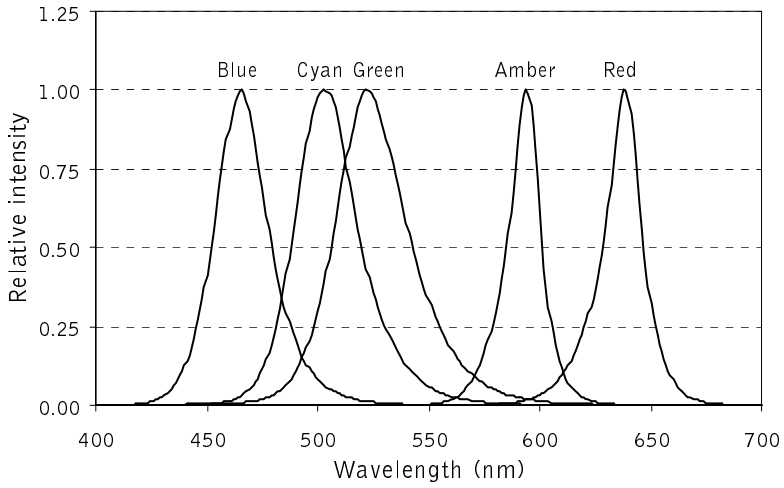


Figure 8 Relative spectral power distributions of the five coloured LEDs.

3.7.1 Luminous intensity versus forward current

The relationship between the forward current and luminous output of an LED in continuous mode was generally not linear. The only exception was the red LED, of which the linearity was very good, except at low currents. The relationship between the target luminance (no filtering applied) and forward current is presented in Figure 9 for all coloured LEDs. Especially green and blue LEDs suffered from the non-linear relationship. The relationship between the digital value and forward current was linear, but the maximum current varied slightly for each target. As the measurements were conducted with digital values in later phases, the digital values are presented here as well.

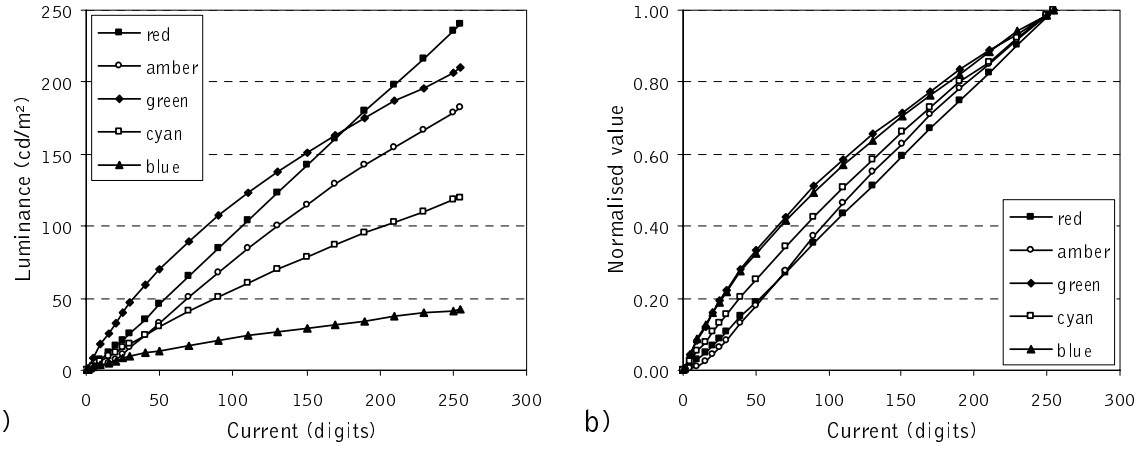


Figure 9 a) Luminance produced by a continuous light as a function of forward current. b) Normalised values. Forward current is presented as digital value, where 255 equals to approximately 28 mA.

3.7.2 Luminous intensity versus duration of the flash

In the reaction time and contrast threshold tests, the targets were presented as short flashes with a duration of either 500 ms or 3000 ms. The duration of the flash affected the

luminous intensity of the LEDs (Figure 10). This was especially true for the amber LEDs, which lost up to 28% of initial intensity, if they were illuminated continuously at maximum current. On the other hand, blue LEDs increased their luminous intensity by 4.6%. The luminous intensity ratio between the short flash and the continuous light is presented in Figure 10. The luminous intensity ratio was greater, with shorter 500 ms flashes, as the shorter flash did not heat the LED as much as the long 3000 ms flash.

The luminous intensity measurements were taken at five different current settings for each coloured LED. The luminous intensity of the flash was divided by the luminous intensity of the continuous light. The relationship could be modelled with a linear equation with high accuracy. The equations were modelled with an NCSS 2001 statistical analysis program, which gave the R^2-value (coefficient of determination) for each equation. The value was at least 0.9976 for all equations for 500 ms flashes and 0.9973 for 3000 ms flashes. It was necessary to model this relationship, because it was not possible to measure the target luminance of a short pulse. Therefore, the luminance of the continuous light was measured instead.

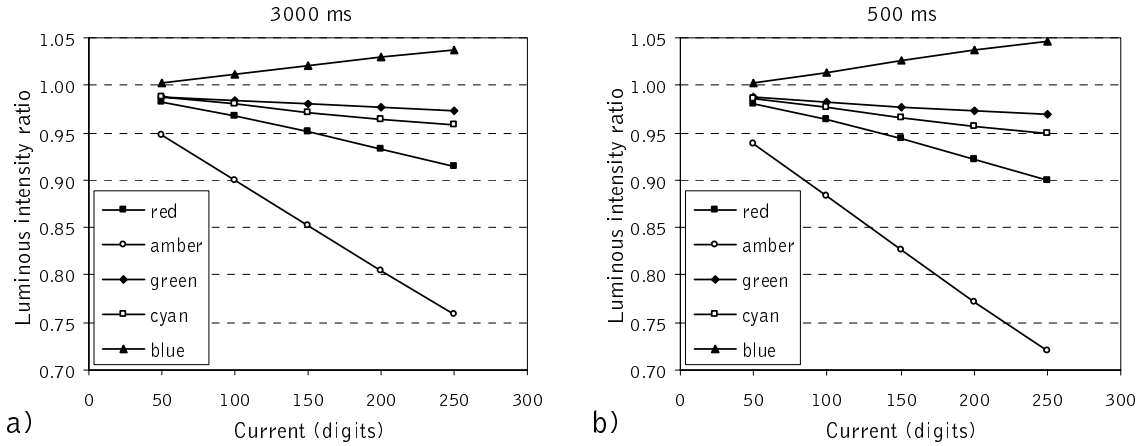


Figure 10 The luminous intensity ratio of a a) 3000 ms and b) 500 ms flash versus continuous light as a function of forward current. The forward current is presented as a digital value, where 255 equals approximately 28 mA.

3.7.3 Spectrum versus forward current

The spectrum of the LED depended on the forward current. The forward current affected especially the spectrum of the green LEDs, of which the peak wavelength shifted approximately 10 nm when the forward current was altered from a low value to the maximum value. With the other LEDs, the shift was much less severe – less than 2 nm. In order to reduce this problem, the forward currents through the green LEDs were limited below 50% of the maximum current in the reaction time and contrast threshold tests.

The changes in the colour coordinates according to the forward current are presented in Figure 11. It should be noted that the curves for red and amber locate very close to the spectral locus; the changes have therefore also been presented in Figure 12, where the

close-by areas have been zoomed closer. The current setting was adjusted between 5 to 255 digits at an interval of 10 digits. Digit value 255 corresponds to approximately 28 mA.

Figure 12 shows that the variation in x-y-coordinates of the red LED is very small. The difference is noticeable for the amber LEDs, and very apparent for blue, cyan and green LEDs. For the green LED especially, the variation is large, which is consistent with the fact that the peak wavelength varied the most with the green LED.

The CIE 1931 standard colorimetric system is not equidistant in colour differences, but shows the problem associated with the colour variation of the LEDs according to the forward current. With the LEDs that were used, only the red was immune to any significant colour variations.

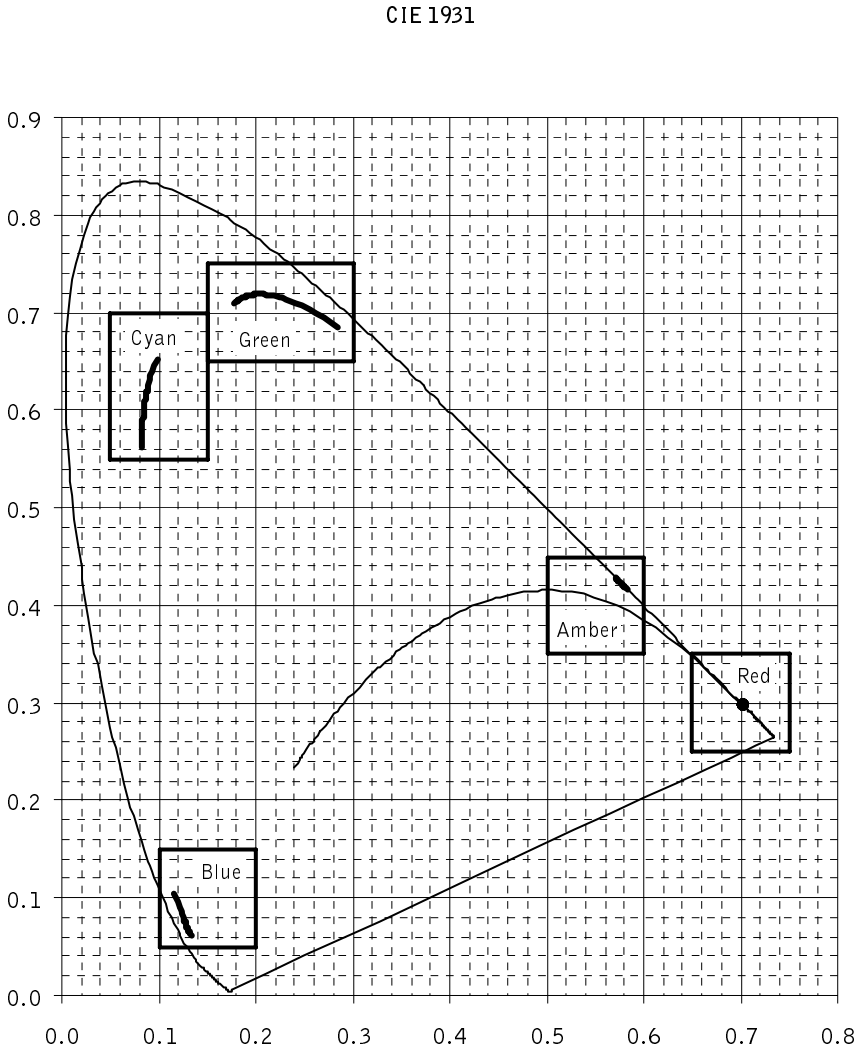


Figure 11 Variation of the x-y-coordinates of five coloured LEDs as presented in the CIE 1931 Standard colorimetric system. Detailed figures of the marked areas can be found in Figure 12.

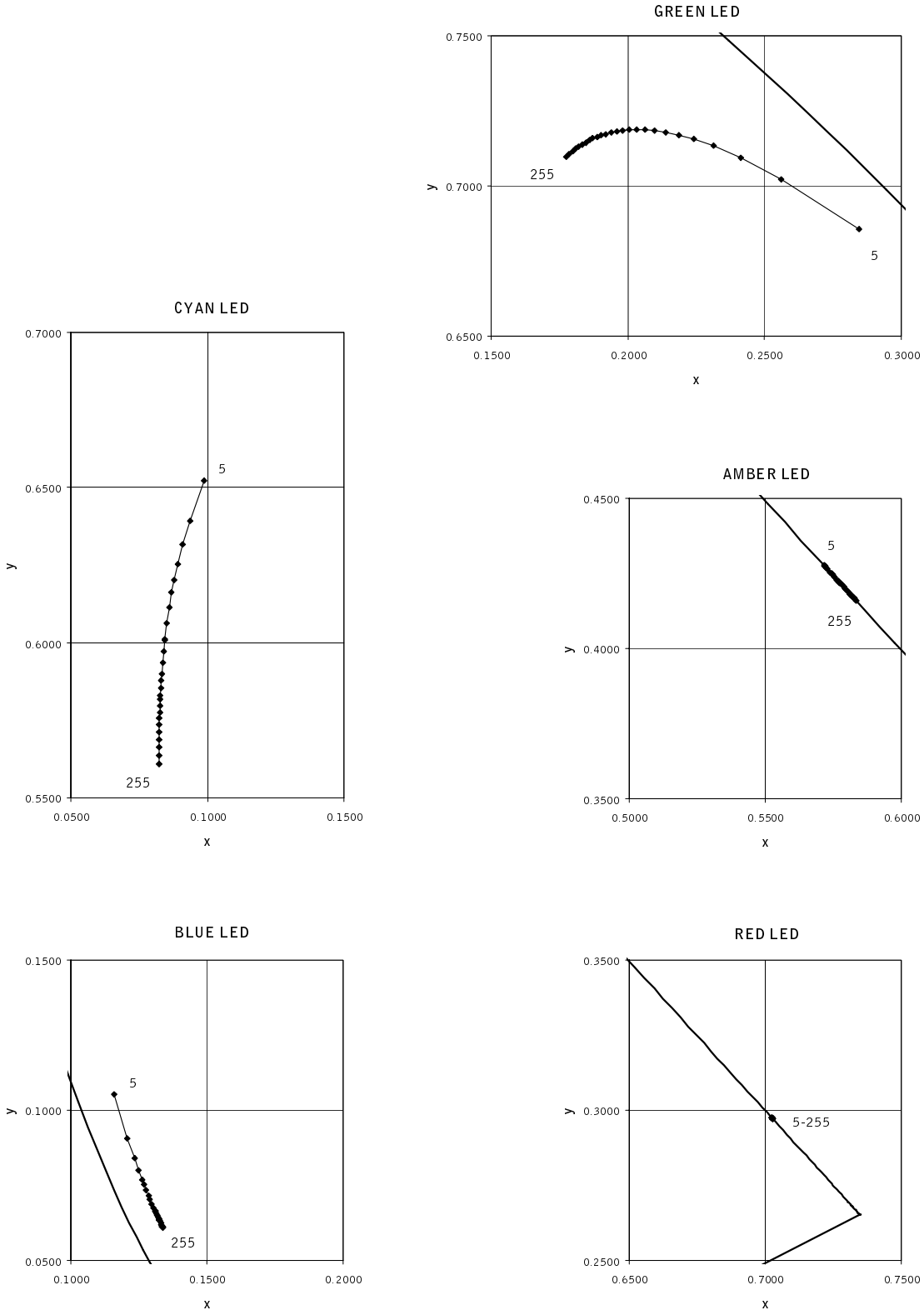


Figure 12 Closer view of the variation of the colour coordinates of the five coloured LEDs (from Figure 11). Numbers 5 and 255 in the figures correspond to the forward current in digital values. 255 is the maximum forward current (approximately 28 mA) and 5 is the lowest measured current (estimated 0.55 mA).

3.7.4 Spectrum of a short flash

When the LED is turned on for a sustained period of time, it heats up and its spectral characteristics change. The luminous intensity measurements revealed that the luminous intensity decreases when the LED heats up (except for the used blue LEDs, for which the luminous intensity increased). The spectral power distributions were measured for all five coloured LEDs with an Ocean Optics HR4000 High-resolution Spectrometer utilising a Toshiba TCD1304AP CCD-unit. The measurements were first conducted for a constant light. The intensity of an LED was set above the maximum current used for that particular colour. After the measurement of the constant light, the LED was turned off and it was let cool down. After this, the measurement was made for a short 500 ms flash. The integration time of the measurements was 5 ms and the measurement interval was approximately 100 ms. The measurement range was from 200 nm to 1100 nm, of which wavelengths from 380 nm to 800 nm were used in the calculations and analysis.

The measurements showed that the intensity difference between the continuous light and the flash was in accordance with previous measurements presented Section 3.7.2. Another difference was also noticed. The spectral power distribution of the flash was slightly narrower in the low-intensity regions. This phenomenon was, however, very weak and concentrated only at low intensities, and was therefore ignored in the calculations. From the measured spectral power distributions, it was calculated that the unchanged part contained at least 98% of the radiation. Therefore, it was decided that the spectral power distribution measured for the constant light could be used without any fear of significant errors.

3.7.5 Rise and fall times and the duration of a single LED flash

The flashes that were presented to the subjects were rectangular in shape and they were produced with LEDs. Sivak and Flannagan (1993) and Sivak et al. (1994) investigated how the rise time of a brake lamp of a car affects the reaction time. They discovered that LED brake lamps yielded shorter reaction times than standard incandescent lamps. Part of the reduction was due to faster ignition time of the LEDs, but the rise time of the signal also had a significant effect on the reaction time. Rise times of LEDs are generally very short, in the order of microseconds or even less. Therefore, the electrical circuit that the LED is connected to is the dominating part when determining the rise and fall times of the whole system. Rise times were measured for all coloured LEDs at a rate of 100 000 samples per second when the current was increased from 0 mA to approximately 28 mA, which was the maximum current produced by the LED controller. Also, half-maximum intensities were measured for comparison.

The rise and fall times were measured ten times for a green LED. The rise time of a flash was defined as the time difference required for the signal to reach 10% and 90% thresholds of the maximum intensity. The fall time is respectively the time difference required for reducing the intensity from 90% to 10% of the maximum intensity. The mean rise and fall times were 4.40 ms and 6.22 ms, respectively. Variation in results was

within ±0.02 ms in both cases. The mean duration of the flashes was 252.89 ms, as measured from 10% thresholds of the rise and fall times. The range of flash durations was between 249.92 ms and 258.11 ms. The full 500 ms flash could not be measured as the system flash meter could only measure data for 320 ms. It was concluded that the rise and fall times of a single colour were constant during the measurements. The duration of the flash varied by 8.2 ms. The variation in the flash durations was caused by the LED controller; it was estimated that its influence was insignificant in the reaction time measurements as the majority of reactions occurred before the end of the flash.

The rise and fall times were measured for all coloured LEDs. Measurements were conducted for full (255 digits) and half (125 digits) maximum flash intensity. The rise and fall times of the coloured LEDs are presented in Table 3. The rise time is a more important characteristic, as the reaction to a flash occurred usually before the flash was turned off. The differences in the rise times of the coloured LEDs was less than 1 ms; it was therefore estimated to have no practical influence on the reaction times.

Table 3 Rise and fall times of the coloured LEDs.

	LED				
	Blue	Cyan	Green	Amber	Red
Full intensity					
Rise time (ms)	4.68	4.68	4.40	4.49	4.89
Fall time (ms)	6.24	5.35	6.24	4.91	4.68
Half intensity					
Rise time (ms)	4.26	4.29	4.24	5.02	5.07
Fall time (ms)	5.58	4.96	5.62	4.42	4.38

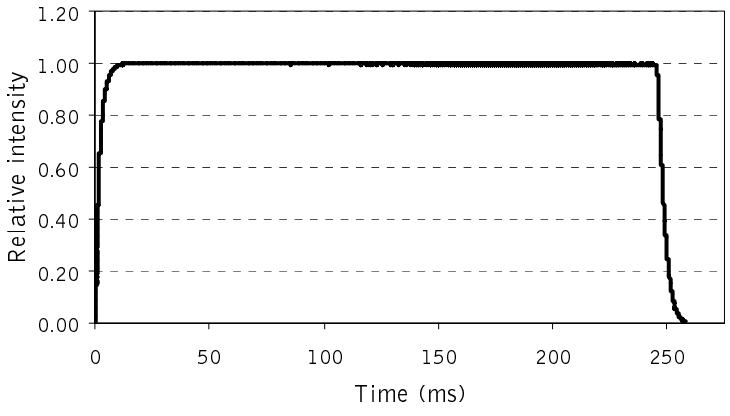


Figure 13 A flash produced by a green LED at maximum forward current. Intended flash duration was 250 ms. The sample rate is 100 000 samples per second.

3.8 System flash meter

System flash meter SF 105, Version B, manufactured by LMT Lichtmesstechnik, Berlin, Germany was used to measure the intensities of the short flashes and continuous lights. These measurements were all made using relative values only. Luminance meter LMT L 1009 was used to measure the absolute luminances. The system flash meter was also used in the reaction time measurements. The system flash meter was the only measurement device that could measure short flashes reliably.

3.8.1 Measurements of single flashes

When the intensity of an LED was measured with the flash meter, the LED was positioned close to the detector. This was done in order to maximize the intensity received by the detector. When the LED was measured in a continuous mode, the forward current of the LED was set to the desired level.

The intensity of a short flash was measured for an LED that was in the ambient temperature. The LED was turned on for 500 ms or 3000 ms and the intensity of the flash was measured. The measurement data was transferred to the Microsoft® Excel program. The intensity of the flash was defined as the average intensity between 10 ms and 490 ms or 2950 ms. The first 10 ms were ignored in order to allow the intensity to reach its maximum value.

The intensity of the flash was compared with the intensity of the continuous light. Since it was not possible to measure the luminance of the flash, the luminance of the continuous light was measured instead. The relationship between the intensities of the flash and the continuous light was used to calculate the luminance produced by the flash.

3.8.2 Recording of reaction times

The recording of the reaction times was done with the system flash meter. The subject had a response button in her or his hand during the measurements. The response button worked as a switch, which closed an electrical circuit. Two red LEDs were connected in series with the response button, a 9-V battery, and a resistor. The resistor was used to limit the current going through the LEDs. The two LEDs pointed towards the flash meter's detector, which recorded the light output of the LEDs.

During the reaction time tests, when a target was illuminated for the subject, another indicator LED that pointed towards the detector of the flash meter was illuminated simultaneously. The subject did not see this indicator LED, the light output of which was recorded by the flash meter.

The system flash meter produced a file where the light output of the LEDs was recorded. From the file, it was possible to see when the indicator LED was turned on and when the response button was pressed. The recorded file rejected all data that was below a certain value, so only the data when either or both of the LEDs were turned on existed in the

final file. The reaction time was defined as the time difference between turn-on times of the two LEDs. The data was recorded at 1-ms intervals.

4 Measurement methods

4.1 Reaction time as criterion

Reaction time was used as a criterion to describe the spectral sensitivity of the eye at different light levels and eccentricities. The use of equal reaction time was based on the assumption that, if a spectral luminous efficiency function describes the spectral sensitivity correctly, equal contrasts calculated using this function yields the same reaction time for all colours. In these measurements, the visual stimuli were presented as rectangular-shaped flashes. The duration of the flash was 500 ms and the flashes were presented in sequences containing 26 flashes. The two first flashes of each sequence were used to arouse the attention of the subject and their reaction times were not recorded. The allowed maximum time for reaction was 1000 ms. The interval between two stimuli was randomised between 2.25 s and 4 s. In these measurements, the contrasts were fixed for each target colour, eccentricity and luminance level individually as they were different from each other. The aim was to find a common reaction time for all colours and eccentricities, and to derive the contrast that was required to achieve that reaction time. The derived contrasts were converted into target luminances by interpolating them from measured target luminances and contrasts. The target luminances were converted into radiances in order to make it possible to test spectral luminous efficiency functions other than $V(\lambda)$.

In the reaction time tests, the presentation of the target was randomised between the foveal and peripheral locations (10° eccentricity). A single target colour was used each time because it was possible to fixate to only one foveal target colour. Several target contrasts were presented during a single session of measurements in random order. The measurements were conducted with three or four target contrasts for each target colour. All five target colours (blue, cyan, green, amber and red) were presented to the subject during one session, which contained fifteen sequences. The order of colours was randomised between the subjects. These measurements were conducted with near threshold contrasts. In addition, measurements were conducted with high-contrast targets in order to yield the asymptotic minimum reaction time required in Equation 2. Each subject participated in two measurement sessions that were held on different days. The total number of repetitions per subject and condition (target colour, contrast, luminance level, eccentricity) was 24. The measurement parameters have been listed in Table 4.

Table 4 Parameters used in the reaction time measurements.

Parameter	Values
Background luminance	0.1, 0.3, 1, 3, 10, 20 cd/m²
Target colour	Blue, cyan, green, amber, red
Target eccentricity	0°, 10°
Flash duration	500 ms (3000 ms in high-contrast measurements)
Contrast	3 or 4 in each measurement condition

The task of the subject was to press a handheld response button as quickly as possible when detecting the target. The aim of the measurements was to find the equation representing the reaction time as a function of target contrast. The equation presented by Piéron (1952) was applied and modified for this purpose. The modified Equation 2 is similar, except that the intensity of the target has been replaced with the target contrast. Contrast was used instead of intensity as it avoids the need to know the maximum luminous efficacy of radiation, K_m. This feature is especially practical when making calculations based on spectral luminous efficiency functions other than $V(\lambda)$ or $V'(\lambda)$, for which the maximum luminous efficacies have been defined.

$$RT = RT_{min} + a \cdot C^b \qquad (2)$$

where RT is the reaction time, RT_{min} the asymptotic minimum reaction time, C the contrast; a and b are coefficients.

Contrast C was calculated with Equation 3.

$$C = \frac{L_t - L_b}{L_b} \qquad (3)$$

where L_t is the luminance of the target and L_b the luminance of the background.

The equations for each target colour were optimised with the NCSS 2001 statistical analysis program. The full set of reaction time data was used in the optimisation. The asymptotic minimum reaction time was gained from the high-contrast ($C > 2$) measurements. Occasionally, the target contrasts were negative and it was not possible to optimise coefficient b, as it had to be negative as well. In these cases, contrast C was replaced with 1+C, which ensured that negative exponent could be used. The target contrasts for each target colour were optimised with the "Goal seek" routine included in the Microsoft® Excel program. The optimisation was performed for a common reaction time. The yielded target contrasts were converted into target luminances with Equation 3. The target luminances were converted into radiances using Equation 4 (see Section 5.4.1). The radiances were used to test various spectral luminous efficiency functions.

4.2 Contrast threshold as criterion

Contrast threshold describes the smallest relative luminance difference between the target and its background above which a target is visible. It was presupposed that if a correct spectral luminous efficiency function was applied, the contrast thresholds within a certain luminance level for each target colour would be the same. The parameters of the contrast threshold measurements have been listed in Table 5.

Table 5 Parameters used in the contrast threshold measurements.

Parameter	Values
Background luminance	0.1, 1, 10 cd/m²
Target colour	Blue, green, red
Target eccentricity	0°, 10°, 30°, 60°
Flash duration	500 ms
Contrast	Several

The method of limits (Forrester et al., 1996) was used in the contrast threshold measurements (Orreveteläinen et al., 2004). The flashes were presented to the subject in descending and ascending order of intensity. The task of the subject was to count the visible flashes when the flashes were presented in descending order of intensity. When the flashes were presented in ascending order of intensity, the task of the subject was to press a response button when the first visible flash was detected. The threshold contrast was defined as the mean value between the last seen and first unseen flash when the order of presentation was in descending order. Both directions were presented twice in succession, yielding four threshold values at each measurement condition.

A total of 47 flash intensities were divided into five groups, which partially overlapped each other. Each group contained between 13 and 15 consecutive intensities. Originally, the aim was that the ratio between two consecutive flashes would be 0.93, but the non-linear relationship between the forward current of the LED and the luminous intensity produced by the LED made this difficult. As the forward current of the LEDs had to be adjusted in discrete steps, it prevented the use of precise ratios between consecutive flashes. The relative intensities of the flashes are presented in Figure 14. The absolute intensities were calculated as the ratio between the constant light and the flash. The ratio was measured with an LMT SF 105 system flash meter. The luminances of the constant light were measured with an LMT L 1009 luminance meter. The most optimal target luminance range was presented to the subject in the measurements. The aim was that approximately half of the flashes would be visible to the subject. All measurements included in one background luminance level were measured during a single session, which lasted between 50 and 75 minutes, depending on the experience of the subject and time spent finding the most optimal range of luminances.

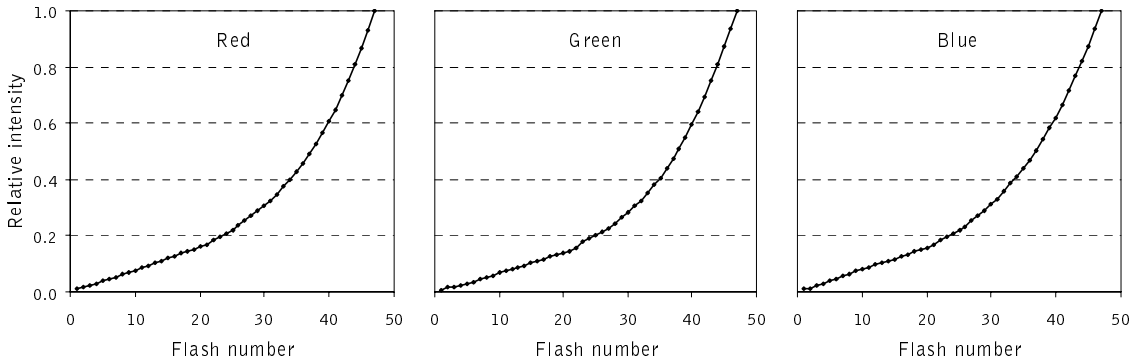


Figure 14 Relative intensities of the flashes produced by three coloured LEDs in the contrast threshold measurements.

4.3 Subjects

Twelve voluntary subjects, including the author, participated in the measurements. The subjects were either students or workers at HUT. The vision of all subjects, except one (subject JJ), was checked by an ophthalmologist. Visual acuity was examined at a distance of 5 m (Snellen charts). 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). The subject who was not checked by the ophthalmologist had her vision checked by an optician one year prior the measurement. None of the subjects used glasses or contact lenses in their daily life or during the tests.

The subjects represented four nationalities. Eight subjects were Finnish, two were Romanian, one was Nepalese and one Indian. The detailed information of the subjects is collected in Table 6.

Table 6 Subjects participating in the measurements. The numbers in the table refer to the age of the subject in full years during the test. RT refers to reaction time measurements conducted at presented luminance levels.

Subject	01	02	03	04	05	06	07	08	09	10	12	13
Initials	PO	JK	PB	VG	BC	ML	TN	MP	MS	VY	MN	JJ
Sex	M	M	M	M	M	F	M	M	M	M	M	F
Nationality	FIN	FIN	NEP	ROM	IND	FIN	FIN	FIN	ROM	FIN	FIN	FIN
Employee at Lighting Lab.	Y	Y	Y	Y		Y						
Participation:												
Contrast threshold		29	26	31	23	23	25	23				24
RT – high contrast					23	23	25	23	28	22	22	
RT – 0.1, 1, 10 cd/m²	34	30	27	31		24						
RT – 0.3 cd/m²			28	32								
RT – 20 cd/m²	35	31	28	32		24						
RT – 3 cd/m²	35	31	28	32		24						

5 Results

5.1 Introduction

In this work, the photopically, scotopically and mesopically weighted lighting units (luminance, contrast, etc.) are referred to as photopic, scotopic and mesopic units. Thus, photopic luminance refers to a luminance weighted with the V(λ) function. This definition has been applied especially in the figures for brevity.

The results of the reaction time and contrast threshold measurements are presented in Appendices 1-7. The results have been presented as average (mean) results of each subject and as the average results of all subjects. Standard deviations have been calculated for the individual and combined results separately.

Where statistical analysis is applied, the analysis of variance (ANOVA) of the NCSS 2001 statistical analysis program by NCSS (Number Cruncher Statistical Systems) was used. If a statistically significant difference at significance level $p < 0.05$ was found, ANOVA was followed by the Tukey-Kramer multiple comparison test recommended by NCSS (2001).

5.2 High-contrast targets

Equation 2 requires a knowledge of the minimum reaction time that can be achieved in a certain condition. A preliminary test was conducted at three low luminance levels in order to see how the reaction time of coloured targets is affected by the luminance level (Eloholma, Ketomäki, Orreveteläinen and Halonen, 2005a). The luminance levels under investigation were 0.01 cd/m², 0.1 cd/m² and 1 cd/m². The photopic contrasts of the targets were C = 3. The test was conducted for foveal and peripheral (10° eccentricity) visions at the same time. The measurement results are presented in Figure 15. The subjects reported that, at 0.01 cd/m², it was impossible to be sure of fixation of the eyes on the foveal target. This could explain the differences in reaction times between the colours of the foveal targets, which would otherwise indicate that the V(λ) function does not apply in the foveal vision at 0.01 cd/m² and is affected by the Purkinje shift.

The results of the peripheral vision indicate that, at 1 cd/m², there are no statistically significant differences in reaction times among the target colours ($p = 0.21$). At 0.1 cd/m², blue targets had statistically significantly ($p = 0.0047$) shorter reaction times than the other colours, except cyan targets, for which a statistical difference was not found. At this luminance level, the difference among the reaction times between colours were, however, small. At 0.01 cd/m², the differences among target colours were clear ($p < 0.001$). Pollack (1968) recorded in her reaction time measurements that differences in reaction times between different target colours emerged when the luminance level decreased enough. It was concluded in this work that when asymptotic minimum reaction times was measured, the contrast has to exceed C = 3 at 0.1 cd/m². The results indicate that lower contrasts could be used at higher luminance levels. It was also concluded that when the contrast is

high enough, there is no difference between colours and only one colour needs to be measured. In the actual reaction time measurements, the green target was selected as the high-contrast target. The applied contrasts and yielded reaction times are shown in Appendix 4.

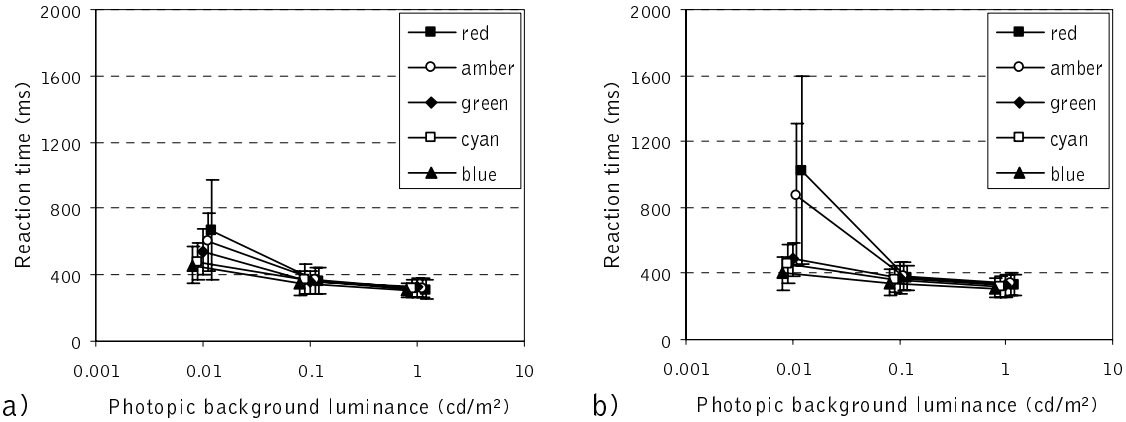


Figure 15 Reaction time results of the high-contrast (C = 3) targets in a) foveal and b) peripheral (10° eccentricity) vision. The data points are slightly shifted in order to make the standard deviations more clear.

5.3 Foveal vision

Reaction time and contrast threshold measurements were conducted for foveal vision in order to see whether the V(λ) function is valid for describing foveal spectral sensitivity for the reaction time and contrast threshold tasks. The results of both measurement methods show that V(λ) describes the spectral sensitivity of the eye in the foveal vision with good accuracy at luminance levels 0.1 cd/m², 1 cd/m² and 10 cd/m². Figure 16 shows that the contrasts of the different target colours are similar at every luminance level indicating that V(λ) is an appropriate spectral luminous efficiency function for foveal vision. The slightly higher contrasts of the blue targets may indicate partial tritanopia associated with targets of small size that consists of short wavelengths as recorded by Abramov and Gordon (1977). Foveal targets were not analysed in the other measured luminance levels, where they were only partially measured in order to maintain the structure of the measurement conditions.

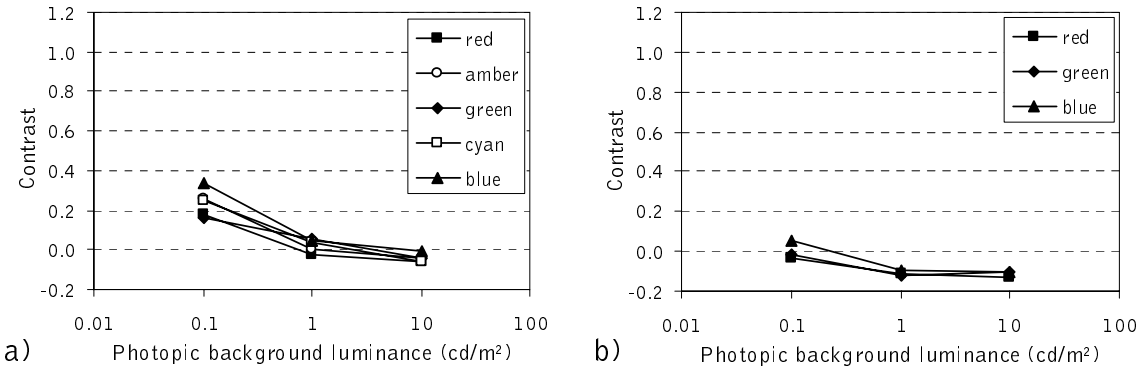


Figure 16 Contrasts yielded for foveal targets in a) reaction time and b) contrasts threshold measurements.

5.4 Peripheral measurements at photopic luminance levels

5.4.1 Measurement results

It was presupposed that, if a spectral luminous efficiency function described the spectral sensitivity for the visual tasks correctly, then, within the same luminance level, reaction times for targets with the same contrast would be the same and the contrast threshold would be the same for targets of a different colour. The contrasts for common reaction times were derived using Equation 2. The measurement results of the reaction time measurements made at 10 cd/m² background luminance are presented in Figure 17. Numerical values are presented in Appendix 2. (Orreveteläinen et al., 2005)

From Figure 17, it can be seen that the reaction times have increased from the asymptotic minimum reaction time (not visible in the figures). The individual variation of results is larger at lower target contrasts, especially for red and amber targets. The percentile bars show that the data is skewed, which is a typical feature for reaction time measurements. From Figure 17f, it can clearly be seen that the blue and cyan targets were perceived better than the other colours, for which the differences are small. This indicates that the spectral luminous efficiency function used, $V(\lambda)$, underestimates the spectral sensitivity of short wavelengths.

Figure 18 shows the reaction time measurements made at 20 cd/m² background luminance. Numerical values are presented in Appendix 3. Figure 18 shows aspects similar to those of Figure 17, with one exception. The difference between the cyan and green targets is small. Red and amber targets still require the highest contrasts in order to yield the same reaction times, and blue targets require the lowest contrasts. Conclusions similar to those drawn from the 10 cd/m² data – $V(\lambda)$ underestimates the short wavelengths and is not a proper measure for describing the spectral sensitivity of targets locating in the peripheral vision.

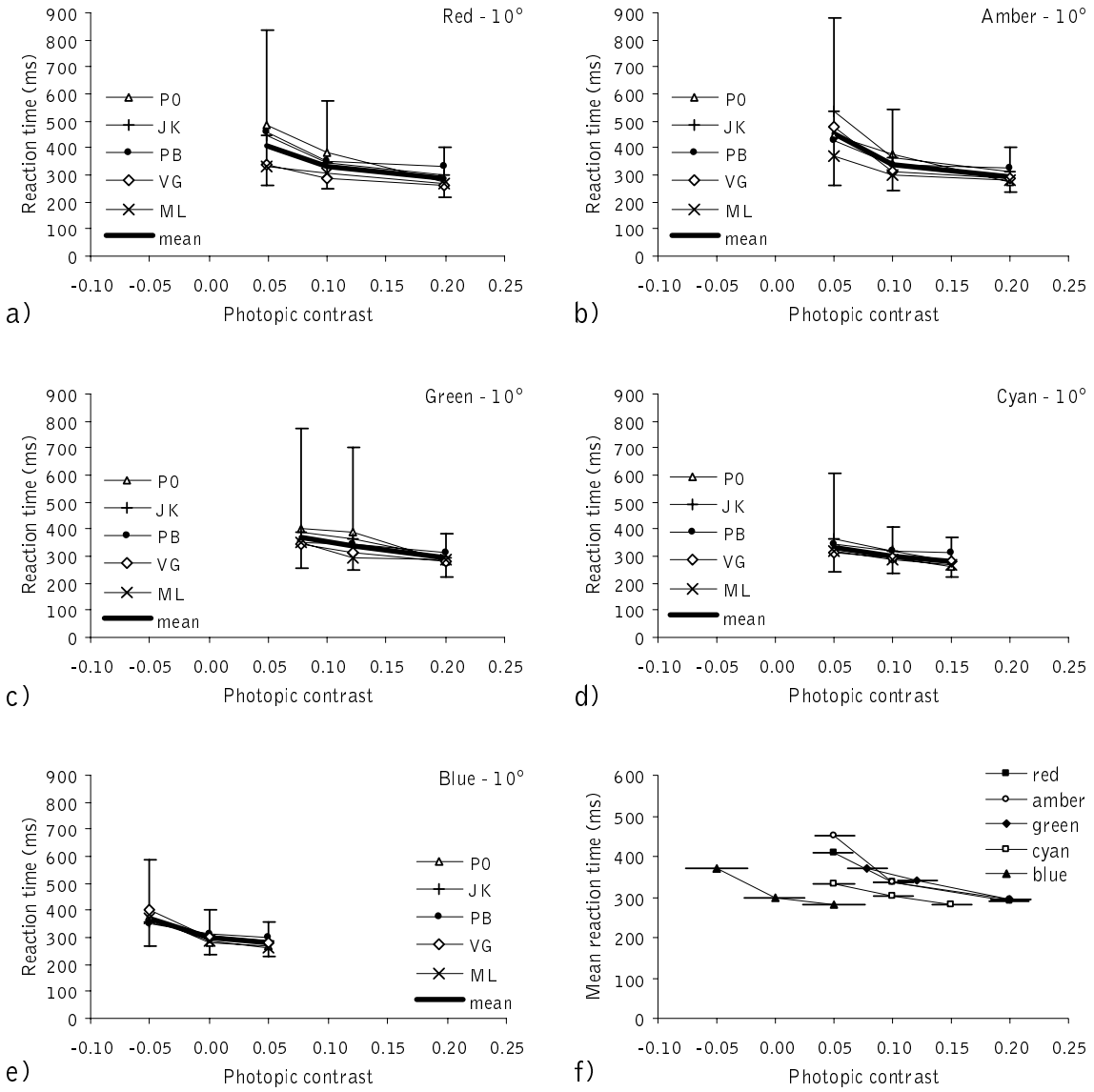


Figure 17 Results of the reaction time measurement at 10 cd/m² for peripheral vision (10° eccentricity). Figures a-e represent each measured colour and figure f represents the collected mean reaction times of all subjects. Vertical error bars represent the 2.5th and 97.5th percentiles of the measurement results. Horizontal error bars represent the estimated error of contrast measurements.

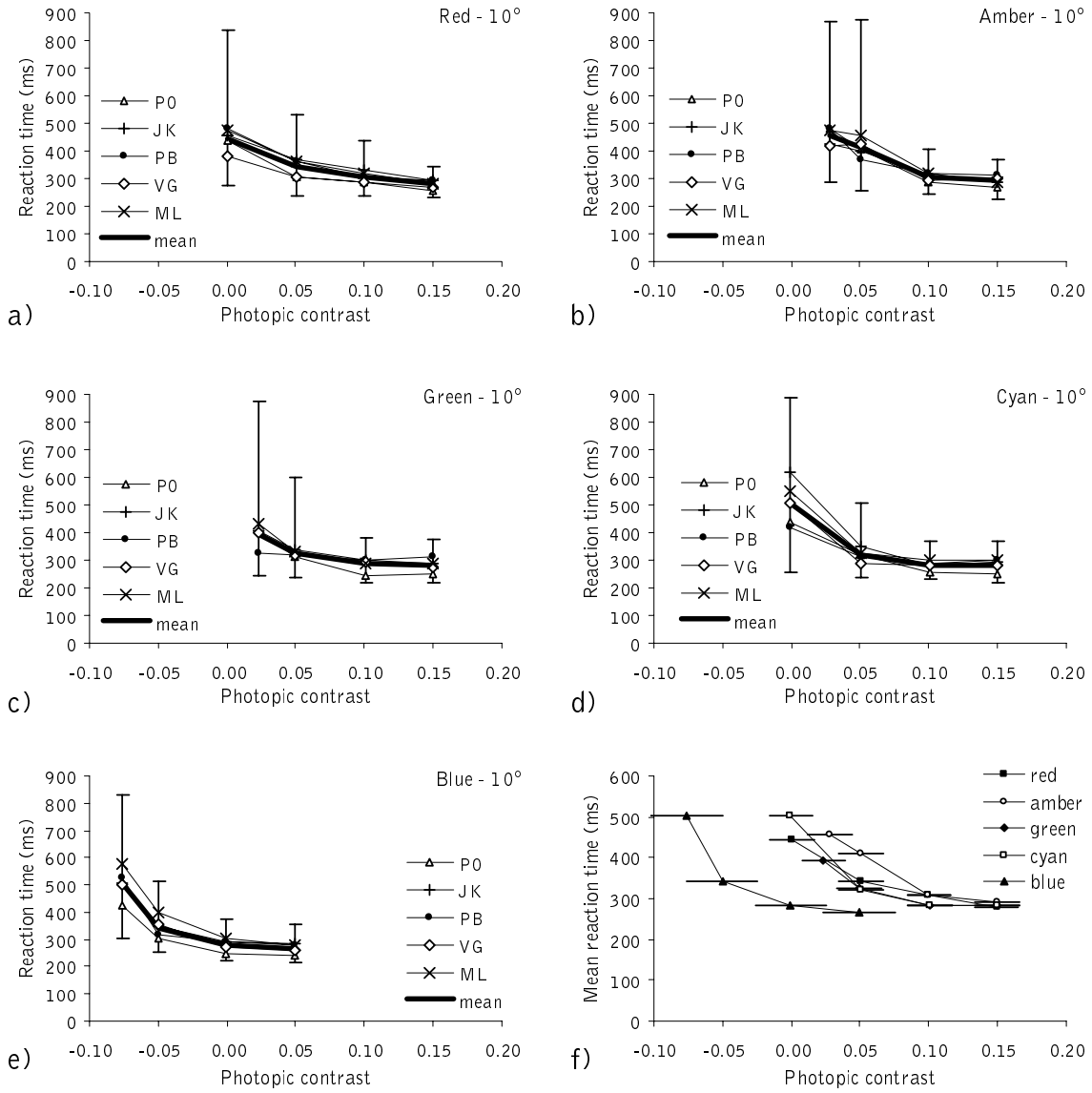


Figure 18 Results of the reaction time measurement at 20 cd/m² for peripheral vision (10° eccentricity). Figures a-e represent each measured colour and figure f represents the collected mean reaction times of all subjects. Vertical error bars represent the 2.5th and 97.5th percentiles of the measurement results. Horizontal error bars represent the estimated error of contrast measurements.

The measurement results of the contrast threshold measurements are presented in Figure 19a. The numerical data can be found in Appendix 5. Figure 19a shows clearly that the data for blue targets differ from the data for red and green targets in the peripheral vision (eccentricities 10°, 30° and 60°). Since the threshold contrasts for blue targets are lower than for the other colours, it indicates that the short wavelengths are underestimated by the used spectral luminous efficiency function, V(λ). The conclusion is, therefore, similar to that drawn from the reaction time measurements.

Figure 17f, Figure 18f and Figure 19a show clearly that, in peripheral vision, the threshold contrasts are different at 10 cd/m² and contrasts yielding the same reaction times are different at 10 cd/m² and 20 cd/m². 10 cd/m² is considered to be in the photopic region or at the limit of photopic and mesopic regions (CIE, 1978). However, there are also those who hold the opinion that 10 cd/m² (Kokoschka, 1997) and even 20 cd/m² (Hough and Ruddock, 1969; LeGrand, 1972) are still in the mesopic region. Aguilar and Stiles (1954) found evidence that rod mechanisms can be active up to luminance levels of between 120 cd/m² and 300 cd/m² in peripheral vision.

The results of contrast threshold and reaction time measurements revealed clear improved spectral sensitivity of targets consisting of short wavelengths. This was concluded as the contrasts for the targets consisting of short wavelengths were lower than the contrasts of targets of other colours. This implies that $V(\lambda)$ underestimates the short wavelengths of the visible spectrum. $V_M(\lambda)$ and $V_{10}(\lambda)$ functions were also applied in the calculations. New contrasts were computed using these functions by applying measured luminance and radiance data (Table 7 and Table 8). The contrasts were calculated with Equation 3.

The luminances for different spectral luminous efficiency functions were calculated using Equation 4 (CIE, 1978). The integral was calculated using the measured relative spectral power distribution. The integral was multiplied with K_m (683 lm/W). The gained value was compared to the measured luminance L. As the values did not match, a correction coefficient for the radiance was calculated by dividing the measured luminance L with the computed luminance. The dimensionless relative spectral power distribution was multiplied with the gained correction coefficient in order to yield the radiance.

$$L = K_m \int L_{e,\lambda} \, V(\lambda) \, d\lambda \qquad (4)$$

Where L is the luminance, K_m is the maximum luminous efficacy of radiation (683 lm/W for $V(\lambda)$), $L_{e,\lambda}$ is the spectral power distribution of the source (radiance) and $V(\lambda)$ is the photopic spectral luminous efficiency function.

Standard deviation was used as the measure to describe how well the applied spectral luminous efficiency function describes the measured contrasts. Standard deviation was also used in order to derive an indication of the goodness of fit. The calculations of the contrasts of the reaction time measurements are presented in Table 7, while the calculations of the contrast threshold measurements are presented in Table 8. The results revealed that the standard deviation decreased slightly for both measurement methods when applying the $V_M(\lambda)$ function, implying a better fit of data. When the $V_{10}(\lambda)$ function was applied, the standard deviations decreased significantly. For both the reaction time and contrast threshold measurement methods, the $V_{10}(\lambda)$ function described the data with better accuracy. Both measurement methods revealed also that the targets consisting of short wavelengths had still lower contrasts than the other targets, implying that the short wavelengths were underestimated by the $V_{10}(\lambda)$ function as well.

Table 7 *Contrasts calculated for common reaction time data at 10 cd/m² and 20 cd/m² applying different spectral luminous efficiency functions. Target eccentricity was 10°. SD refers to the standard deviation of the contrasts.*

Spectral luminous efficiency function	Target colour						
	Red	Amber	Green	Cyan	Blue	Mean	SD
10 cd/m²							
V(λ)	0.1246	0.1346	0.1498	0.0679	-0.0135	0.0927	0.0670
$V_M(\lambda)$	0.1235	0.1335	0.1486	0.0670	-0.0124	0.0920	0.0660
$V_{10}(\lambda)$	0.1163	0.1224	0.1402	0.0854	0.0614	0.1052	0.0315
20 cd/m²							
V(λ)	0.0609	0.1128	0.0580	0.0626	-0.0348	0.0519	0.0535
$V_M(\lambda)$	0.0602	0.1120	0.0573	0.0619	-0.0344	0.0514	0.0530
$V_{10}(\lambda)$	0.0556	0.1027	0.0516	0.0812	0.0245	0.0631	0.0299

Table 8 *Mean threshold contrasts and their standard deviations for the three measured target colours (red, green, blue) at 10 cd/m². SD refers to the standard deviation of the contrasts. Data for foveal targets (0° eccentricity) have been presented for comparison.*

Spectral luminous efficiency function		Eccentricity			
		0°	10°	30°	60°
V(λ)	Mean	-0.1138	-0.0495	0.0996	0.4323
	SD	0.0149	0.0391	0.1116	0.2681
$V_M(\lambda)$	Mean	-0.1140	-0.0499	0.0988	0.4307
	SD	0.0149	0.0388	0.1109	0.2660
$V_{10}(\lambda)$	Mean	-0.1111	-0.0451	0.1177	0.4713
	SD	0.0195	0.0246	0.0617	0.1663

5.4.2 A new spectral luminous efficiency function for peripheral vision

The measurement results of both reaction time and contrast threshold measurements showed that the spectral sensitivity of short wavelengths is underestimated by V(λ), $V_M(\lambda)$ and $V_{10}(\lambda)$ spectral luminous efficiency functions. A new spectral luminous efficiency function in which spectral sensitivity in the short wavelengths is increased, was developed. The new spectral luminous efficiency function, $V_{per}(\lambda)$, for peripheral vision was based on $V_{10}(\lambda)$, which was the best descriptor of the tested photopic spectral luminous efficiency functions for the investigated tasks. In order to keep the new function simple, the sensitivity to short wavelengths was enhanced by adding the difference between the $V_{10}(\lambda)$ and V(λ) functions multiplied by a coefficient k. Equation 5 represents the new spectral luminous efficiency function. The transition wavelength from $V_{10}(\lambda)$ to $V_{per}(\lambda)$ was selected as 557 nm, because it is the peak wavelength of the $V_{10}(\lambda)$ function. Wald (1945) found in his research where he measured the absolute thresholds of light-adapted cones

that sensitivity to wavelengths below 550 nm is relatively higher in peripheral vision than in foveal vision. This supports the decision of the transition wavelength.

$$V_{per}(\lambda) = V_{10}(\lambda) + k \cdot (V_{10}(\lambda) - V(\lambda)),\ \lambda < 557\ nm \quad (5)$$
$$V_{per}(\lambda) = V_{10}(\lambda),\ \lambda \geq 557\ nm$$

where $V_{per}(\lambda)$ is the peripheral spectral luminous efficiency function, $V(\lambda)$ is the photopic spectral luminous efficiency function for a 2° field, $V_{10}(\lambda)$ is the photopic spectral luminous efficiency function for a 10° field, and k is the modification coefficient.

Coefficient k was optimised for the measured data by minimising the standard deviation of the target contrasts. The results revealed that the new $V_{per}(\lambda)$ function was the best descriptive function for peripheral vision as compared to $V(\lambda)$, $V_M(\lambda)$ and $V_{10}(\lambda)$ functions. This was true for both reaction time and contrast threshold measurement methods and all eccentricities (10°, 30° and 60°) at photopic luminance level 10 cd/m².

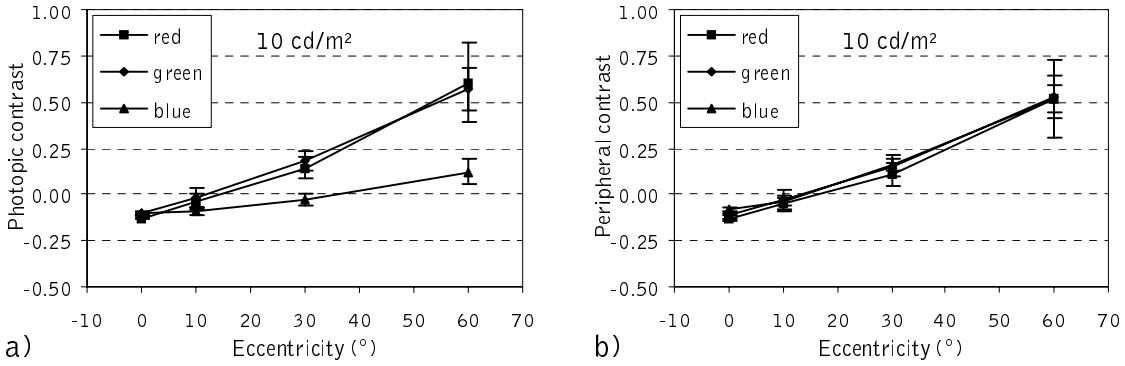


Figure 19 Threshold contrasts of three target colours (red, green, blue) based on a) $V(\lambda)$ and b) $V_{per}(\lambda)$. Error bars represent the standard deviations of the measurement data. $V_{per}(\lambda)$ function was calculated with coefficient k = 1.7322.

Figure 19a shows that the threshold contrasts in peripheral vision were not well described by the $V(\lambda)$ function. The threshold contrasts for the blue target deviate from the two other target colours. This deviation increases with increasing eccentricity. When the $V_{per}(\lambda)$ function is applied to the data (Figure 19b), the contrast thresholds are close to each other at every eccentricity, indicating a better fit of data. Coefficient k = 1.7322 was optimised by minimising the standard deviation of the threshold contrasts at 10° eccentricity. For foveal vision, the $V_{per}(\lambda)$ is slightly worse than $V(\lambda)$. This was an expected result, since the $V(\lambda)$ describes the threshold contrasts with good accuracy in foveal vision.

The $V_{per}(\lambda)$ function was applied to the reaction time data. Coefficient k was optimised for 10 cd/m² and 20 cd/m² luminance levels simultaneously. New contrasts have been calculated in Table 9 with the optimised coefficient k = 0.7684. When the calculated values are compared to values calculated with $V(\lambda)$, $V_M(\lambda)$ and $V_{10}(\lambda)$ spectral luminous

efficiency functions (Table 7), the results show that the contrasts of the reaction time measurements at photopic luminance levels (10 cd/m² and 20 cd/m²) are best described by the $V_{per}(\lambda)$ function. When using the $V(\lambda)$, $V_M(\lambda)$ and $V_{10}(\lambda)$ functions, blue and cyan targets had the lowest contrasts implying underestimated spectral sensitivity of the short wavelengths.

Table 9 *Contrasts of reaction times calculated with the developed $V_{per}(\lambda)$ spectral luminous efficiency function. Coefficient k = 0.7684 was optimised for both 10 cd/m² and 20 cd/m² luminance levels simultaneously. Compare with Table 7. SD is the standard deviation of the contrasts.*

Luminance level	Target colour						
	Red	Amber	Green	Cyan	Blue	Mean	SD
10 cd/m²	0.1056	0.1114	0.1354	0.0989	0.1143	0.1131	0.0138
20 cd/m²	0.0480	0.0933	0.0484	0.0955	0.0668	0.0704	0.0232

In Figure 20, the developed spectral luminous efficiency functions using the reaction time data (k = 0.7684) and contrast threshold data (k = 1.7322) are presented. The developed function enhances the spectral sensitivity of the short wavelengths as compared to $V(\lambda)$ and $V_{10}(\lambda)$ functions.

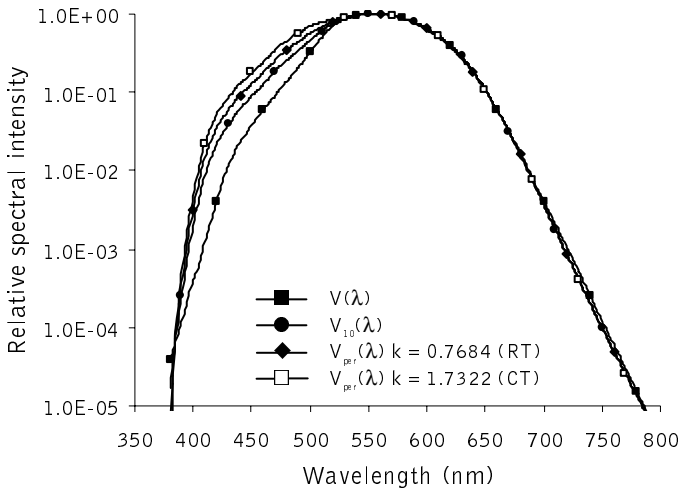


Figure 20 *Photopic spectral luminous efficiency functions for 2° ($V(\lambda)$) and 10° ($V_{10}(\lambda)$) fields and the developed spectral luminous efficiency function $V_{per}(\lambda)$ for peripheral vision at low photopic luminance levels calculated with two coefficients, k = 0.7684 (reaction time data, RT) and k = 1.7322 (contrast threshold data, CT).*

5.5 Mesopic $V_{mes}(\lambda)$ for peripheral vision

5.5.1 Reaction time

The mean reaction times yielded for each target colour at mesopic luminance levels 3 cd/m², 1 cd/m², 0.3 cd/m² and 0.1 cd/m² are presented in Figure 21. Measurements at 0.3 cd/m² were conducted for two subjects only. The other measurements were conducted for five subjects, including the two subjects measured at 0.3 cd/m². The figures show that when the luminance level decreases, targets consisting of longer wavelengths need higher contrasts than the targets consisting of short wavelengths in order to achieve the same reaction time. The range of contrasts is wider at lower luminance levels. The reaction times are longer at lower luminance levels when the same target contrast is applied; this can be seen especially well for the blue targets, which were presented at almost equal contrast at every luminance level. Numerical values are presented in Appendices 2 and 3.

The asymptotic minimum reaction time was not measured for the 0.3 cd/m² luminance level. The asymptotic minimum reaction time was calculated as the mean of reaction times yielded at 0.1 cd/m² and 1 cd/m² for the two subjects. This decision made the results at 0.3 cd/m² less accurate.

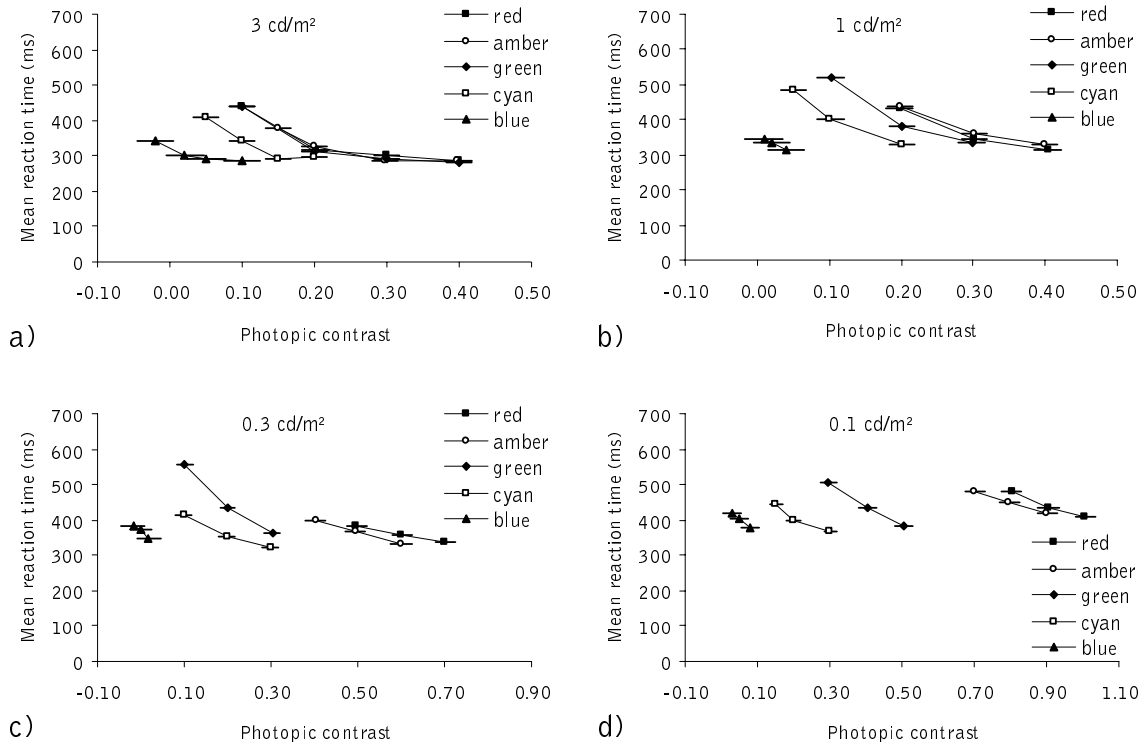


Figure 21 Mean reaction times of each target colour at luminance levels a) 3 cd/m², b) 1 cd/m², c) 0.3 cd/m² and d) 0.1 cd/m². Measurements at 0.3 cd/m² were conducted for two subjects only. Error bars represent the estimated error of contrast measurements.

Figure 22a shows that the contrasts yielded for common reaction times at mesopic luminance levels 0.1 cd/m², 0.3 cd/m², 1 cd/m² and 3 cd/m² are arranged according to the spectral wavelength of the target colour, indicating the Purkinje shift. The difference between target colours is more pronounced at lower luminance levels, indicating that the rods in the peripheral retina becomes more active and dominating with decreasing luminance level. At all mesopic luminance levels, the difference between target colours is larger than at 10 cd/m² and 20 cd/m². The results indicate that the $V(\lambda)$ function cannot describe the spectral sensitivity at mesopic luminance levels in peripheral vision. The $V_{10}(\lambda)$ function was also applied for the reaction time data (Figure 22b), which shows a smaller deviation in the results. There is still a clear dependency of target colour on the luminance level, indicating that the $V_{10}(\lambda)$ function cannot describe the data with sufficient accuracy.

It was tested whether a function, which is a linear combination between photopic and scotopic spectral luminous efficiency functions (Equation 6) would describe the data. $V'(\lambda)$ was the scotopic spectral luminous efficiency function in all cases and three photopic spectral luminous efficiency functions were used in the calculations: $V(\lambda)$, $V_{10}(\lambda)$ and $V_{per}(\lambda)$. Coefficient x was optimised for each luminance level and spectral luminous efficiency function separately. The model of Rea et al. (2004) was also investigated for comparison as it is also based on reaction-time measurements and is used to calculate the mesopic spectral luminous efficiency function.

$$M(x) \cdot V_{mes}(\lambda) = x \cdot V_{phot}(\lambda) + (1 - x) \cdot V'(\lambda) \qquad (6)$$

where $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function multiplied by coefficient M(x) to yield the maximum value of unity. $V_{phot}(\lambda)$ is the used photopic spectral luminous efficiency function and $V'(\lambda)$ is the scotopic spectral luminous efficiency function. Coefficient x is used to weight the photopic and scotopic spectral luminous efficiency functions.

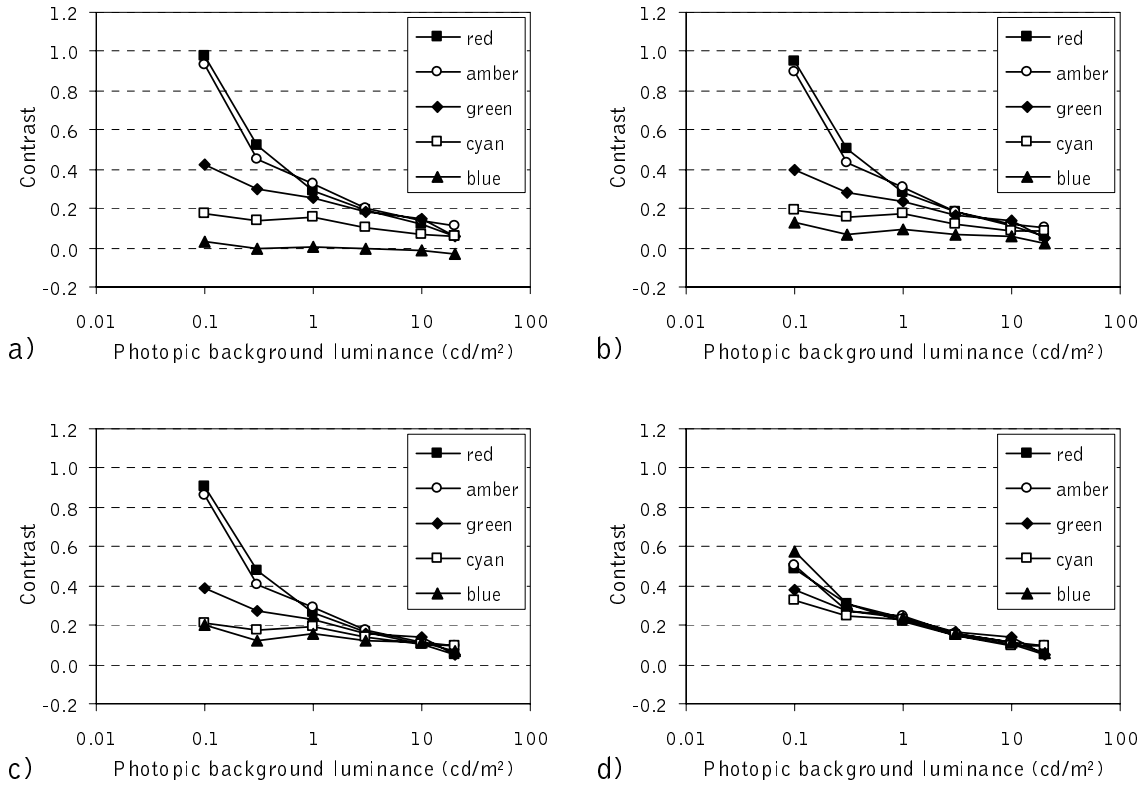


Figure 22 Contrasts of reaction time measurements for 10° eccentricity computed with different spectral luminous efficiency functions a) $V(\lambda)$, b) $V_{10}(\lambda)$, c) $V_{per}(\lambda)$, d) $V_{mes}(\lambda)$. The $V_{per}(\lambda)$ function was calculated with coefficient k = 0.7684. $V_{mes}(\lambda)$ is the linear combination of $V_{per}(\lambda)$ and $V'(\lambda)$ functions. The data for luminance level 0.3 cd/m² was measured for two subjects only. Therefore, the data is less accurate and deviates from the general trend. Photopic luminance levels (10 cd/m² and 20 cd/m²) have been included for comparison.

Figure 22 shows that the developed $V_{mes}(\lambda)$ describes the reaction time data with best accuracy at mesopic luminance levels when compared to $V(\lambda)$, $V_{10}(\lambda)$ and $V_{per}(\lambda)$ functions. The improved accuracy is the result of optimisation of coefficient x in Equation 6. The development of a proper model for the mesopic luminance levels requires a knowledge of how coefficient x depends on the luminance level.

The results presented in Figure 23 show that the optimised values of coefficient x (x-values) at luminance levels 10 cd/m² and 20 cd/m² are almost identical, indicating that coefficient x has saturated to a certain level or is about to do so. The results of the lower luminance levels show a decrease of x-values with decreasing luminance levels. Three measurement points at 1 cd/m², 0.3 cd/m² and 0.1 cd/m² show an almost linear trend in Figure 23. There are, however, significant differences in the values when different photopic spectral luminous efficiency functions are applied.

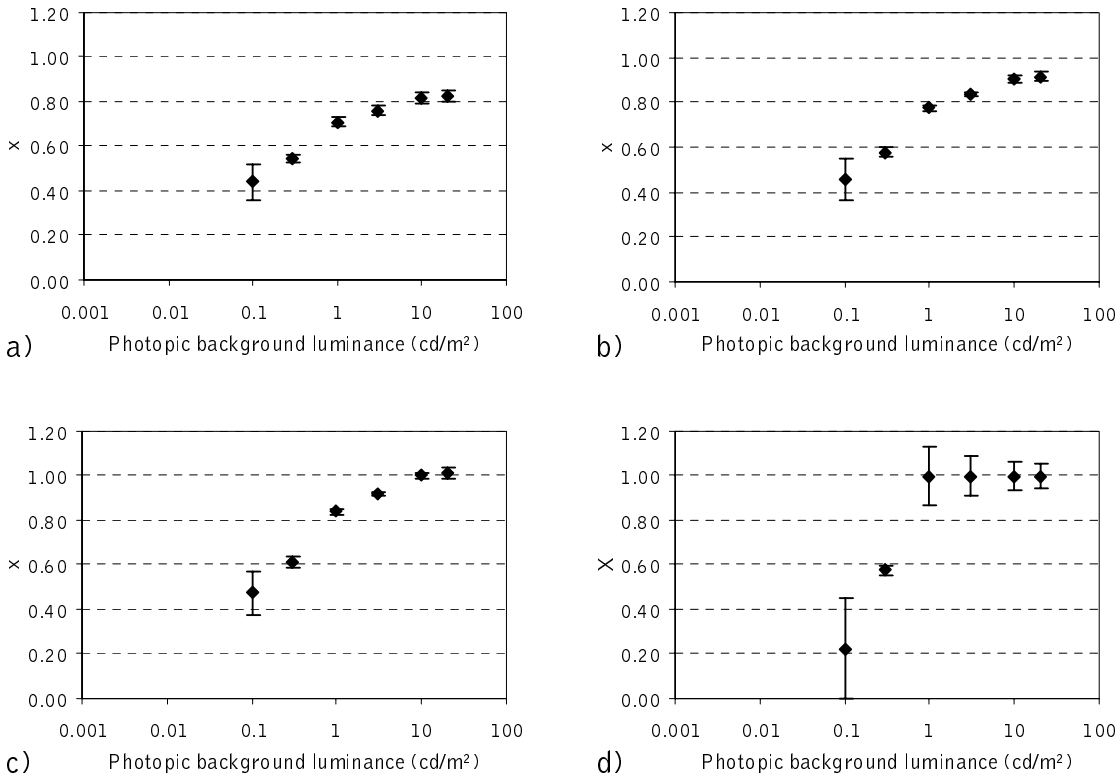


Figure 23 Optimised values for coefficient x using the reaction time data. Luminance is the background (adaptation) luminance. The plotted dots are the optimised x-values at measured luminance levels. The error bars show the standard deviations of the contrasts of the five colours. The photopic spectral luminous efficiency function used for calculating the luminance is a) V(λ), b) $V_{10}(\lambda)$ and c) $V_{per}(\lambda)$. Figure d represents the proposed unified system of photometry by Rea et al. (2004).

When V(λ) is applied, the x-values do not reach unity as expected at 10 cd/m² or 20 cd/m². This indicates either that photopic luminance levels have not been reached or that V(λ) does not describe the spectral sensitivity in the peripheral vision properly. Since the x-values for 10 cd/m² and 20 cd/m² are very close to each other, indicating saturation of results, it implies that the V(λ) does not describe the spectral sensitivity in peripheral photopic vision properly. When the $V_{10}(\lambda)$ function is applied, the x-values increase, but do not reach unity. With $V_{per}(\lambda)$ function, the values reach unity (in fact, they become slightly higher than unity) indicating that photopic luminance levels have been reached. The other luminance levels (0.1 cd/m², 0.3 cd/m², 1 cd/m² and 3 cd/m²) are clearly in the mesopic range, which is indicated by the reduction of coefficient x. The proposed unified system of photometry by Rea et al. (2004) assumes that the V(λ) function can already be used at 0.6 cd/m², and therefore coefficient x is unity at luminance levels above 0.6 cd/m². Figure 23 shows that the system of Rea et al. yields clearly the worst fit of data at every luminance level, indicating that it does not describe data with sufficient accuracy.

Two types of curves were fitted to the $V_{mes}(\lambda)$ data that was derived from the linear combination of $V_{per}(\lambda)$ and $V'(\lambda)$ functions (Figure 23c). The fitted curves are referred to as linear and sigmoid according to their visual appearance. Linear fitting was managed in two ways. The first fit divided the data points into two parts: mesopic and photopic. A horizontal line was drawn through the 10 cd/m² and 20 cd/m² data points; this represents the photopic luminance level. Another line was drawn through the mesopic data points (Table 10 and Figure 24a). In the second fit, the data points were divided into three groups. 10 cd/m² and 20 cd/m² represent the photopic luminance levels, 0.1 cd/m², 0.3 cd/m² and 1 cd/m² represent the mid-mesopic luminance levels, and 1 cd/m², 3 cd/m² and 10 cd/m² were grouped as the intermediate luminance levels between the mesopic and photopic luminance levels (Table 10 and Figure 24b). The fitting of data was made for the mean contrasts of the five target colours.

Visually inspected, the data points of Figure 23c appear to locate along a sigmoid curve. Whether it was possible to describe all luminance levels simultaneously with a single function was therefore examined. Equation 7 was selected as the sigmoid function.

$$x = x_{max} - \frac{x_{max} - x_{min}}{1 + a \cdot L^{b}} \tag{7}$$

where x_{max} and x_{min} are the maximum and minimum values of coefficient x, respectively. L is the photopic luminance; a and b are coefficients.

The optimisation was completed in several steps. During the first step, the parameters were allowed to have any value without any specific restrictions. As the maximum and minimum values for coefficient x were expected to be 1 and 0, respectively, these values were fixed in the following steps. The remaining two parameters were optimised simultaneously. As the parameters appeared to be close to 5 and 0.8, these values were fixed one by one to see whether the coefficient of determination R^2 would remain sufficiently high. In the final step, both parameters were fixed. The results of the optimisation are presented in Table 11. The R^2-values of Table 11 show that, when all four parameters are fixed, the fit of data is very good. It is apparent that a sigmoid function with simple parameters can be used to calculate the x-values. Equation 8 presents the gained function in a simple form.

$$x = \frac{5 \cdot L^{0.8}}{1 + 5 \cdot L^{0.8}} \tag{8}$$

Table 10 Equations for coefficient x and R^2-values of the linearly optimised curves (Figure 24a-b).

	Range (cd/m²)	Equation	R^2
Two lines			
Photopic	≥ 4.5	x = 1.00705	Not applicable
Mesopic	< 4.5	x = 0.79413 + 0.31636 log L	0.97581
Three lines			
Photopic	≥ 10.5	x = 1.00705	Not applicable
Transition	1.14 – 10.5	x = 0.84051 + 0.16286 log L	0.99989
Mesopic	< 1.14	x = 0.82861 + 0.36729 log L	0.98749

Table 11 Coefficients and R^2-values of the optimised sigmoid curves (Figure 24c-d). Fixed values are marked in bold.

x_{max}	x_{min}	a	b	R^2
1.021373	0.348846	2.367047	1.029277	0.99605
1	**0**	4.905313	0.7849666	0.97982
1	**0**	5.005932	**0.8**	0.97966
1	**0**	**5**	0.7934734	0.97973
1	**0**	**5**	**0.8**	0.97966

The main drawback of Equation 8 can be seen in Figure 24d. To be exact, the sigmoid curve never reaches the asymptotic x = 1. In practise, a high value such as x = 0.99 is reached at 42 cd/m². Such a high limit is, however, not justified by the measurement results. Another optimisation was conducted, allowing the x_{max} to be 1.02, the value gained in the first optimisation. The results of the optimisation can be seen in Figure 25. In Equation 9, x = 1 is reached at approximately 28 cd/m² when the new optimisation is applied. The value of coefficient x has been limited to x = 1 in the figure. The values presented below 0.1 cd/m² in Figure 24 and Figure 25 are purely speculative and added for illustrative purposes only.

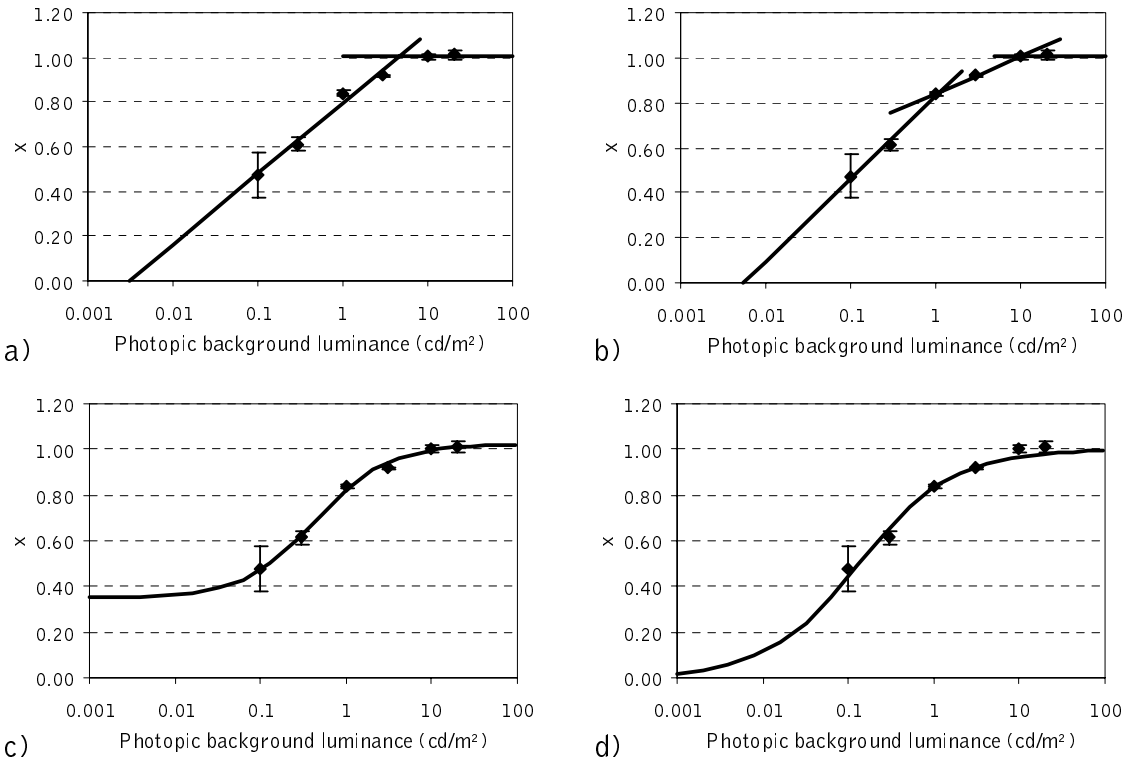
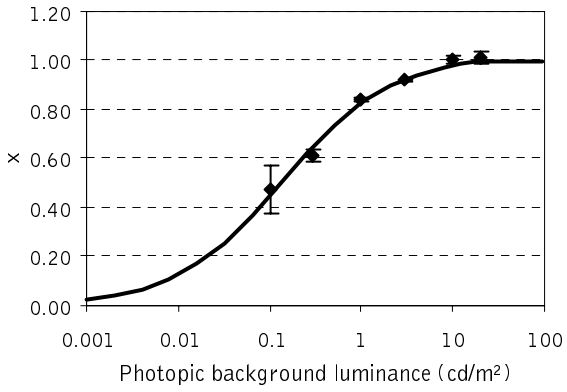


Figure 24 Different curves fitted to the reaction time data. $V_{per}(\lambda)$ was used as the photopic spectral luminous efficiency function. a) Two linear curves separately for photopic and mesopic data, b) Three linear curves for photopic, mesopic and intermediate data, c) Sigmoid curve with free parameter optimisation and d) Sigmoid curve with simplified coefficients.



$$x = \frac{4.386 \cdot L^{0.74}}{1 + 4.3 \cdot L^{0.74}} \qquad (9)$$

$$\max(x) = 1$$

$$R^2 = 0.98685$$

Figure 25 Optimised sigmoid curve with fixed $x_{max} = 1.02$ and $x_{min} = 0$. Coefficients a and b were optimised and simplified to 4.3 and 0.74, respectively. Values below 0.1 cd/m² are purely speculative and are presented for illustrative purposes only.

5.5.2 Contrast threshold

From Figure 26 it can be seen that the V(λ) function is an inadequate measure of the spectral sensitivity in peripheral vision at 10 cd/m². The threshold contrasts for blue targets are clearly lower than for red and green targets. This indicates that the short wavelengths

are underestimated by this function. This is more pronounced at eccentricities 30° and 60° as compared to 10°. The $V_{mes}(\lambda)$ function that was modelled using the reaction time data was applied to the contrast threshold data. $V_{mes}(\lambda)$ calculated for the contrast threshold data used the x-values gained for the reaction time data, but $V_{per}(\lambda)$ was derived from contrast threshold data for 10 cd/m² (coefficient k = 1.7322). Figure 26 shows that the difference between the contrasts of the colours is significantly reduced when the mesopic $V_{mes}(\lambda)$ function is applied in peripheral vision. The data for 10° eccentricity, in particular, shows excellent fit of data at all luminance levels. The fit of data at other eccentricities is significantly worse. In order to improve the fit of data at eccentricities other than 10°, new x-values were computed for the contrast threshold data. Figure 27 shows two computed optimisations. In the first case, coefficient x has been optimised for all eccentricities simultaneously, while, in the second case, the optimisation has been performed for all eccentricities individually.

Comparison of Figure 26 and Figure 27 shows that the new optimisation of the $V_{mes}(\lambda)$ function decreases the differences between contrasts of target colours in the far peripheral vision (30° and 60° eccentricities) at 1 cd/m² and 0.1 cd/m². In Figure 27, the differences of contrasts between colours at 60° eccentricity are smaller than in Figure 26. When the optimisation was made for all eccentricities simultaneously, the difference between contrasts of target colours increases at 10° eccentricity, indicating a poorer fit of data. Individual optimisation of each eccentricity improves the situation by reducing the difference between target colours.

Table 12 Simultaneously and individually optimised coefficient x for the contrast threshold data.

	Simultaneous	Individual		
	All eccentricities	10°	30°	60°
10 cd/m²	1.0055	1.0754	1.1005	0.9993
1 cd/m²	0.4975	0.8649	0.6423	0.4621
0.1 cd/m²	0.2084	0.5367	0.3052	0.1916

Table 12 shows that, at mesopic luminance levels (1 cd/m² and 0.1 cd/m²), the simultaneously optimised coefficient x locates in between the individually optimised coefficients for 30° and 60° eccentricities. This implies that, if the coefficient x should be optimised for the whole peripheral vision, the optimal eccentricity for measurements could be found between 30° and 60°. The optimal eccentricity depends, however, on the visual field of the task and especially the visual field of importance.

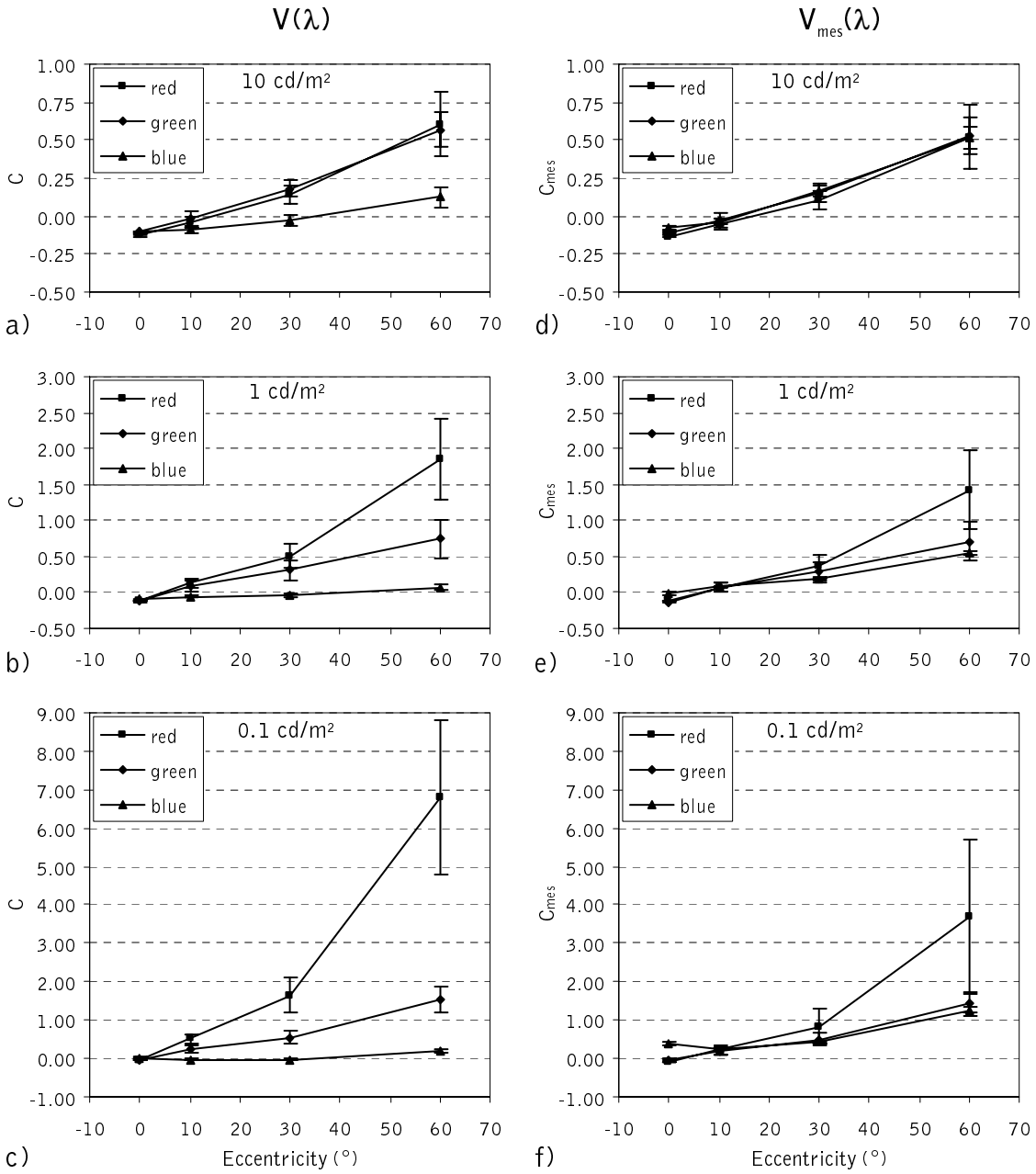


Figure 26 Threshold contrasts for three target colours and three luminance levels. a-c) the photopic and d-f) the mesopic threshold contrasts of each colour for each measured luminance level. The contrasts were computed using the $V_{per}(\lambda)$ function as the photopic spectral luminous efficiency function (coefficient k = 1.7322) and the x-values optimised for the reaction time data at 10° eccentricity. Error bars represent the standard deviations of the measurement results.

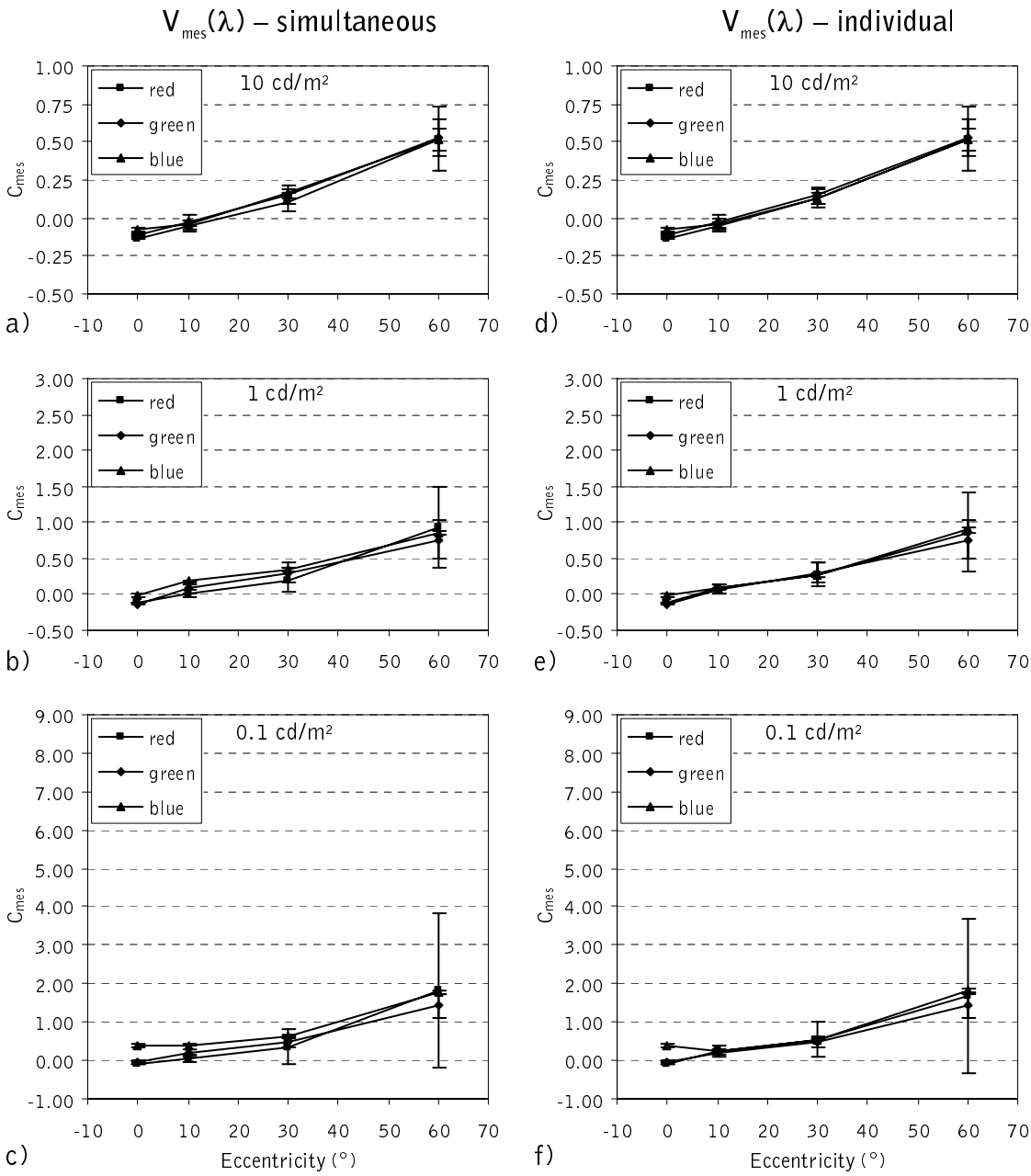


Figure 27 Threshold contrasts optimised with the x-values of the $V_{mes}(\lambda)$ function a-c) for all eccentricities simultaneously and d-f) for each eccentricity individually. Error bars represent the standard deviations of the measurement results.

6 Discussion

6.1 Spectral luminous efficiency function for peripheral vision – $V_{per}(\lambda)$

Results gained from the reaction time and contrast threshold measurements at luminance levels 10 cd/m² and 20 cd/m² revealed that V(λ) is not the best spectral luminous efficiency function for describing the spectral sensitivity of peripheral vision, at least for the performed reaction time and contrast threshold tasks. Further analysis showed that the

$V(\lambda)$ function underestimates the spectral sensitivity of the short wavelengths in these visual tasks. Currently, there is no photopic spectral luminous efficiency function that would describe the spectral sensitivity of targets locating entirely in the peripheral vision. The $V_{10}(\lambda)$ function is designed for describing the spectral sensitivity of a 10° field surrounding the fovea. Due to the different distribution of photoreceptors in the foveal and peripheral retina, it is not possible to know what the actual spectral luminous efficiency function for targets locating entirely in the extra-foveal vision would be. Therefore, it is not possible to know how targets that locate in the peripheral vision are perceived. An attempt was made to create a spectral luminous efficiency function for describing the spectral sensitivity to targets locating in the peripheral vision. The results revealed that the developed function, $V_{per}(\lambda)$, was the best descriptive function with the measurement set-up used.

The importance of establishing a peripheral spectral luminous efficiency function rises from the fact that the spectral sensitivity of peripheral retina changes in mesopic vision. The results reveal that the $V(\lambda)$ function is valid in the foveal vision at mesopic light levels. The mesopic spectral luminous efficiency functions are usually combinations of photopic and scotopic spectral luminous efficiency functions. The scotopic spectral luminous efficiency function is $V'(\lambda)$, but the photopic spectral luminous efficiency function is either $V(\lambda)$ or $V_{10}(\lambda)$. The measurements made in this work indicate that this is an inaccurate starting point, since the spectral sensitivity of short wavelengths is higher than indicated by both $V(\lambda)$ and $V_{10}(\lambda)$ functions.

The results presented in this work show that $V_{per}(\lambda)$ was the best descriptor of the spectral sensitivity at low photopic luminance levels in peripheral vision at 10° eccentricity. This was found for both reaction time and contrast threshold measurement methods. In addition, the contrast threshold measurements showed that $V_{per}(\lambda)$ was the best descriptor at 30° and 60° eccentricities as well. The $V_{per}(\lambda)$ function enhances the spectral sensitivity of short wavelengths as compared to the $V(\lambda)$ and $V_{10}(\lambda)$ functions. The enhanced spectral sensitivity of short wavelengths in the peripheral retina has been shown by other researchers using different measurement methods as presented in Sections 2.1 and 2.2. Currently, only the $V_{10}(\lambda)$ function is appropriate for determining the spectral sensitivity of the peripheral vision. The results presented in this work justify the development of a spectral luminous efficiency function for peripheral vision at photopic light levels. The $V_{per}(\lambda)$ function can be used as a basis for this work.

6.2 Spectral luminous efficiency function for mesopic vision – $V_{mes}(\lambda)$

A linear function for describing the spectral sensitivity at mesopic luminance levels in peripheral vision was developed based on the scotopic spectral luminous efficiency function $V'(\lambda)$ and a photopic spectral luminous efficiency function. Photopic spectral luminous efficiency functions $V(\lambda)$, $V_{10}(\lambda)$ and $V_{per}(\lambda)$ were tested in order to find the best descriptive function. It turned out that, at higher mesopic luminance levels ($\geq$ 1 cd/m^2), the developed $V_{per}(\lambda)$ function was the best candidate to be used in the linear model. At

lower mesopic luminance levels, the V(λ) was the best descriptive function. According to the results, it appears that luminance levels 10 cd/m² and 20 cd/m² are in the photopic range, or at least very close to it. Almost identical values for coefficient x reveal this fact. The computation made with the $V_{per}(\lambda)$ function for the contrast threshold data at 10 cd/m² confirm this assumption, because the $V_{per}(\lambda)$ function showed a very good fit of data at all eccentricities, which was not the case in the mesopic range of luminances. The optimised x-values showed that spectral sensitivity in the luminance range between 0.1 cd/m² and 20 cd/m² can be described with a linear combination of $V_{per}(\lambda)$ and V'(λ) functions, where coefficient x is derived from a simple sigmoid curve (Figure 25). The development of the $V_{mes}(\lambda)$ function was thus based on the reaction time data.

When the $V_{per}(\lambda)$ function optimised for contrast threshold data and the x-values optimised for the reaction time data were applied to the contrast threshold data, the fit of data became worse in the far peripheral vision. The x-values for the $V_{mes}(\lambda)$ function were optimised with the reaction time data, and that data was available for 10° eccentricity only. Therefore, the accuracy at that eccentricity was very good at every measured light level. The situation in the far peripheral vision (eccentricities 30° and 60°) at mesopic light levels (0.1 cd/m² and 1 cd/m²) was different. The targets were arranged according to their colour, where the targets consisting of the shortest wavelengths had the lowest contrast thresholds. This indicates enhanced rod intrusion in the far peripheral vision. A similar type of eccentricity dependency was recorded by Stabell and Stabell (1980a, 1980b), as they concluded that 7° eccentricity resembles photopic vision and 45° scotopic vision at 10 Td and 1000 Td, respectively. They suggested that, in the far periphery, the rods may dominate the spectral sensitivity at a higher intensity than in the near-peripheral retina. This feature appears to be true in nature and should be taken into account when optimising the mesopic function for different target eccentricities.

The results show that, if the spectral sensitivity of the entire peripheral retina at mesopic light levels needs to be modelled, the optimal eccentricity for optimisation is not 10°. If that eccentricity is used in the optimisation, the shift of spectral sensitivities towards the shorter wavelengths in the far peripheral vision is clearly underestimated. A better candidate for optimal target eccentricity is estimated to be found between 30° and 60°, because, when the coefficient x was optimised for all eccentricities simultaneously, its value was between the individually optimised values of the 30° and 60° eccentricities.

6.3 Constraints of peripheral and mesopic models

According to Berman and Clear (2001), the mesopic region does not follow all basic laws associated with photometry. These laws are called Abney's laws and they prescribe symmetry, transitivity, proportionality and additivity. Berman and Clear show that, in fact, it is not even possible for any mesopic function to follow the Abney's law of additivity. On the other hand, Lennie et al. (1993) state that a working system of photometry must be additive. As these statements contradict each other, it is perhaps not even possible to achieve a "perfect" general mesopic model. He et al. (1997) claim that additivity likely

holds in mesopic systems based on reaction times, although only within a certain luminance level. A satisfactory mesopic model for describing the spectral sensitivity in the peripheral vision at mesopic luminance levels could therefore be based on linear combination of photopic and scotopic spectral luminous efficiency functions, as long as the constraint associated with additivity is kept in mind. Additivity was not tested in this work.

In this work, the modelled mesopic linear function $V_{mes}(\lambda)$ required the use of the developed $V_{per}(\lambda)$ function for photopic peripheral vision. It is obvious that the $V_{per}(\lambda)$ function should first be validated in order to proceed with the $V_{mes}(\lambda)$. The model of Rea et al. (2004) used the $V(\lambda)$ function for practical reasons, despite their being aware of the limitations of that function. One major question associated with the selection of a proper photopic spectral luminous efficiency function is that $V(\lambda)$ has been used for 80 years, and all practical photometry has been based on that function. Should the $V(\lambda)$ be used in the future as well? The major advantage of using the $V(\lambda)$ function is that most of the measurement devices are already calibrated to it. Manufacturers have a good knowledge of how to produce accurate equipment with proper $V(\lambda)$ filtering. The measurement results gained in the past decades are also directly usable and comparable without any conversions or additional errors. Financial savings would be considerable if the situation would remain as it is. Not only would the manufacturers keep their system as they are, but also all the light measuring equipment would not need to be replaced or corrected for.

On the other hand, as already mentioned, the $V(\lambda)$ is not perfect in the sense that it is known to underestimate short wavelengths at photopic light levels (e.g., Judd, 1951; Vos, 1978). Also, several studies have shown that, for peripheral vision, the $V(\lambda)$ function is no longer a sufficient descriptor of spectral sensitivity in the photopic region (e.g., Wald, 1945; Wooten et al., 1975; Abramov and Gordon, 1977). New methods for measuring the spectral sensitivity of the eye have emerged since the establishment of the $V(\lambda)$ function. A more universal spectral luminous efficiency function could predict the spectral sensitivity with better accuracy. It should, however, be pointed out that the measurement results presented in this work support the use of $V(\lambda)$ for foveal vision of small targets at photopic, as well as mesopic, light levels.

Both peripheral and mesopic spectral luminous efficiency functions were derived from experimental data using a white background produced by filtered “daylight” fluorescent lamps (correlated colour temperature, 5400 K). The correlated colour temperature of the filtered light was 4920 K ± 100 K. The model of Rea et al. (2004) takes into account the S/P-ratio of the light and the photopic luminance level. The expansion of the $V_{mes}(\lambda)$ model presented in this work to a wider range of S/P-ratios is expected to need more research. The size of the target used in the measurements was small (0.29°), especially when compared to the large field measurements conducted at mesopic luminance levels as presented in Section 2.2. More research should be conducted in order to validate the generality of the mesopic model developed in this work. The measurements showed that

the spectral sensitivity in the peripheral vision at mesopic light levels is affected by the eccentricity of the target. A general model should either take into account the target eccentricity or the model should be established for a certain optimised eccentricity.

Reaction time and contrast threshold measurements yielded similar results at 10 cd/m² luminance level and 10° target eccentricity, but optimal coefficient k was not the same for both measurement methods. Since coefficient k is larger for the contrast threshold measurements, it implies that, in this measurement method, the spectral sensitivity would be higher in the short wavelengths of the visible spectrum. The subjects were partially different in the two measurements, which can explain the difference partially. More research is required to validate the $V_{per}(\lambda)$ function and coefficient k.

6.4 Reliability of the results

The analysis of the reliability of the results has been divided according to the measurement equipment and method used. The significant sources of error in the measurements in the order of severity are estimated to be the spectral power distribution produced by the target, luminance measurement, non-linearity of the spectroradiometer and the error in the relative intensities measured by the LMT SF 105B system flash meter.

The radiance of the target was calculated by multiplying the irradiance of the LED with the transmittances of the diffusers and the filters. As it was not possible to measure the radiance of the target directly, it was done by first measuring the spectral power distribution of the LED as an irradiance measurement. The transmittances of the filters and the diffusers were measured using a white LED as a reference light. The final irradiance was achieved by multiplying the spectral power distribution of the LED with the transmittances of the applied filters and diffusers. The final irradiance of the target was converted into radiance by measuring the luminance of the target and applying Equation 4. The use of filters had the strongest effect on the green LED's spectral power distribution, for which a double peak emerged at lowest luminance levels (≤ 1 cd/m²). The peak wavelength of the cyan LED shifted approximately 8 nm at 0.1 cd/m². Otherwise, the differences in the spectral power distributions of the LEDs were small and were restricted to between a 0 nm and 3 nm shift in the peak wavelengths. The spectral power distribution was mostly affected at low luminance levels, where the reduction of intensity required the strongest filtering. In general, the spectral power distribution was similar to the spectral power distribution of the plain LED. It is therefore assumed that the results for green LEDs are the least accurate in the sense of spectral power distribution.

The deviation of relative spectral responsivity from the $V(\lambda)$ function of the LMT L 1009 luminance meter was described as fine (f_1 = 1.7% according to DIN 5032, Part 6 and f_1' CIE publ. No. 69 (1987)) by the manufacturer, LMT Lichtmesstechnik GmbH, Berlin, Germany. From the manufacturer's certificate it was computed that the measurement error in luminance for the blue target could be as large as -2.9%. The luminances of the targets were measured with a close-up lens that had a correction factor of 1.01.

Combining the V(λ) correction error and the correction factor of the close-up lens, the total error of luminance measurement for the blue LED was -2%, and for the other colours the error was smaller.

Spectral measurements were made with an upgraded OL 754 Portable UV-Visible High-Accuracy Spectroradiometer by Optronics, Inc., USA. The spectral measurements were used to get the relative spectral power distributions. The absolute values were never used, because these were not required for the computing of the radiances. It was estimated from the reference lamp measurements that the error in the linearity of the response curve of the spectroradiometer was within ±1.9%. This also applies to the spectral power distribution measurements of the different light sources and for the filters and diffusers.

The luminous intensities produced by the LEDs were measured with the LMT SF 105B system flash meter. The deviation of relative spectral responsivity from the V(λ) function of the LMT SF 105B system flash meter was described as fine (f_1 = 1.8%, according to DIN 5032, Part 6 and f_1' CIE publ. No. 69 (1987)) by the manufacturer, LMT Lichtmesstechnik GmbH, Berlin, Germany. The measurements were relative and absolute values were never used. The purpose of the intensity measurements was to get a correction factor for the luminance measured for continuous light. As the luminance of a short flash could not be measured directly, the luminance of the continuous light had to be multiplied with the correction factor gained by dividing the intensity of the short flash with the intensity of the constant light. It was estimated that the error was within 1%.

The spectral power distribution of the LED flash was measured with an Ocean Optics HR4000 High-resolution Spectrometer. The measurements showed that, although the peak intensity was different for the continuous light and the short flash, the variation in the shape of the spectral power distribution and its peak wavelength was minimal. Only a minor reduction in relative intensity was detected for the short flash at the edges of the spectral power distribution. It was estimated that this feature could be ignored.

The measurements of the rise and fall times of the flashes produced by the LEDs were shown to have very little effect. As the rise times of the flashes were within 1 ms between all five test colours (blue, cyan, green, amber and red), the difference between the rise times could be ignored. The duration of the flash varied approximately 8 ms. In the reaction time measurements, a majority of reactions occurred before the end of the flash, so this made no relevant difference. In the contrast threshold measurements, this feature could have some effect, but it was most likely random in nature and therefore did not bias the results.

The reaction times were recorded using the LMT SF 105B system flash meter. This device was not designed for measuring multiple flashes in a single session, but it worked well when the time for data collecting was properly adjusted. The recording of the data was designed so that the values above a given threshold were recorded to an ASCII-file

and the values below the threshold were rejected from the file. This feature might have led to the first few measurement points being left out of the file. It was estimated that a maximum of three data points could have been missed. This feature was random in nature and it was estimated that it did not affect the reaction times in such a manner that it would have distorted the results.

7 Conclusions

Spectral sensitivity in the peripheral vision at low photopic luminance levels (10 cd/m² and 20 cd/m²) is best described by the proposed peripheral $V_{per}(\lambda)$ function. Reaction time and contrast threshold measurements reveal the same aspect that $V(\lambda)$ or $V_{10}(\lambda)$ functions are not equally good descriptors for spectral sensitivity of peripheral vision at these luminance levels. The $V(\lambda)$ function clearly underestimated the short wavelengths. The application of the $V_{10}(\lambda)$ function improved the situation by reducing the differences between target colours, but the overall trend that short wavelengths were underestimated still remained. The $V_{per}(\lambda)$ function described the spectral sensitivity with better accuracy. It was also noticed that, according to the contrast threshold measurements, the accuracy of the $V_{per}(\lambda)$ function was good even at 60° eccentricity. The conclusion is that there is a need for a photopic spectral luminous efficiency function for conditions where the target locates entirely in the peripheral vision.

$$V_{per}(\lambda) = V_{10}(\lambda) + k \cdot (V_{10}(\lambda) - V(\lambda)),\ \lambda < 557\ \text{nm}$$
$$V_{per}(\lambda) = V_{10}(\lambda),\ \lambda \geq 557\ \text{nm}$$

where $V_{per}(\lambda)$ is the peripheral spectral luminous efficiency function, $V(\lambda)$ the photopic spectral luminous efficiency function for a 2° field, $V_{10}(\lambda)$ the photopic spectral luminous efficiency function for a 10° field, and k the modification coefficient.

In mesopic vision, when modelling the $V_{mes}(\lambda)$ function, the linear combination of $V_{per}(\lambda)$ and $V'(\lambda)$ functions yielded the best fit for reaction time data at high (≥ 1 cd/m²) mesopic luminance levels. At luminance levels below 1 cd/m², the linear combination of $V(\lambda)$ and $V'(\lambda)$ functions yielded the best fit of data. A sigmoid curve was optimised to fit the weighting coefficients (x-values) through luminance levels between 0.1 cd/m² and 20 cd/m². The x-values gained in the modelling of reaction time data were applied to the contrast threshold data. A good fit of data was found for 10° eccentricity at both measured mesopic luminance levels (0.1 cd/m² and 1 cd/m²). Eccentricities 30° and 60° were, however, not described well by the $V_{mes}(\lambda)$ function optimised for the 10° eccentricity. In addition, it was noticed that the threshold contrasts calculated with the $V_{mes}(\lambda)$ function were wavelength dependent. The targets consisting of long wavelengths yielded higher threshold contrast than targets consisting of short wavelengths. It was therefore concluded that the far peripheral (30° and larger eccentricities) retina is more sensitive to short wavelengths than the near peripheral (10° eccentricity) vision. New optimisations were performed for coefficient x, and the results showed that a better fit of data in the far

peripheral vision was found. The fit of data was improved further when coefficient x was optimised for each eccentricity individually. The data was also applied to the model introduced by Rea et al. (2004), but this model could not describe the data with similar accuracy. It was concluded that the $V_{mes}(\lambda)$ developed in this work was the best descriptive function for describing the spectral sensitivity of the peripheral retina at mesopic luminance levels.

$$M(x) \cdot V_{mes}(\lambda) = x \cdot V_{phot}(\lambda) + (1 - x) \cdot V'(\lambda)$$

where $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function multiplied by coefficient M(x) to yield the maximum value of unity. $V_{phot}(\lambda)$ is the used photopic spectral luminous efficiency function and $V'(\lambda)$ is the scotopic spectral luminous efficiency function. Coefficient x is used to weight the photopic and scotopic spectral luminous efficiency functions.

$$x = \frac{4.386 \cdot L^{0.74}}{1 + 4.3 \cdot L^{0.74}}$$

where L is the photopic luminance of the background.

The results show that there is a need for a photopic spectral luminous efficiency function in conditions where the target locates entirely in the peripheral vision. Although the presented research was limited to using one small visual target size only, the results of several cited experiments in Section 2.2 indicate a similar aspect. As any developed spectral luminous efficiency function is dependent on the task and test conditions in general, it is likely that there cannot be found a general model that would not take into account the eccentricity of the target. Further research on this topic is required, especially with respect to the evaluation of the contribution of the performance-based methods and models. CIE Division 1 (2005) has established a Technical Committee TC1-58 Visual Performance in the Mesopic Range to define mesopic visual performance and related terms, to investigate performance-based photometry in the luminance region below approximately 10 cd/m^2, and to propose a model for the basis of performance-based mesopic photometry.

8 Summary

Spectral sensitivity of the human eye has traditionally been investigated using the methods of brightness matching and flicker photometry. Both methods have been used in the mesopic luminance range. Despite this, it has been noticed that brightness matching fails to express the spectral sensitivity even at photopic light levels (Berman and Clear, 2001). Kaiser and Wyszecki (1978) found evidence of both enhancement and cancellation type of additivity failures when analysing results yielded with heterochromatic brightness matching. Flicker photometry, which works well in the photopic range, has been noticed

to fail in the mesopic range (Vienot and Chiron, 1991). Therefore new performance-based methods have been introduced to investigate spectral sensitivity in the mesopic range (He et al., 1997, 1998; Hurden et al., 1999; Rea et al., 2004; Eloholma et al., 2005b).

In this work, spectral sensitivity of the human eye was investigated with two different performance-based methods: reaction time and contrast threshold. Both measurement methods revealed similar aspects of the spectral sensitivity at low photopic and high mesopic luminance levels. The current photopic spectral luminous efficiency functions ($V(\lambda)$,$V_M(\lambda)$ and $V_{10}(\lambda)$) defined by the CIE do not describe the spectral sensitivity in the peripheral vision at photopic or mesopic levels with best accuracy. According to the results, peripheral vision at low photopic levels is more sensitive to short wavelengths than described by the current photopic spectral luminous efficiency functions.

Reaction time measurements were conducted with short flashes of 500 ms duration. Five colours were investigated in the tests: blue, cyan, green, amber and red. The targets were presented at two eccentricities: 0° and 10°. The aim of the measurements was to find a common reaction time for all targets in order to be able to model the mesopic spectral luminous efficiency. The measurements were conducted with contrasts that were below the limit yielding the asymptotic minimum reaction time. At photopic luminance levels (10 cd/m² and 20 cd/m²) the targets consisting of shortest wavelengths required the lowest contrasts in order to achieve the same reaction time. At mesopic luminance levels (0.1 cd/m², 0.3 cd/m², 1 cd/m² and 3 cd/m²) the difference between target colours became more pronounced.

Contrast threshold measurements were conducted with 500-ms flashes and three target colours: blue, green and red. The contrast threshold was searched with the method of limits. The contrast thresholds were measured for four eccentricities: 0°, 10°, 30° and 60°. Three luminance levels were used in the measurements: 10 cd/m², 1 cd/m² and 0.1 cd/m². The results showed that only a minor increase of threshold contrast was recorded for the blue targets, but for the red targets a higher increment was needed when either the luminance level decreased or the target eccentricity increased.

The results of the reaction time and contrast threshold measurements in the photopic range showed that the $V(\lambda)$ function is not the most accurate descriptor of spectral sensitivity in peripheral vision. The results showed that the short wavelengths were clearly underestimated by the $V(\lambda)$ function. A new spectral luminous efficiency function $V_{per}(\lambda)$ was developed for the peripheral vision at photopic light levels. This function is a combination of the $V_{10}(\lambda)$ and $V(\lambda)$ functions. With the new $V_{per}(\lambda)$ function, the results of the contrast threshold measurements showed an excellent fit of data at all eccentricities. The data of the reaction time measurements also showed a better fit with the $V_{per}(\lambda)$ function than with the $V(\lambda)$, $V_M(\lambda)$ and $V_{10}(\lambda)$ functions.

A spectral luminous efficiency function $V_{mes}(\lambda)$ was developed for the peripheral vision at mesopic luminance levels. This function is a linear combination of $V_{per}(\lambda)$ and $V'(\lambda)$ functions. The coefficient in the function was optimised with the reaction time data. The results show that the function had best accuracy at high mesopic luminance levels, whereas for lower mesopic luminance levels, the combination of $V(\lambda)$ and $V'(\lambda)$ functions yielded the best fit of data. The results of the contrast threshold measurements showed that the model is less accurate in the far peripheral vision. As the mesopic function was optimised for 10° eccentricity using the reaction time data, the far peripheral vision was not considered in this function. The contrast threshold measurements showed that the blue part of the spectrum was underestimated in the far periphery by this function. The results showed that the far peripheral retina is clearly more sensitive to short wavelengths than the near peripheral retina, indicating an increased scotopic effect at mesopic luminance levels. New coefficients were computed for the contrast threshold data.

According to the results, a new spectral luminous efficiency function is required for the peripheral vision at photopic light levels. It is not likely that 10 cd/m² is in the mesopic range, because no difference was recorded in the reaction time measurements for green, amber and red targets. The measurements were limited to a single, small, target size. Therefore more investigation is required in this field. The mesopic data showed improved accuracy when the developed mesopic spectral luminous efficiency function was applied. It was, however, revealed that the model is less accurate in the far peripheral vision. The results indicate that it is difficult to gain a proper function that would describe the whole peripheral vision with a high degree of accuracy. The eccentricity that is the best representative region in the peripheral vision should therefore first be ascertained. After this, it might be possible to aim for a general model.

9 Contribution

9.1 Scientific contribution

The vision experiments revealed that the commonly-used spectral luminous efficiency function $V(\lambda)$ does not describe the peripheral spectral sensitivity at photopic light levels for either reaction time or contrast threshold measurements that were performed in this work. This applies also to the $V_{10}(\lambda)$ function. Instead, a new spectral luminous efficiency function, $V_{per}(\lambda)$, was developed, which described the spectral sensitivity with better accuracy at all measured target eccentricities (10°, 30° and 60°) at 10 cd/m² and 20 cd/m².

The results revealed that the spectral luminous efficiency in peripheral vision at mesopic light levels can be described by a linear function that is a combination of photopic and scotopic spectral luminous efficiency functions. $V'(\lambda)$ was the scotopic spectral luminous efficiency function, and several photopic spectral luminous efficiency functions – $V(\lambda)$, $V_{10}(\lambda)$ and $V_{per}(\lambda)$ – were tested. The combination of $V'(\lambda)$ and the new $V_{per}(\lambda)$ function for peripheral vision described the spectral sensitivity with best accuracy. A new spectral

luminous efficiency function, $V_{mes}(\lambda)$, was developed for the peripheral vision at mesopic luminance levels. Both reaction time and contrast threshold measurement methods confirmed that this result showed a significant improvement over the current spectral luminous efficiency functions: $V(\lambda)$, $V_{10}(\lambda)$ and $V'(\lambda)$.

9.2 Author's contribution

The author designed the measurement system and the measurement procedures. The measurement system was constructed under the supervision of the author. Part of the parameters of the reaction time measurements were jointly agreed by the author and the Steering Committee of the MOVE project. The reaction time measurements were performed or supervised by the author. The contrast threshold measurements were designed and performed by the author in all parts.

The results of all measurements were analysed and the conclusions were made by the author. The $V_{per}(\lambda)$ spectral luminous efficiency function was developed by the author. Parameters of the $V_{mes}(\lambda)$ function and the sigmoid function representing the coefficient x were optimised by the author.

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11 Appendices

Appendix 1 *Results of the reaction time measurements in foveal vision at 10 cd/m², 1 cd/m², and 0.1 cd/m² luminance levels. Ave is the average reaction time, SD the standard deviation and M the total amount of missed flashes.*

L		Subject 01		Subject 02		Subject 03		Subject 04		Subject 06		All subjects		
(cd/m²)	C	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	M
10														
Red	0.000	260	31	297	53	334	50	271	28	276	24	288	47	1
	-0.051	269	44	295	44	376	64	268	33	283	42	298	61	2
	-0.100	317	58	355	57	502	165	336	65	357	74	369	108	4
Amber	0.100	254	26	278	32	320	44	267	32	264	26	277	40	1
	0.000	266	41	320	67	347	100	292	50	300	42	305	69	1
	-0.050	298	95	351	80	362	67	288	32	278	29	315	74	2
Green	0.100	249	30	284	40	304	32	267	32	285	52	277	42	2
	0.000	255	32	298	85	340	110	279	50	272	27	289	73	1
	-0.050	324	105	320	70	377	116	318	97	294	48	326	92	3
Cyan	0.100	272	90	275	41	295	32	288	72	258	20	277	58	1
	0.000	268	33	304	60	306	45	277	30	273	31	285	44	1
	-0.050	309	70	356	72	336	103	295	45	285	29	315	72	4
Blue	0.100	278	40	313	33	285	26	289	88	256	27	285	51	0
	0.000	297	56	336	49	309	37	273	33	271	34	297	48	1
	-0.050	379	97	432	144	342	133	307	42	285	23	349	112	1
1														
Red	0.011	305	45	335	46	363	52	343	52	303	48	330	53	0
	-0.019	317	69	338	48	401	106	352	73	315	36	344	76	1
	-0.047	326	49	366	46	404	76	395	116	358	93	370	84	2
Amber	0.008	303	63	321	45	365	51	395	96	334	79	343	75	2
	-0.013	296	27	376	109	406	124	375	90	372	96	365	100	1
	-0.034	348	105	395	108	407	98	453	168	336	56	386	117	4
Green	0.020	351	86	367	61	374	76	366	98	335	43	358	75	3
	0.010	356	76	349	63	405	132	387	116	342	57	367	95	2
	0.005	356	109	348	44	377	78	420	153	366	47	372	96	2
Cyan	0.019	324	56	340	47	371	61	375	86	344	71	351	67	7
	0.009	339	47	344	67	395	113	399	167	317	34	359	102	0
	0.004	338	66	360	59	386	160	367	86	339	66	358	94	3
Blue	0.099	355	63	354	42	313	35	312	69	294	40	326	56	1
	0.049	385	73	375	50	315	40	328	72	309	51	343	65	4
	0.020	476	155	431	88	362	81	334	49	321	50	384	110	3
0.1														
Red	0.302	372	93	350	40	437	100	349	40	386	42	379	75	1
	0.201	379	76	357	36	468	113	382	62	424	76	403	86	3
	0.100	423	98	431	113	484	94	491	124	549	144	474	122	13
Amber	0.398	351	106	346	49	411	61	389	106	435	71	386	87	3
	0.303	367	114	351	64	468	97	405	130	458	95	408	111	4
	0.201	414	125	361	49	542	141	410	66	470	118	434	120	22
Green	0.301	373	137	354	57	359	52	356	35	449	119	377	93	4
	0.202	411	154	359	49	384	65	427	123	474	119	406	112	9
	0.149	428	169	374	81	385	51	444	144	515	162	418	129	17
Cyan	0.400	456	166	342	40	385	52	359	48	361	62	380	93	4
	0.300	442	140	368	57	382	64	381	74	395	66	393	87	2
	0.199	501	171	412	82	403	74	415	110	492	119	439	117	11
Blue	0.399	547	154	441	84	380	59	349	56	351	53	411	113	5
	0.302	569	149	498	153	391	52	329	69	361	31	411	123	18
	0.199	684	181	465	130	433	85	388	66	428	110	457	140	19

Appendix 2 *Results of the reaction time measurements in peripheral vision (10°) at 10 cd/m², 1 cd/m², and 0.1 cd/m² luminance levels. Ave is the average reaction time, SD the standard deviation and M the total amount of missed flashes.*

L		Subject 01		Subject 02		Subject 03		Subject 04		Subject 06		All subjects		
(cd/m²)	C	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	M
10														
Red	0.200	277	28	301	44	329	47	261	25	269	28	287	43	0
	0.100	386	111	343	106	352	59	288	32	304	44	334	84	1
	0.049	486	152	448	181	459	193	337	45	330	57	410	152	6
Amber	0.200	277	33	312	71	323	40	284	60	281	32	296	52	0
	0.100	378	103	362	86	338	65	315	62	298	23	337	77	4
	0.050	448	120	539	243	429	144	479	198	371	113	451	173	21
Green	0.200	283	46	292	44	316	43	283	35	285	34	292	42	1
	0.121	388	149	362	125	346	82	310	50	296	39	340	103	0
	0.078	403	160	388	137	351	103	346	68	354	115	368	121	5
Cyan	0.151	261	22	279	64	312	44	279	29	267	35	279	44	0
	0.100	294	49	316	61	316	34	291	41	290	40	301	47	1
	0.050	325	113	365	124	344	134	315	65	318	47	333	103	1
Blue	0.050	265	24	287	47	298	39	282	42	264	32	279	39	0
	0.000	280	36	308	55	312	38	299	48	285	37	297	44	0
	-0.050	374	65	360	53	350	65	403	97	373	87	372	76	1
1														
Red	0.404	309	35	303	35	357	76	303	35	308	37	316	50	1
	0.302	349	69	340	40	362	63	330	45	345	55	345	55	4
	0.198	469	119	454	132	406	96	397	77	438	107	433	109	4
Amber	0.400	294	26	323	50	393	127	337	70	307	26	331	77	0
	0.301	335	39	374	91	376	103	347	67	361	99	359	84	2
	0.199	406	103	440	125	397	105	539	173	420	136	438	137	15
Green	0.298	300	25	339	65	340	35	343	50	346	50	334	50	3
	0.202	344	46	349	65	374	65	412	100	433	131	382	92	1
	0.102	557	164	548	223	447	138	616	204	491	161	521	179	57
Cyan	0.201	297	31	311	76	344	53	333	62	351	89	327	67	1
	0.102	390	100	404	108	363	47	420	145	420	154	399	116	5
	0.050	467	170	417	91	508	202	587	231	442	111	483	177	39
Blue	0.040	312	30	305	29	323	29	316	31	305	31	312	30	0
	0.021	323	48	332	47	334	42	354	102	323	49	333	62	0
	0.009	347	47	333	56	339	56	360	84	353	65	346	63	1
0.1														
Red	1.006	449	95	393	68	417	68	371	58	409	48	407	72	4
	0.905	482	102	405	48	429	66	399	59	467	90	434	80	5
	0.804	521	136	469	71	459	70	432	75	529	115	479	101	10
Amber	0.901	409	91	381	42	415	61	405	41	493	128	420	86	1
	0.796	470	159	405	43	457	121	418	70	503	114	450	112	3
	0.701	479	102	452	115	455	67	469	83	558	125	480	105	9
Green	0.505	368	44	353	35	384	56	364	39	441	75	381	59	2
	0.405	439	69	382	70	432	85	433	64	482	108	433	86	0
	0.296	483	148	417	73	474	115	530	127	617	196	490	137	21
Cyan	0.301	386	48	332	34	380	60	376	35	362	34	367	47	3
	0.200	444	75	351	31	397	48	406	83	395	64	398	68	1
	0.153	541	155	385	52	419	53	434	76	437	125	439	108	5
Blue	0.079	429	54	347	56	404	67	365	73	349	29	379	66	0
	0.051	477	80	384	73	397	40	384	63	385	53	405	72	1
	0.030	467	74	398	100	416	43	410	78	398	50	418	75	2

Appendix 3 *Results of the reaction time measurements in peripheral (10°) vision at 20 cd/m², 3 cd/m², and 0.3 cd/m² luminance levels. Ave is the average reaction time, SD the standard deviation and M the total amount of missed flashes.*

L		Subject 01		Subject 02		Subject 03		Subject 04		Subject 06		All subjects		
(cd/m²)	C	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	M
20														
Red	0.149	256	21	295	37	296	21	272	27	280	27	280	31	2
	0.100	289	52	331	44	305	30	288	41	320	55	306	47	2
	0.051	307	61	370	67	364	89	309	47	360	91	343	77	4
	0.000	436	123	453	77	482	176	382	70	473	169	444	140	32
Amber	0.150	267	35	288	38	311	24	302	148	289	35	292	73	3
	0.100	287	51	311	69	317	31	294	61	321	47	306	54	2
	0.051	407	138	398	138	371	133	424	155	456	204	411	155	6
	0.028	479	149	427	160	481	170	418	126	473	174	456	155	24
Green	0.150	250	38	289	26	314	53	273	33	288	37	283	43	2
	0.101	242	26	297	58	299	25	296	42	289	32	285	44	1
	0.049	313	144	339	107	318	36	316	45	330	65	323	88	1
	0.024	403	227	404	183	324	32	400	163	431	160	392	168	10
Cyan	0.150	247	34	291	55	299	25	278	39	300	32	283	42	0
	0.101	257	28	282	38	285	26	282	43	299	33	281	36	1
	0.051	318	107	351	94	313	39	288	51	327	55	319	75	3
	0.000	438	213	617	264	417	131	505	192	550	214	505	215	22
Blue	0.050	240	17	287	31	277	23	258	34	276	38	268	34	0
	0.000	245	23	292	35	293	20	273	34	303	40	281	37	0
	-0.050	301	35	350	71	319	33	355	70	399	117	344	78	1
	-0.076	423	89	507	119	526	166	503	148	577	142	504	143	16
3														
Red	0.400	272	35	293	30	317	49	275	26	271	25	286	38	1
	0.301	295	71	302	32	328	42	294	35	283	29	300	46	2
	0.201	321	45	333	74	337	36	295	48	298	19	317	51	2
	0.100	454	167	490	162	511	166	377	129	375	88	438	152	16
Amber	0.399	270	32	302	29	310	30	276	32	284	27	288	33	1
	0.297	268	21	300	37	307	30	276	34	280	20	286	32	0
	0.200	342	106	339	59	326	44	322	77	300	31	326	69	0
	0.150	417	137	359	44	406	125	379	77	337	54	379	98	5
Green	0.400	272	45	300	42	297	23	272	24	277	21	284	34	1
	0.300	291	39	294	28	320	33	276	37	280	23	292	35	1
	0.200	334	88	318	50	310	35	295	45	306	45	313	56	1
	0.100	507	181	408	139	411	142	427	147	454	139	441	152	8
Cyan	0.200	279	35	307	31	318	62	288	43	293	36	297	44	0
	0.151	308	77	297	29	297	21	273	37	280	38	291	46	0
	0.100	382	154	327	79	380	134	313	61	315	53	343	108	1
	0.050	520	169	392	89	366	118	368	131	413	135	406	137	10
Blue	0.100	270	32	291	27	292	25	285	54	283	30	284	36	0
	0.050	273	22	302	33	302	25	291	35	295	26	293	30	1
	0.020	304	55	310	33	301	26	304	54	294	22	303	40	0
	-0.020	387	60	328	50	335	64	333	63	340	52	344	61	1
0.3														
Red	0.700					352	45	320	60			336	54	0
	0.600					357	34	360	63			358	50	0
	0.497					390	68	371	58			381	63	2
Amber	0.600					331	29	335	49			333	40	0
	0.496					377	59	356	48			366	54	0
	0.403					379	50	414	99			397	79	0
Green	0.302					359	51	370	75			365	64	0
	0.201					391	74	477	144			434	121	0
	0.101					576	212	485	175			558	199	38
Cyan	0.298					330	31	311	37			320	35	0
	0.199					370	83	338	46			354	68	0
	0.099					434	155	398	105			415	131	4
Blue	0.019					376	127	320	31			348	96	0
	0.000					405	91	337	49			372	81	1
	-0.018					406	86	362	42			385	71	3

Appendix 4 *Results of the high-contrast reaction time measurements. Measurements were performed with green targets only. Ave is the average reaction time and SD is the standard deviation.*

L		Subject 01		Subject 02		Subject 03		Subject 04		Subject 06		All subjects	
(cd/m²)	C	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
Foveal													
10	2.13	209	26	243	35	258	23	238	28	231	21	236	31
1	3.62	208	12	254	33	273	30	246	28	247	32	246	35
0.1	3.62	241	24	275	41	300	22	272	24	262	24	270	33
Peripheral													
20	2.19	219	19	264	41	246	23	241	25	241	25	242	31
10	2.16	227	29	264	35	281	28	235	22	250	28	251	34
3	3.34	232	17	276	29	278	33	256	30	243	22	257	32
1	3.90	224	18	278	28	286	27	261	30	256	27	261	34
0.1	3.40	254	21	289	26	305	35	269	16	277	21	279	30

Appendix 5 *Results of the contrast threshold measurements at 10 cd/m² luminance level. Ave is the average reaction time and SD is the standard deviation.*

		0°		10°		30°		60°	
10 cd/m²	Subj.	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
Red	02	-0.1325	0.0015	-0.0589	0.0037	0.1424	0.0320	0.6063	0.0725
	03	-0.1326	0.0008	-0.0627	0.0017	0.1805	0.0187	0.7251	0.0832
	04	-0.1354	0.0003	-0.0966	0.0049	0.0123	0.0212	0.1918	0.0382
	05	-0.1183	0.0053	-0.0478	0.0121	0.1805	0.0246	0.7671	0.0792
	06	-0.1283	0.0019	0.0197	0.0139	0.1659	0.0275	0.3622	0.0278
	07	-0.1350	0.0000	-0.0589	0.0037	0.1278	0.0145	0.6966	0.0674
	08	-0.1313	0.0006	0.0177	0.0234	0.1911	0.0262	0.7874	0.1370
	13	-0.1350	0.0008	-0.0286	0.0076	0.1506	0.0473	0.7492	0.1632
	All	-0.1310	0.0057	-0.0395	0.0406	0.1439	0.0573	0.6107	0.2180
Green	02	-0.1047	0.0047	-0.0678	0.0056	0.1700	0.0188	0.5103	0.1033
	03	-0.1092	0.0011	-0.0398	0.0066	0.1585	0.0124	0.5062	0.0728
	04	-0.1082	0.0024	-0.0768	0.0069	0.1262	0.0583	0.5563	0.1568
	05	-0.0917	0.0060	-0.0169	0.0247	0.1902	0.0511	0.7306	0.0341
	06	-0.0994	0.0031	0.0586	0.0076	0.2244	0.0133	0.4821	0.0565
	07	-0.1116	0.0004	-0.0364	0.0056	0.1308	0.0137	0.5577	0.0875
	08	-0.1017	0.0008	-0.0081	0.0057	0.2057	0.0139	0.5927	0.1501
	13	-0.1145	0.0019	0.0559	0.0194	0.2529	0.0837	0.6128	0.0942
	All	-0.1051	0.0074	-0.0164	0.0509	0.1823	0.0445	0.5686	0.0791
Blue	02	-0.0877	0.0056	-0.1068	0.0024	-0.0370	0.0128	0.0809	0.0287
	03	-0.1059	0.0023	-0.0995	0.0009	-0.0371	0.0163	0.1109	0.0127
	04	-0.1171	0.0012	-0.1097	0.0029	-0.0723	0.0141	-0.0128	0.0147
	05	-0.1055	0.0030	-0.0930	0.0037	-0.0360	0.0067	0.2044	0.0403
	06	-0.0988	0.0021	-0.0560	0.0129	0.0129	0.0172	0.1203	0.0281
	07	-0.1021	0.0029	-0.0816	0.0016	-0.0343	0.0070	0.1563	0.0253
	08	-0.1176	0.0025	-0.0893	0.0060	-0.0395	0.0067	0.1930	0.0459
	13	-0.1081	0.0017	-0.1057	0.0091	0.0244	0.0294	0.1340	0.0365
	All	-0.1054	0.0097	-0.0927	0.0177	-0.0274	0.0311	0.1234	0.0688

Appendix 6 Results of the contrast threshold measurements at 1 cd/m² luminance level. Ave is the average reaction time and SD is the standard deviation.

		0°		10°		30°		60°	
1 cd/m²	Subj.	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
Red	02	-0.1188	0.0036	0.1327	0.0140	0.5655	0.1137	2.1176	0.4114
	03	-0.1177	0.0009	0.1811	0.0275	0.4609	0.0189	1.8632	0.0790
	04	-0.1184	0.0015	0.0384	0.0169	0.2813	0.0139	2.2544	0.1387
	05	-0.1041	0.0019	0.1674	0.0415	0.8570	0.0335	2.2180	0.2492
	06	-0.1055	0.0032	0.1700	0.0167	0.5475	0.0705	1.1306	0.1235
	07	-0.1235	0.0021	0.0431	0.0058	0.5214	0.0214	2.4267	0.0000
	08	-0.1051	0.0018	0.1763	0.0293	0.5582	0.0614	2.0351	0.3622
	13	-0.1183	0.0036	0.1808	0.0204	0.4235	0.0475	1.8405	0.2283
	All	-0.1139	0.0077	0.1362	0.0609	0.5269	0.1635	1.9858	0.3978
Green	02	-0.1391	0.0042	0.0536	0.0164	0.3359	0.0195	0.8907	0.1019
	03	-0.1312	0.0011	0.0825	0.0079	0.3815	0.0192	0.7755	0.0342
	04	-0.1335	0.0029	0.0872	0.0239	0.3191	0.0273	0.7471	0.1010
	05	-0.1299	0.0051	0.1172	0.0185	0.3604	0.0881	0.8689	0.0629
	06	-0.1246	0.0050	0.1472	0.0265	0.3851	0.0682	0.6359	0.0747
	07	-0.1287	0.0031	0.0864	0.0000	0.3443	0.0169	0.8030	0.1465
	08	-0.1101	0.0019	0.1366	0.0197	0.3624	0.0192	0.9591	0.1739
	13	-0.1338	0.0013	0.1524	0.0271	0.3741	0.0493	0.9511	0.0957
	All	-0.1289	0.0087	0.1079	0.0357	0.3579	0.0232	0.8289	0.1100
Blue	02	-0.0789	0.0113	-0.0702	0.0042	-0.0531	0.0159	0.0699	0.0183
	03	-0.0859	0.0032	-0.0682	0.0035	-0.0426	0.0096	0.0808	0.0087
	04	-0.1123	0.0015	-0.0675	0.0108	-0.0847	0.0060	0.0358	0.0163
	05	-0.0907	0.0030	-0.0669	0.0074	-0.0522	0.0043	0.0493	0.0225
	06	-0.0757	0.0060	-0.0363	0.0085	-0.0233	0.0126	0.0631	0.0240
	07	-0.0943	0.0028	-0.0635	0.0063	-0.0535	0.0119	0.0977	0.0219
	08	-0.1191	0.0026	-0.0682	0.0035	-0.0326	0.0069	0.1241	0.0266
	13	-0.1002	0.0059	-0.0587	0.0074	-0.0280	0.0115	0.0691	0.0452
	All	-0.0947	0.0153	-0.0624	0.0112	-0.0462	0.0195	0.0737	0.0276

Appendix 7 *Results of the contrast threshold measurements at 0.1 cd/m² luminance level. Ave is the average reaction time and SD is the standard deviation.*

		0°		10°		30°		60°	
0.1 cd/m²	Subj.	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
Red	02	-0.0084	0.0155	0.6765	0.0557	2.1574	0.1465	8.0016	0.4532
	03	-0.0465	0.0145	0.3798	0.0234	1.6235	0.1447	6.1643	0.4594
	04	-0.0466	0.0073	0.4621	0.0982	1.1036	0.2438	8.7254	1.2714
	05	-0.0331	0.0213	0.3915	0.0853	2.2471	0.1045	8.4190	0.6990
	06	0.0212	0.0053	0.5805	0.0390	1.9344	0.1702	3.7249	0.2887
	07	-0.0443	0.0085	0.4616	0.0270	1.2748	0.1413	5.6057	0.3466
	08	-0.0377	0.0126	0.5567	0.0829	1.1027	0.1398	4.6120	0.2078
	13	-0.0639	0.0159	0.5805	0.0677	1.6680	0.1698	8.9780	0.8383
	All	-0.0324	0.0268	0.5112	0.1038	1.6389	0.4526	6.7789	2.0208
Green	02	-0.0097	0.0255	0.1523	0.0248	0.3100	0.1241	1.4427	0.2822
	03	-0.0392	0.0086	0.1718	0.0148	0.5067	0.0354	1.1533	0.1522
	04	-0.0429	0.0074	0.1968	0.0488	0.4536	0.0409	1.6655	0.1777
	05	0.0050	0.0143	0.2224	0.0145	0.5943	0.0902	1.5707	0.2161
	06	0.0595	0.0205	0.2596	0.0286	0.7493	0.0338	1.1855	0.1966
	07	-0.0429	0.0074	0.1908	0.0318	0.4713	0.0354	1.7906	0.1013
	08	-0.0207	0.0186	0.2472	0.0321	0.6636	0.0888	1.4751	0.2448
	13	-0.0730	0.0229	0.4217	0.0863	0.6631	0.1181	1.9742	0.1491
	All	-0.0205	0.0401	0.2328	0.0845	0.5515	0.1426	1.5322	0.2819
Blue	02	0.0763	0.0190	-0.0623	0.0147	-0.0706	0.0133	0.1251	0.0450
	03	-0.0098	0.0118	-0.0458	0.0046	-0.0198	0.0075	0.1403	0.0149
	04	-0.0674	0.0157	-0.0359	0.0039	-0.0507	0.0196	0.2397	0.0613
	05	-0.0069	0.0028	-0.0398	0.0076	-0.0087	0.0121	0.2122	0.0423
	06	0.0227	0.0251	-0.0399	0.0099	0.0096	0.0072	0.1476	0.0241
	07	-0.0285	0.0060	-0.0478	0.0078	-0.0050	0.0073	0.2123	0.0353
	08	-0.0982	0.0069	-0.0148	0.0043	-0.0125	0.0188	0.2544	0.0138
	13	-0.0042	0.0143	-0.0022	0.0217	0.0024	0.0073	0.1698	0.0279
	All	-0.0145	0.0532	-0.0361	0.0191	-0.0194	0.0275	0.1877	0.0485