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EFFECTS OF LIGHTING PARAMETERS ON CONTRAST THRESHOLD IN THE MESOPIC AND PHOTOPIC LUMINANCE RANGES

Jaakko Ketomäki

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Author	Jaakko Ketomäki
Name of the dissertation	Effects of lighting parameters on contrast threshold in mesopic and photopic luminance range

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Opponent(s)	Dr. Mike Pointer
Supervisor	Prof. Liisa Halonen

The first objective of this thesis was to find out how the background luminance level, spectra of the background and stimulus, and eccentricity of the stimulus affect contrast thresholds in the mesopic luminance range. The background luminance levels used were between L_B=0.01...20 cd/m^2. They cover the typical luminance levels of road lighting. The spectra of the background and stimulus were broadband white, blue, green, and red. The measurements were made at eccentricities of 0 and 10°. The results of this thesis confirmed that when the photopic background luminance level decreases from L_B=10 cd/m^2 to L_B=0.01 cd/m^2 the contrast threshold increases at stimulus eccentricities of both 0 and 10°. It was found that the contrast threshold increased the least with blue and the most with red background spectra when the background and stimulus had the same spectrum. When the background was white, the contrast threshold increased the least with blue and the most with red stimulus spectra. The results show that the spectral sensitivity of the eye is shifted towards shorter wavelengths when photopic background luminance levels are reduced from L_B=10 to L_B=0.01 cd/m^2.

The second objective was to find out the differences in the contrast threshold when a white or coloured background spectrum was used. It was found that the differences between the contrast thresholds measured with different stimuli and background spectra were larger when the measurements were taken with a coloured stimulus and a white background.

The measured contrast thresholds were applied to existing models for mesopic spectral sensitivity. The goal was to find out if the models describe the mesopic contrast threshold in the same way for different stimulus and background spectra. The models used were Palmer's model [Palmer 1968], the X model [Rea et al 2004], and the MOVE model [Eloholma and Halonen 2005]. It was found that all the models used describe the spectral sensitivity at an eccentricity of 10° at the photopic background luminance levels L_B=0.01...10 cd/m^2 better than the photopic spectral luminous efficiency function V(λ), when contrast threshold is used as a visual task. It was found that the MOVE model describes the mesopic contrast threshold best at the photopic background luminance levels L_B=0.01...3 cd/m^2 when a white background and a coloured stimulus were used.

Keywords	contrast threshold, mesopic vision, peripheral vision, mesopic spectral sensitivity, models for mesopic vision		
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Tekijä	Jaakko Ketomäki
Väitöskirjan nimi	Valaistusparametrien vaikutus kontrastikynnykseen mesoopisella ja fotooppisella luminanssialueella

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Väitöskirjan ensimmäisenä tavoitteena oli selvittää, kuinka taustan luminanssitaso, taustan spektri ja ärsykkeen epäkeskeisyys vaikuttavat kontrastikynnykseen mesoopisella luminanssialueella. Käytetyt taustan luminassit olivat välillä L_B=0.01...20 cd/m^2. Nämä luminanssitasot käsittivät tyypilliset tievalaistuksessa esiintyvät luminanssitasot. Taustan ja ärsykkeen spektrit olivat laajakaistaiset sininen, vihreä ja punainen. Mittaukset tehtiin 0 ja 10° epäkeskisyyksillä. Väitöskirjan tulokset vahvistivat sen, että taustan luminanssitason laskiessa arvosta L_B=10 cd/m^2 arvoon L_B=0.01 cd/m^2 kontrastikynnys nousee sekä 0 että 10° epäkeskisyyksillä. Tuloksista nähtiin myös, että kontrastikynnys kasvaa vähiten sinisellä ja eniten punaisella taustan spektrillä kun taustan ja ärsykkeen spektrit olivat samat. Kun tausta oli valkoinen, kasvoi kynnyskontrasti vähiten sinisellä ja eniten punaisella ärsykkeellä. Tuloksista voitiin nähdä, että silmän spektriherkkyys siirtyy kohti lyhyitä aallonpituuksia kun taustan luminanssitaso laskee arvosta L_B=10 cd/m^2 arvoon L_B=0.01 cd/m^2.

Toinen tavoite oli selvittää, onko kynnyskontrastissa eroja kun taustan spektri oli valkoinen tai värillinen. Tuloksista nähtiin, että erot kontrastikynnyksissä olivat suuremmat, kun mittaukset oli tehty värillisellä ärsykkeellä ja valkoisella taustalla.

Mitattuja kontrastikynnyksiä sovellettiin olemassa oleviin mesoopisiin malleihin. Tavoitteena oli selvittää, kuvaavatko mallit mesoopisia kontrastikynnyksiä samalla tavalla kun taustan ja ärsykkeen spektrit ovat samanlaiset ja kun ne olivat erilaiset. Sovelletut mallit olivat Palmerin malli [Palmer 1968], X-malli [Rea et al 2004] ja MOVE-malli [Eloholma ja Halonen 2005]. Tuloksista nähdään, että sovelletut mallit kuvaavat mesoopista spektriherkkyyttä 10° epäkeskisyydellä taustan luminanssitasoilla L_B=0.01...10 cd/m^2 paremmin kuin fotooppinen silmän spektriherkkyysfunktio V(λ) kun kontrasti kynnystä käytetään näkötehtävänä. Tuloksista nähdään myös, että MOVE-malli kuvaa mesoopista kontrastikynnystä parhaiten taustan luminanssitasoilla L_B=0.01...3 cd/m^2 kun tausta on valkoinen ja ärsyke on värillinen.

Avainsanat	kontrastikynnys, mesooppinen näkeminen, ääreisnäkö, mesooppinen spektriherkkyys, mesooppinen malli		
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Preface

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My dear wife Joaniina I thank for supporting me during the whole dissertation process and for being the best possible person for me to live with. Many thanks also go to my son Elias who really showed that there is life outside the academic world. I would also like to thank my parents for supporting me during my studies and my whole life.

Finally, I want to thank the Lord who has created a very interesting world for us and given me this opportunity to investigate it.

Espoo, August 2006

Jaakko Ketomäki

Contents

Symbols and abbreviations

λ	wavelength
δ_B	uncertainty of the background luminance
δ_{BS}	uncertainty of the luminance difference between the stimulus and the background
δ_C	uncertainty of the contrast of the stimulus
τ_{gap}	transmittance of the adjustable gap
ΔL_{actual}	luminance difference between the target and its background when calculating the visibility level
ΔL_{SB}	luminance difference between the stimulus and the background
$\Delta L_{threshold}$	luminance difference needed between a target of a certain angular size and its background for the target to be just visible when calculating the visibility level
τ_{ND}	transmittance of the neutral density filter
a	constant in the mesopic MOVE model [Eloholma and Halonen 2005]
ANOVA	analysis of variance
a_P	parameter in Palmer's model [Palmer 1968]
b	constant in the mesopic MOVE model [Eloholma and Halonen 2005]
C	contrast, photopic contrast
C_{actual}	contrast between the target and its background when calculating the visibility level
CCD	Charge-Coupled Device
CEN	Comité Européen de Normalisation, European Committee of Standardisation
CIE	Commission Internationale de l'Éclairage, International Commission on Illumination
C_{mes}	mesopic contrast
cpd	cycles per degree
$C_{threshold}$	contrast needed between a target of a certain angular size and its background for the target to be just visible when calculating the visibility level
C_{tr}	contrast threshold
d	gap size
E_0	illuminance value without the neutral density filter
E_{ND}	illuminance value with the neutral density filter
F	correction factor of the close-up lens of the LMT 1009 luminance meter
k	coefficient in the model of peripheral spectral luminous efficiency [Orreveteläinen 2005]
k_1	normalisation constant in He et al's [1997] model for mesopic spectral sensitivity
K_m	luminous efficacy of radiation
L_{10}	large-field photopic luminance, luminance based on $V_{10}(\lambda)$
L_B	luminance of the background
$L_{B, mes}$	mesopic background luminance
$L_{e,\lambda}$	corresponding spectral concentration of radiance

L_{gap}(4 mm)	stimulus luminance at adjustable gap in position d=4 mm
L_{gap}(d)	luminance of the stimulus at gap size d
L_{mes}	mesopic luminance, luminance based on $V_{mes}(\lambda)$
LMT	Lichtmetechnik GmbH Berlin
L_P	luminance, photopic luminance
L_S	scotopic luminance, luminance based on V'(λ)
Matlab	a mathematical computer program
M(x)	normalising function in the MOVE model [Eloholma and Halonen 2005]
MOVE model	model for mesopic spectral sensitivity [Eloholma and Halonen 2005]
M_{P1}	parameter in Palmer's [Palmer 1968] model for mesopic spectral sensitivity
M_{P2}	parameter in Palmer's [CIE 2001] model for mesopic spectral sensitivity
NPL	National Physical Laboratory,
p	probability value
PMMA	optical fibre whose material is polymethylmethacrylate (acrylic)
S/P ratio	ratio of scotopic and photopic luminous output
Td	troland
V(λ)	photopic spectral luminous efficiency function
V(555)	value of photopic spectral luminous efficiency function at λ=555 nm
V'(λ)	scotopic spectral luminous efficiency function
V'(555)	value of scotopic spectral luminous efficiency function at λ=555 nm
$V_{10}(\lambda)$	photopic spectral luminous efficiency function for a 10° field
VL	visibility level
$V_M(\lambda)$	photopic spectral luminous efficiency function with Judd-Vos modification
$V_{mes}(\lambda)$	mesopic spectral luminous efficiency function
$V_{per}(\lambda)$	peripheral spectral luminous efficiency function
x	parameter in the mesopic MOVE model [Eloholma et al 2005]
X	parameter in the mesopic X model [Rea et al 2004]
x(λ)	CIE 2° colour matching function
X_{10}	CIE 1964 tristimulus value
$x_{10}(\lambda)$	CIE 10° colour matching function
x_{He}	parameter in He et al's [1997] model for mesopic spectral sensitivity
x_k	estimate for x in the mesopic MOVE model [Eloholma and Halonen 2005]
x_{k+1}	estimate for x in the mesopic MOVE model [Eloholma and Halonen 2005]
X model	model for mesopic spectral sensitivity [Rea et al 2004]
y(λ)	CIE 2° colour matching function
Y_{10}	CIE 1964 tristimulus value
$y_{10}(\lambda)$	CIE 10° colour matching function
z(λ)	CIE 2° colour matching function
Z_{10}	CIE 1964 tristimulus value
$z_{10}(\lambda)$	CIE 10° colour matching function

Definitions

Brightness is an attribute of a visual sensation according to which an area appears to emit more or less light [SFS 1992].

Contrast is a ratio between the difference of the luminances of the stimulus and the background and luminance of the background, as shown in Equation (14).

Contrast threshold is the smallest contrast produced in the eye of an observer by a given object which renders the object perceptible against a given background [SFS 1992]. In the measurements of this thesis the object is the stimulus in the modified Goldman perimeter and the background is the background of the modified Goldman perimeter.

Large-field photopic luminance is a radiance weighted by the large-field photopic spectral luminous efficiency function $V_{10}(\lambda)$.

Luminance is a radiance weighted by the photopic spectral luminous efficiency function $V(\lambda)$, as shown in Equation (1).

Mesopic contrast is the ratio between the difference of the mesopic luminances of the stimulus and the background and mesopic luminance of the background.

Mesopic contrast threshold is a contrast threshold which is defined using the difference between the mesopic luminances of the stimulus and the background and the mesopic luminance of the background.

Mesopic luminance range is the luminance range in which both rods and cones are active. CIE has defined this as between about 0.001 cd/m^2 to 'several cd/m^2'

Mesopic luminance is a radiance weighted by the mesopic spectral luminous efficiency function $V_{mes}(\lambda)$. Mesopic luminance could be approximated using a model for mesopic spectral sensitivity.

Peripheral contrast threshold is a contrast threshold which is defined using the peripheral spectral luminous efficiency function instead of the photopic spectral luminous efficiency function.

Photopic contrast is used instead of 'contrast' when it is presumable that there could be confusion between photopic and mesopic contrasts.

Photopic contrast threshold is used instead of 'contrast thresholds' when it is presumable that there could be a confusion between contrast thresholds and the mesopic contrast threshold.

Photopic luminance is used instead of 'luminance' when it is presumable that there could be confusion between photopic luminance and mesopic, large-field photopic, or scotopic luminances.

Photopic luminance range is the luminance range in which only cones are active. CIE has defined this as luminances above 'several cd/m^2' [CIE 1978].

Scotopic luminance is a radiance weighted by the scotopic spectral luminous efficiency function $V'(\lambda)$.

Scotopic luminance range is the luminance range in which only rods are active. CIE has defined this as luminance levels below about 0.001 cd/m^2 [CIE 1978]

1 Introduction

1.1 Background

In the photopic luminance range the spectral sensitivity of the eye can be described by the photopic spectral luminous efficiency function V(λ). When luminances are in the scotopic luminance range, the spectral sensitivity of the eye can be described by the scotopic spectral luminous efficiency function V'(λ). Between the scotopic and photopic luminance range there is the mesopic luminance range. According to the Commission Internationale de l'Éclairage (International Commission on Illumination, CIE), the lower luminance limit of the mesopic luminance range is about 0.001 cd/m^2 and the upper limit is 'at least several cd/m^2' [CIE 1978].

The photopic spectral luminous efficiency function V(λ) and the scotopic spectral luminous efficiency function V'(λ) describe the spectral sensitivity of the eye when either the cone or the rod photoreceptors, respectively, are active. Thus neither of them alone describes the spectral sensitivity of the eye in the mesopic luminance range, when both rods and cones are active. Because of the different spectral sensitivities of the rods and cones, the spectral sensitivity of the eye in the mesopic luminance range is a function of the luminance level at eccentricities outside the fovea. Because the distribution of the rods and cones is different in different parts of the retina, the spectral sensitivity of the eye in the mesopic luminance range is also dependent on the eccentricity [Wald 1945a, Wooten et al 1975]. The maximum values of the photopic spectral luminous efficiency function V(λ) and the scotopic spectral luminous efficiency function V'(λ) are at the wavelengths 555 and 507 nm correspondingly. In passing from the photopic to the mesopic or scotopic luminance range, the spectral sensitivity of the eye changes and the wavelength of maximum sensitivity is displaced towards shorter wavelengths. This is known as the Purkinje phenomenon [SFS 1992].

Mesopic conditions can be found in e.g. road and outdoor lighting, in navigation, and in emergency lighting. The CEN standard [EN 13201] recommends that the average luminance of the road surface is in the range 0.3...2 cd/m^2. The problem is that the definition of luminance is based on the photopic spectral luminous efficiency function V(λ), although it is known that the spectral sensitivity of the eye differs from V(λ) in the mesopic luminance range [Kinney 1958, Palmer 1967]. The spectral sensitivity of the eye in the mesopic luminance range could be defined using a model for mesopic spectral sensitivity.

CIE has not standardised spectral luminous efficiency functions for mesopic photometry. In many studies mesopic spectral sensitivity has been defined using the brightness matching method. In a CIE report [CIE 2001] the models for mesopic spectral sensitivity of Palmer [Palmer 1968, CIE 2001], Sagawa and Takeichi [1992], Nakano and Ikeda [CIE 1989, CIE 2001], Kokoschka and Bodmann [CIE 2001], and Trezona [Trezona 1987] have been compared. These models were based on brightness matching measurements.

Another way to study mesopic spectral sensitivity is to use performance-based methods. These methods are based on visual tasks, which are closer to realistic visual tasks than brightness matching. In this work four performance-based models for mesopic spectral sensitivity are presented [He et al 1997, He et al 1998, Rea et al 2004, Eloholma and Halonen 2005].

In this thesis mesopic vision is studied by measuring the contrast threshold. The contrast threshold is defined as "the smallest contrast produced in the eye of an observer by a given object which renders the object perceptible against a given background" [SFS 1992]. The contrast threshold was selected because it is among the fundamental visual tasks in driving [Lamble et al 2002]. Current road lighting design practice [Adrian 2004, Raynhamn 2004] is broadly based on the concept of visibility, which is basically defined by the contrast threshold.

It is known that when the adaptation luminance decreases the contrast threshold increases [Blackwell H.R 1946, Blackwell O.M. and Blackwell H.R. 1971]. This is also true for coloured stimuli [Pearson and Swanson 2000]. In the mesopic luminance range the mesopic luminance differs from the photopic luminance. Because the contrast threshold is dependent on the photopic luminance level, it is a good indicator when studying mesopic spectral sensitivity. Eloholma et al [2004] found in simulated road lighting conditions that the light spectrum has an effect on the visibility of a pedestrian. Lewis [1999] performed experiments using light sources used for general outdoor lighting and found that the spectral distribution has an effect on the contrast threshold at mesopic luminance levels. Bodrogi et al [2003] studied the spectral sensitivity of the eye at mesopic luminance levels by making contrast threshold measurements with quasi-monochromatic stimuli.

1.2 Objectives of the work

The first objective of this thesis was to find out how the background luminance level, background spectra, stimulus spectra and eccentricity of the stimulus affect contrast thresholds in the mesopic luminance range. The background luminance levels were selected so as to cover the typical luminance levels of road lighting. The spectra of the stimuli were broadband.

The second objective was to find out the differences in the contrast threshold when a white or coloured background spectrum was used. This was a new approach to the study of the behaviour of contrast thresholds under viewing conditions simulating the conditions encountered in road lighting.

The third objective was to apply the measured contrast thresholds to three existing models for mesopic spectral sensitivity and find out if there are differences between the models and whether they describe the mesopic contrast threshold in the same way for different stimuli and background spectra.

2 State of the art

2.1 Current spectral luminous efficiency functions

The CIE published the photopic spectral luminous efficiency function V(λ) in 1926 [CIE 1926]. It was based on the results presented in Gibson and Tyndall's [1923] publication. Both brightness matching and flicker photometry were used when defining the photopic spectral luminous efficiency function V(λ). The photopic spectral luminous efficiency function V(λ) was finally standardised by CIE in 2004 [CIE 2004].

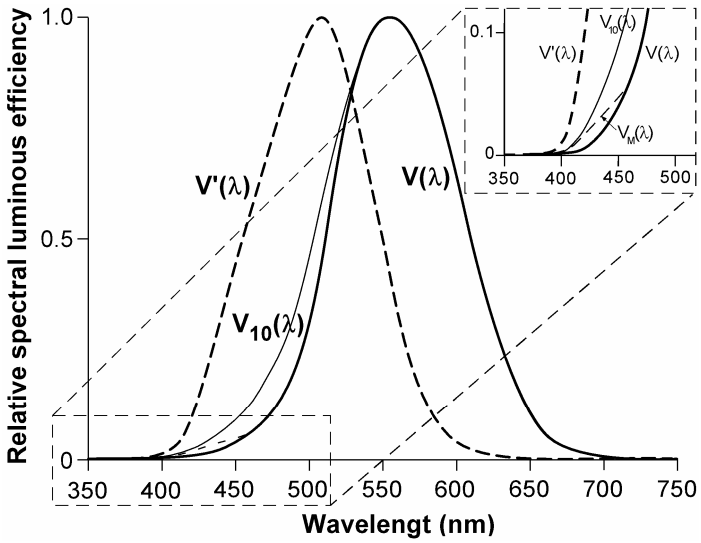

Figure 1. The spectral luminous efficiency functions $V(\lambda)$, $V_{10}(\lambda)$, $V_M(\lambda)$ and $V'(\lambda)$.

The photopic spectral luminous efficiency function V(λ) describes the spectral sensitivity of the 2° foveal field in the photopic luminance range. All lighting measurements, such as the measurement of luminance and illuminance, are based on the photopic spectral luminous efficiency function V(λ).

The CIE [1964] has also published the spectral luminous efficiency function for 10° field $V_{10}(\lambda)$. The photopic spectral luminous efficiency function for 10° field $V_{10}(\lambda)$ has higher spectral sensitivity values in the blue part of the spectrum, in comparison to V(λ). There are three types of cones on the retina. They are active at the photopic and mesopic luminance levels. These cone types are called S-, M-, and L-cones, and they are sensitive to short-, middle-, and long-wavelength light respectively. In the middle part of the fovea, where the density of the cones is highest, there are no S-cones [Calkins 2001, Curcio et al 1991]. Around the central part of the retina the ratio of S-cones to the total amount of cones is lower than at the peripheral parts of the retina [Curcio et al 1991]. This causes differences between the photopic spectral luminous efficiency function V(λ) and photopic spectral luminous efficiency function for 10° field $V_{10}(\lambda)$.

In 1990 the CIE published another function for photopic vision for the 2° foveal field [CIE 1990]. This function, known as the photopic spectral luminous efficiency function with Judd-Vos modification $V_M(\lambda)$, is based on the studies of Judd [1951]. Vos [1978] revised Judd's results. The photopic spectral luminous efficiency function with Judd-Vos modification $V_M(\lambda)$ has higher spectral sensitivity values at the wavelengths λ=380...460 nm than the photopic spectral luminous efficiency function V(λ).

For the scotopic luminance range the CIE [1951] has published the scotopic spectral luminous efficiency function V'(λ). It is based on two different studies. Wald [1945b] used the detection threshold method and Crawford [1949] used direct brightness matching. The spectral luminous efficiency functions V(λ), $V_M(\lambda)$, $V_{10}(\lambda)$, and V'(λ) are presented in Figure 1.

2.2.1 Background

The definition of luminance (also called photopic luminance in this thesis), marked as $L_{P,}$ is [CIE 2004]

$$L_P = K_m \int_0^\infty L_{e,\lambda} \cdot V(\lambda) d\lambda \quad (1)$$

where L_P is the luminance [cd/m^2], K_m is the luminous efficacy of radiation [683 lm/W], $L_{e,\lambda}$ is the corresponding spectral concentration of radiance [W/m^2, nm], and $V(\lambda)$ is the photopic spectral luminous efficiency function.

If the photopic spectral luminous efficiency function for 10° field $V_{10}(\lambda)$ is used instead of $V(\lambda)$ in Equation (1), the result is known as large-field photopic luminance [CIE 2001] and if the scotopic spectral luminous efficiency function $V'(\lambda)$ is used instead of $V(\lambda)$ in Equation (1), the result is known as scotopic luminance. In this thesis they are indicated as L_{10} and L_S correspondingly.

The spectral sensitivity of both rods and cones must be taken into consideration when defining the mesopic luminance (marked as L_{mes}). Many models for mesopic luminance have been developed during recent decades. In this thesis ten models for mesopic spectral sensitivity are presented. These models are Palmer's first model [Palmer 1968], Palmer's second model [CIE 2001], Sagawa and Takeichi's model [Sagawa and Takeichi 1992], Nakano and Ikeda's model [CIE 1989, CIE 2001], Kokoschka-Bodmann's model [CIE 2001], Trezona's model [Trezona 1987], the first model of He et al [He et al 1997], the second model of He et al [He et al 1998], the X model [Rea et al 2004], and the MOVE model [Eloholma and Halonen 2005].

The models for mesopic spectral sensitivity can be categorised according to the research method used. The models of Palmer [Palmer 1968, Palmer 1981], Sagawa and Takeichi [1992], Nakano and Ikeda [CIE 1986, CIE 2001], Kokoschka-Bodmann [CIE 2001], and Trezona [1987] are based on heterochromatic brightness matching. In heterochromatic brightness matching one half of a bipartite field is illuminated with a reference light and the other half is illuminated with a test light. The subject's task is to adjust the intensity of the test light in such a manner that the brightnesses of the test light and the reference light are equal.

The models of He et al [1997] and He et al [1998], the X model [Rea et al 2004], and the MOVE model [Eloholma and Halonen 2005] are performance-based models. These models are based on measurements with realistic visual tasks, e.g. reaction time, contrast threshold, or visual acuity.

2.2.2 Models based on heterochromatic brightness matching

Palmer [1968] developed his first model for mesopic spectral sensitivity using heterochromatic brightness matching with bipartite central visual fields sized 5, 15, and 45° at the photopic luminance levels 0.316, 0.0316, 0.00316, and 0.000316 cd/m^2 [Palmer 1967]. The defined mesopic luminance is calculated as a combination of large-field photopic luminance and scotopic luminance:

$$L_{mes} = \frac{M_{P1} L_S + L_{10}^2}{M_{P1} + L_{10}} \tag{2}$$

where L_{mes} is the mesopic luminance [cd/m^2], L_S is the scotopic luminance [cd/m^2], L_{10} is the large-field photopic luminance [cd/m^2], and M_{P1} is a parameter [cd/m^2] which gets the value M_{P1}=0.0143 cd/m^2 for a 5° field size, M_{P1}=0.0628 cd/m^2 for a 15° field size, and M_{P1}=0.123 cd/m^2 for a 45° field size. In the CIE report [CIE 2001] Equation (2) is simplified and is presented in the form

$$\begin{aligned} L_{mes} &= a_P \times L_s + (1 - a_P) \times L_{10} \\ a_P &= \frac{M_{P1}}{L_{10} + M_{P1}} \end{aligned} \tag{3}$$

where L_{mes} is the mesopic luminance [cd/m^2], L_S is the scotopic luminance [cd/m^2], and L_{10} is the large-field photopic luminance [cd/m^2], a_P is a parameter, and M_{P1} is a parameter [cd/m^2]. It can be seen from Equation (3) that Palmer's first model [Palmer 1968] is a weighted mean of the scotopic and large-field photopic luminances.

Palmer's second model [CIE 2001] is an improved version of his first model [Palmer 1968]. The information concerning Palmer's second model [1981] is taken from the CIE report [2001] because the original reference was not available. In Palmer's second model the mesopic luminance is a function of the large-field photopic luminance and the scotopic luminance, as in his first [1968] model. The equation in Palmer's second model [CIE 2001] is

$$L_{mes} = \sqrt{M_{P2} L_s} + L_{10} + \frac{M_{P2}}{2} - \sqrt{M_{P2} \sqrt{M_{P2} L_{10}} + L_{10} + \frac{M_{P2}}{4}} \tag{4}$$

where L_{mes} is the mesopic luminance [cd/m^2], M_{P2} is a parameter [cd/m^2], L_S is the scotopic luminance [cd/m^2], and L_{10} is the large-field photopic luminance [cd/m^2]. The parameter M_{P2} gets a value of 0.06 cd/m^2 for a 10° field size.

Sagawa and Takeichi [1992] developed their model on the basis of brightness matching using a 10° bipartite field, fixated foveally at nine retinal illuminance levels between 0.01....100 Td. The model is based on the geometric mean of the photopic and scotopic equivalent luminances $L_{eq.p}$ and $L_{eq.s}$. These equivalent luminances are calculated using the CIE 2° colour matching functions $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ and the scotopic spectral luminous efficiency function $V'(\lambda)$. Thus the input values are different than in Palmer's first [Palmer 1968] and second [CIE 2001] models. Another difference between Palmer's models [Palmer 1968, CIE 2001] and Sagawa and Takeichi's [1992] models is that in the model of Sagawa and Takeichi [1992] the weighting factor between photopic and scotopic luminances is a function of the mesopic luminance L_{mes}. Thus the calculation of the mesopic luminance L_{mes} needs iteration.

Nakano and Ikeda [CIE 1989, CIE 2001] made their brightness matching measurements using a bipartite 10° foveally fixated field at the retinal illuminance levels 0.01, 0.1, 1, 10, and 100 Td. The original references [Nakano and Ikeda 1986, Nakano 1992] are in Japanese, so the information concerning Nakano and Ikeda's model is taken from the CIE [1989, 2001] reports. Each test light in Nakano and Ikeda's studies was a combination of two monochromatic lights. White light was used as a reference

light. The model of Nakano and Ikeda combines the photopic and scotopic luminances using non-linear equations. The parameters in the equations are calculated using the CIE 10° colour matching functions $x_{10}(\lambda)$, $y_{10}(\lambda)$, and $z_{10}(\lambda)$ and the scotopic spectral luminous efficiency function $V'(\lambda)$.

Kokoschka and Bodmann's [CIE 2001] model uses the CIE 10° colour matching functions $x_{10}(\lambda)$, $y_{10}(\lambda)$, and $z_{10}(\lambda)$ and the scotopic luminance as input values. The brightness matching method was used with 3, 9.5, and 64° field sizes at the retinal illuminance levels 0.003...30 Td. The original reference for the model of Kokoschka and Bodmann [1975] was available only in German, so the information concerning the model is taken from the CIE [2001] report.

Trezona's [Trezona 1987] model uses the CIE 10° colour matching functions $x_{10}(\lambda)$, $y_{10}(\lambda)$, and $z_{10}(\lambda)$.Trezona's model is based on brightness matching. In the experiment she used a 10° bipartite field and photopic luminance levels from the photopic luminance range to the absolute threshold. The reference field was illuminated using 588-nm monochromatic light. 17 monochromatic and 24 non-monochromatic lights were used as the test field.

In the CIE report [CIE 2001] the previous six models for mesopic spectral sensitivity based on brightness matching are compared. The models were applied to the brightness matching data measured in seven different laboratories. The conclusion was that all the models compared for mesopic spectral sensitivity gave a better estimation of brightness at mesopic luminance levels than the use of the current spectral luminous efficiency functions alone. However, the criterion of agreement with experimental data did not permit a choice to be made from among the systems.

2.2.3 Performance-based models

Berman and Clear [2001] criticised the brightness matching method in the mesopic luminance range as being difficult and imprecise. Kaiser and Wyszecki [1978] found additivity failures in the photopic luminance range in their measurements when brightness matching was used. The spectral luminous efficiency function $V(\lambda)$ was partly based on measurements made with flicker photometry. In flicker photometry the test and reference light are presented one after the other at high frequency. Because the critical flicker fusion frequency of colours is lower than the critical flicker fusion frequency of brightness [Kelly and Norren 1977], the subject's task is only to adjust the brightness of the test light so that the flicker is not detectable. Although flicker photometry works well at photopic light levels [Viénot and Chiron 1991], it is not useful at mesopic levels, because the rods and cones have different critical flicker fusion frequencies for colour and brightness [Forrester et al 1996].

During the last decade performance-based models for mesopic spectral sensitivity have been introduced [He et al 1997 and 1998, Rea et al 2004, Eloholma and Halonen 2005]. These models are based on studies of spectral sensitivity in which realistic visual tasks, such as detection threshold, reaction time, and visual acuity are performed.

He et al [1997] developed their model by measuring reaction times at eight photopic luminance levels between 0.003...10 cd/m^2 under high-pressure sodium and metal halide lamp spectra. The 2° stimulus was presented at eccentricities of 0 and 15°. The subject's task was to react as fast as possible to an unexpectedly-appearing stimulus.

The model is based on the combination of the spectral luminous efficiency function for 10° field $V_{10}(\lambda)$ and the scotopic spectral luminous efficiency function $V'(\lambda)$. The basic equation of the model is

$$V_{mes}(\lambda) = k_{He}\left(x_{He} \cdot V_{10}(\lambda) + (1 - x_{He}) \cdot V'(\lambda)\right) \tag{5}$$

where $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function, $V_{10}(\lambda)$ is the photopic spectral luminous efficiency function for the 10° field, $V'(\lambda)$ is the scotopic spectral luminous efficiency function, x_{He} is a parameter between 0...1, and k_{He} is the normalisation constant such that the mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ attains a maximum value of 1.

It can be seen from Equation (5) that the mesopic spectral luminous efficiency function calculated with the model of He et al [1997] is a weighted mean of the photopic spectral luminous efficiency function for 10° field $V_{10}(\lambda)$ and the scotopic spectral luminous efficiency function $V'(\lambda)$, while in Palmer's first model the mesopic luminance [Palmer 1968, CIE 2001] in Equation (3) is a weighted mean of the photopic luminance L_P and scotopic luminance L_S.

In Equation (5) the x_{He} is a function of the mesopic luminance. Thus iteration is needed in calculating the mesopic spectral luminous efficiency function.

He et al [1998] introduced a model which was based on measurements using a binocular simultaneity method. In the measurements the left eye of the subject was adapted to five different monochromatic lights and the right eye was adapted to the spectrum of a low-pressure sodium lamp. The stimuli flashed at the same time for both eyes and the photopic luminance of the left field was adjusted in such a way that the flashes of the stimuli appeared simultaneously. Retinal illuminance levels of 0.3, 3, and 10 Td were used. The eccentricity of the stimulus was 12°. The model of He et al [1998] used the same equation (5) as used in the previous model of He et al [1997]. As in the model of He et al [1997], iteration is needed when calculating the mesopic spectral luminous efficiency function or mesopic luminance using the model of He et al [1998].

The model of Rea et al [2004], henceforth referred to as the X model, is based on the relationships found in the studies of He et al [1997, 1998]. In the X model the mesopic luminances can be calculated when either the photopic luminance and scotopic luminance or photopic luminance and S/P ratio of the light source are known. The main equations of the X model [Rea et al 2004] are

$$\begin{aligned}
&L_{mes} = \left[\frac{X \cdot L_P}{683} + \frac{(1-X) \cdot L_S}{1700}\right] \cdot \frac{683}{X + 0.402 \cdot (1-X)}, \text{when } 0.001\,\text{cd/m}^2 \le L_P \le 0.6\,\text{cd/m}^2 \\
&L_{mes} = L_P, \text{when } L_P > 0.6\,\text{cd/m}^2 \\
&L_{mes} = L_S, \text{when } L_p < 0.001\,\text{cd/m}^2 \\
&X = \frac{1}{0.599} L_{mes} - \frac{0.001}{0.599}
\end{aligned} \tag{6}$$

where L_{mes} is the mesopic luminance [cd/m^2], L_P is the photopic luminance [cd/m^2], L_S is the scotopic luminance [cd/m^2], and X is a parameter. By substituting the X, Equation (6) can be rewritten as follows

$$
\begin{aligned}
L_{mes} &= 0.834L_P - 0.335L_S - 0.2 \\
&\quad + \sqrt{0.696L_P^2 - 0.333L_P - 0.56L_PL_S + 0.113L_S^2 + 0.537L_S + 0.04}, \\
&\quad \text{when } \; 0.001\,\text{cd/m}^2 \le L_P \le 0.6\,\text{cd/m}^2 \\
L_{mes} &= L_P, \text{ when } \; L_P > 0.6\,\text{cd/m}^2 \\
L_{mes} &= L_S, \text{ when } \; L_p < 0.001\,\text{cd/m}^2
\end{aligned}
\tag{7}
$$

where L_{mes} is the mesopic luminance [cd/m^2], L_P is the photopic luminance [cd/m^2], and L_S is the scotopic luminance [cd/m^2].

In the X model [Rea et al 2004] Equation (7) for mesopic luminance can be solved in closed form and thus the mesopic luminance can be calculated without iteration. The mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ can also be calculated with the X model [Rea et al 2004] by using Equation (5) of He et al [1997] and substituting the parameter X from Equation (6) in the place of the x_{He} and using $V(\lambda)$ instead of $V_{10}(\lambda)$.

The fourth performance-based model presented in this thesis was created by a European research consortium, MOVE [Eloholma and Halonen 2005]. In MOVE contrast threshold, reaction time, and visual acuity measurements were made at background photopic luminance levels of 0.01, 0.1, 1, and 10 cd/m^2. The stimulus eccentricity was 10° and the stimulus sizes were 2 or 0.3°. Some of the measurements were made using quasi-monochromatic stimuli with half bandwidth 10-nm, some using narrow-band stimuli with half bandwidth 15...40-nm and some using broadband stimuli. The number of subjects was 109. The MOVE model is partly based on the contrast threshold data presented in Chapter 5.2.1 of this thesis. The MOVE work resulted in a practical model for mesopic photometry (the MOVE model). The MOVE model defines the mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ as a weighted mean of the photopic spectral luminous efficiency function $V(\lambda)$ and the scotopic spectral luminous efficiency function $V'(\lambda)$ as

$$
\begin{aligned}
V_{mes}(\lambda) &= \frac{1}{M(x)}\left[xV(\lambda) + (1-x)V'(\lambda)\right] \\
M(x) &= \max\left[xV(\lambda) + (1-x)V'(\lambda)\right] \approx 1 - 0.65x + 0.65x^2
\end{aligned}
\tag{8}
$$

where $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function, M(x) is a normalising function such that the mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ attains a maximum value of 1, x is a parameter which is dependent on the photopic and scotopic values of the background quantity (luminance, illuminance), $V(\lambda)$ is the photopic spectral luminous efficiency function, and $V'(\lambda)$ is the scotopic spectral luminous efficiency function. The normalising function M(x) can be approximated as shown in Equation (8). The error of the approximation is less than 1%.

The parameter x in Equation (8) can be calculated if the photopic luminance L_P and the scotopic luminance L_S are known. The equation for x is

$$x = a + b\log_{10}\left[\frac{1}{M(x)}\cdot\left(x\frac{L_P}{683}+(1-x)\frac{L_S}{1699}\right)\right]$$
$$\approx a + b\log_{10}\left[\frac{1}{1-0.65x+0.65x^2}\cdot\left(x\frac{L_P}{683}+(1-x)\frac{L_S}{1699}\right)\right] \quad (9)$$

where x is a parameter, M(x) is the normalising function as in Equation (8), L_P is the photopic luminance, L_S is the scotopic luminance, and a and b are constants which have the values a=1.49 and b=0.282.

Equation (9) cannot be solved in closed form, so x must be solved using iteration. If x_k is the estimate for x, the new estimate can be calculated as

$$x_{k+1} = a + b\log_{10}\left[\frac{1}{M(x_k)}\cdot\left(x_k\frac{L_P}{683}+(1-x_k)\frac{L_S}{1699}\right)\right] \quad (10)$$

where x_{k+1} is the new estimate for x, x_k is the previous estimate for x, a and b are constant parameters, and M(x) is the normalising function, as in Equation (9). The iteration should be continued until the difference between x_k and x_{k+1} is negligible. Typically, fewer than six iterations are needed if the value of x is presented by four decimals.

After x has been calculated, the mesopic luminance can be calculated using Equation (11)

$$L_{mes} = \left(\frac{683}{xV(555)+(1-x)V'(555)}\right)\left(x\frac{L_P}{683}+(1-x)\frac{L_S}{1699}\right) \quad (11)$$

where L_{mes} is the mesopic luminance, x is the parameter from Equation (10), V(555) is the value of the photopic spectral luminous efficiency function V(λ) at λ=555 nm, V'(555) is the value of the scotopic spectral luminous efficiency function V'(λ) at λ=555 nm, L_P is the photopic luminance [cd/m^2], and L_S is the scotopic luminance [cd/m^2].

Besides the different calculation methods, another difference between the X model [Rea et al 2004] and the MOVE model [Eloholma and Halonen 2005] is that the MOVE model defines mesopic luminance at photopic luminance levels from L_p=0.01 to $L_B \approx 10$ cd/m^2 and the X model defines mesopic luminance at the photopic luminance levels L_p=0.001...0.6 cd/m^2.

Walkey et al [2005] derived a model for mesopic contrast based on the comparison of contrasts of chromatic and achromatic stimuli. The experiments were made at 7° eccentricity and at background luminance levels 0.011...10 cd/m^2. Using this model, it is possible to calculate the mesopic contrast when photopic and scotopic contrasts and the linear distance in a transformed version of CIE 1964 chromaticity space between the stimulus and the background colours are known. Using the model of Walkey et al [2005], it is not possible to calculate mesopic luminance.

2.3 Model for spectral luminous efficiency in peripheral vision

Orreveteläinen [2005] performed experiments based on reaction time measurements at the photopic background luminance levels L_B=10 and 20 cd/m^2 at eccentricities of 0, 10, 30, and 60°. He found that the photopic spectral luminous efficiency function V(λ) is not valid for peripheral vision, even at photopic luminance levels (10 and 20 cd/m^2). He

developed a model for the spectral sensitivity of peripheral vision. This peripheral spectral luminous efficiency function $V_{per}(\lambda)$ is a combination of the photopic spectral luminous efficiency function for 10° field $V_{10}(\lambda)$ and the photopic spectral luminous efficiency function $V(\lambda)$. Orreveteläinen [2005] describes $V_{per}(\lambda)$ as

$$V_{per}(\lambda) = V_{10}(\lambda) + k \cdot (V_{10}(\lambda) - V(\lambda)), \lambda < 557 \text{ nm} \quad (12)$$

$$V_{per}(\lambda) = V_{10}(\lambda), \lambda \geq 557 \text{ nm}$$

where $V_{per}(\lambda)$ is the peripheral spectral luminous efficiency function, $V_{10}(\lambda)$ is the photopic spectral luminous efficiency function for the 10° field, $V(\lambda)$ is the photopic spectral luminous efficiency function, k is a coefficient (k=1.7322), and λ is the wavelength.

The study of Orreveteläinen [2005] confirms that the spectral sensitivity of the eye is also dependent on the eccentricity in the photopic luminance range.

2.4 Contrast threshold

The visual contrast threshold has been defined as "the smallest contrast produced in the eye of an observer by a given object which renders the object perceptible against a given background" [SFS 1992].

In the contrast threshold measurements of Blackwell H.R. [1946], both stimuli which were brighter than the background and stimuli which were darker than the background were used. He used background photopic luminance levels of 0...412 cd/m^2 and stimuli sized 0.595...121'. The stimuli were viewed at an eccentricity of 0° and the presentation time of the stimuli was up to 60 s. He found that the contrast threshold increases when the photopic background luminance level decreases.

Blackwell O.M. and Blackwell H.R. [1971] used background luminance levels of 0.003...1710 cd/m^2. The stimulus size was 4' at an eccentricity of 0° and the presentation time of the stimulus was 0.2 s. They found, as did Blackwell H.R. [1946], that the contrast threshold increases when the background photopic level decreases. The increase in the contrast threshold was stronger at photopic background luminance levels of 0.003...1 cd/m^2 than at photopic background luminance levels of 1...1710 cd/m^2. On the basis of the data of Blackwell O.M. and Blackwell H.R. [1971], CIE [1981] published the analytic equation for the contrast threshold for a 4' stimulus.

Pearson and Swanson [2000] studied the visibility of white, blue, and red stimuli against a white background at eccentricities of 0 and 12°. They used the retinal illuminance levels 0.1...3 Td. The colour temperature of the white background light and the white stimulus was 4853 K. The CIE chromaticity coordinates were (0.1394, 0.0632) for the blue and (0.6928, 0.3053) for the red stimulus. The results of Pearson and Swanson's [2000] study showed that at low retinal illuminances, below 1 Td, the peripheral retina is more sensitive to blue than red light. In foveal vision the difference between the visibilities of blue and red stimuli was smaller.

Eloholma et al [2004] conducted pedestrian visibility experiments in road lighting conditions at photopic luminance levels of 0.1, 0.5, 1.5, and 2.0 cd/m^2. The measurements were made with a high-pressure sodium lamp with an S/P ratio of 0.56, a metal halide lamp with an S/P ratio of 2.0, yellow light with an S/P ratio of 0.79, and blue light with an S/P ratio of 2.58. The measurements were made using eccentricities of 0, 15,

and 20°. It was found that pedestrian visibility was better at the photopic luminance levels 0.1 and 0.5 cd/m^2 at eccentricities of 15 and 20° when blue light or the light of the metal halide lamp was used, in comparison to visibility in yellow light or the light of the high-pressure sodium lamp. At photopic luminance levels of 1.5 and 2.0 cd/m^2 no differences in pedestrian visibility could be found between different spectra.

Lewis [1999] made contrast threshold measurements using different light sources. An incandescent lamp, a low-pressure sodium lamp, a high-pressure sodium lamp, a high-pressure mercury lamp, and a metal halide lamp were used. The photopic background luminance levels used were 0.1, 1.0, 3.0, and 10.0 cd/m^2. Lewis used gratings with spatial frequencies of 0.5, 1.0, 3.0, and 10.0 cpd. A stimulus 13° wide and 10° high was presented at an eccentricity of 0°. The results indicated that at photopic luminance levels of 3 and 10 cd/m^2 there were no differences in contrast thresholds between different spectral power distributions. At photopic luminance levels of 0.1 and 1.0 cd/m^2 contrast thresholds were lower under light sources which had more of their spectral power at short wavelengths than under light sources which had more of their spectral power at longer wavelengths.

In the study of Patel [1956] it was found that the contrast threshold increases when mean retinal illuminance decreases from 1000 Td to 3 Td.

Lingard and Rea [2002] studied off-axis detection in the mesopic luminance range. They used high-pressure sodium and metal halide lamps with S/P ratios of 0.5 and 1.8. The photopic background luminance levels used were 0.1, 0.3, 1.0, and 3.0 cd/m^2 and the eccentricities used were 12, 18, 24, and 29°. They found that stimulus contrast has a significant effect on the detection rate. With a stimulus contrast of 0.1 the detection rate was significantly lower that at the higher contrasts 0.4, 0.7, and 1.0. At lower photopic luminance levels the detection rate was better under a metal halide lamp than a high-pressure sodium lamp.

Bodrogi et al [2003] measured the spectral sensitivity of the eye using the contrast threshold. They used five 2°-sized quasi-monochromatic stimuli with a half-bandwidth of 10 nm. Eccentricities of 0 and 10° were used. The photopic background luminance level was 0.1 cd/m^2. They found that in off-axis vision the spectral sensitivity is shifted towards shorter wavelengths, compared to the spectral sensitivity in central vision.

Contrast thresholds play an important role in night-time driving. CIE [1992] compartmentalised the visual performance of the driving task into five functions. These are visual attention, visual detection, visual recognition, decision-making, and visually guided responses. Visual detection is dependent on the contrast of the target against its surroundings. One way to model visual detection is the visibility level [CIE 1992]. It indicates how much the contrast of the target is above the contrast threshold. In the CIE report [CIE 1992] the visibility level is described as

$$VL = \frac{\Delta L_{actual}}{\Delta L_{threshold}} = \frac{C_{actual}}{C_{threshold}} \tag{13}$$

where VL is the visibility level, ΔL_{actual} is the luminance difference between the target and its background, $\Delta L_{threshold}$ is the luminance difference needed between a target of a certain angular size and its background for the target to be just visible, C_{actual} is the photopic contrast between the target and its background, and $C_{threshold}$ is the photopic contrast

needed between a target of a certain angular size and its background for the target to be just visible [CIE 1995, Adrian 2004].

When developing and selecting light sources for road lighting installations it is important to know how the spectrum of the light and the spectral sensitivity of the eye together affect the contrast threshold in the mesopic luminance range. Using light sources with different spectra than today and using mesopic luminances when dimensioning road lighting, it could be possible to reach the same visibility level as today with less lamp power.

The studies of Eloholma et al [2004], Lewis [1999], and Pearson and Swanson [2000] show that the light spectrum has a significant effect on contrast thresholds at the luminance levels used in road lighting when peripheral or large foveal stimuli are used. The studies of Blackwell H.R. [1946] and Blackwell O.M. and Blackwell H.R. [1971] show that the contrast threshold is dependent on the background luminance.

In this thesis contrast threshold measurements are made in laboratory conditions using background luminance levels which are in the mesopic luminance range and light spectra with a bandwidth of 100 nm. The experiments are made with binocular vision. The novelty value of this thesis is that the contrast threshold measurements are made using both coloured and white backgrounds with a coloured stimulus.

3 Experimental set-up

3.1 The modified Goldman perimeter

The contrast threshold measurements in this study were made using a modified Goldman perimeter. The Goldman perimeter is used by ophthalmologists for visual field measurements.

The modified Goldman perimeter is a hemisphere 600 mm in diameter with a white inner surface. It was used as a background in the contrast threshold measurements. An elliptical light spot sized 8×11 mm was used as a stimulus. The distance between the eye of the subject and the stimulus was 300 mm, so the angular size of the stimulus was $2.1 \times 1.5°$. The stimulus was superimposed onto the background. The luminance of the background could be adjusted from 0.01 cd/m^2 to the photopic luminance range. The contrast between the background and the stimulus was also adjustable. It was possible to use different spectra in the background and in the stimulus.

In the centre of the hemisphere there was a fixation point. In the experiments the subject was sitting in front of the perimeter and, using an adjustable chin rest, the left eye of the subject was fixated towards the fixation point. The researcher could see the position of the subject's eye through an ocular and the fixation of the subject's eye could be monitored.

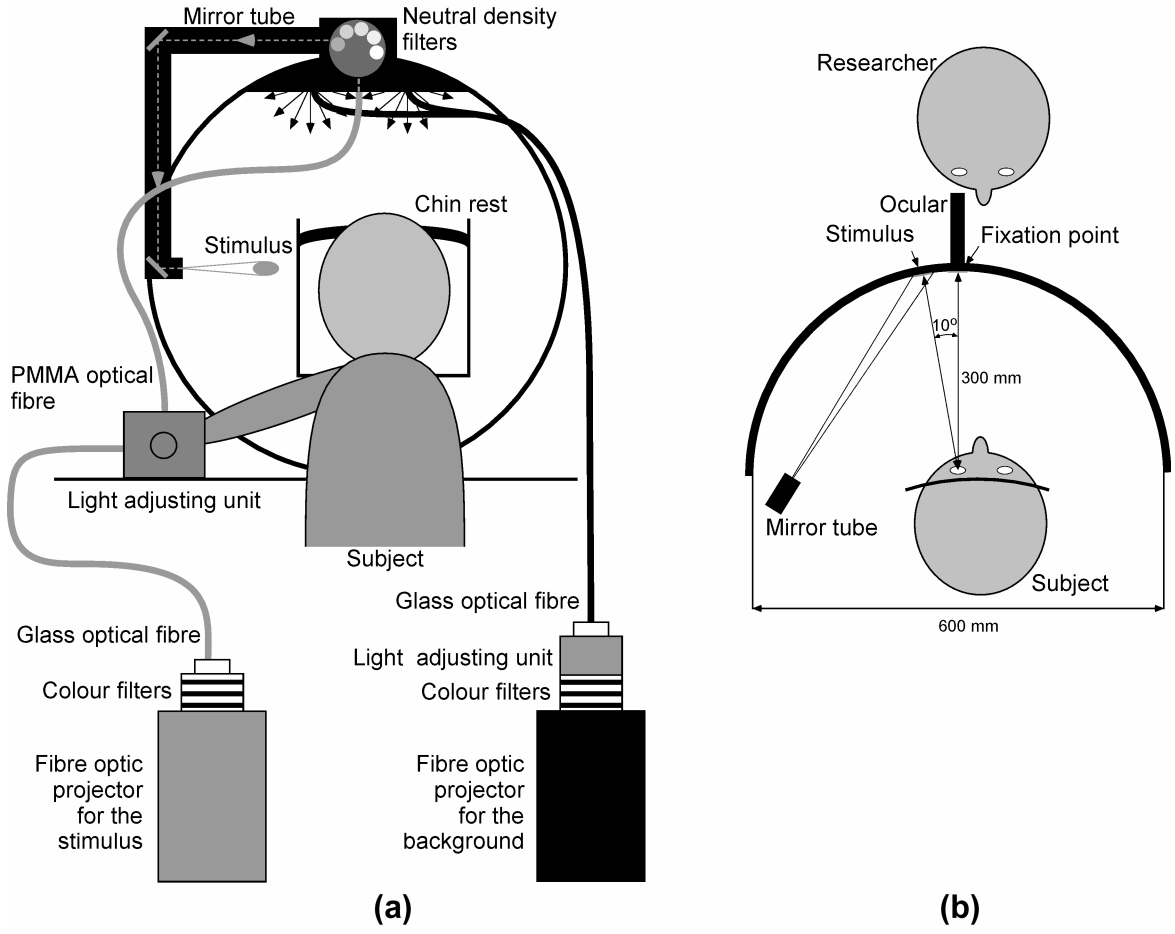

Figure 2. The structure of the modified Goldman perimeter from behind the subject (a) and from above (b).

The light was transmitted to the background and to the stimulus from fibre optic projectors using optical fibres. A General Electric 150 W Arcstream metal halide lamp with a colour temperature of 4000 K was used as a light source in the fibre optic projectors. Semiconductor ballasts were used in the fibre optic projectors to minimise the flicker of the background and the stimulus light.

The background was illuminated by placing the glass optical fibres at the upper part of the perimeter, as shown in Figure 2. From the upper part of the perimeter the light reflected onto the whole background surface. Between the lamp of the fibre optic projector and the glass optical fibres there was a light adjusting unit. It consisted of two parts, an adjustable gap with an opening of from d=0 mm to d=4 mm and a fixed gap sized 1 mm. By adjusting the size of the adjustable gap, it was possible to adjust the light reaching the fibres and thus adjust the luminance level of the background of the hemisphere. Between the lamp of the fibre optic projector and the optical fibres there was a replaceable dichroic colour filter. By changing the colour filter is was possible to change the spectrum of the background.

The light was transmitted to the stimulus from the fibre optic projector using glass and PMMA optical fibres. The light passed through the glass optical fibres to the light adjusting unit, which consisted of an adjustable gap with an opening from d=0 mm to d=4 mm. The size of the adjustable gap was adjusted using a micrometer. After the adjustable gap the light passed via a 3-mm diameter PMMA optical fibre and neutral density filters to a mirror tube which reflected the stimulus onto the surface of the hemisphere. By adjusting the size of the adjustable gap and using neutral density filters with different densities, it was possible to adjust the luminance level of the stimulus. For selecting the spectrum of the stimulus, there were replaceable dichroic colour filters between the lamp of the fibre optic projector and the glass optical fibres.

3.2 Luminance and contrast measurements

3.2.1 Meters used

The luminance levels were measured using an LMT 1009 luminance meter. The measured luminances were between 0.01...20 cd/m^2. The accuracy of the LMT 1009 luminance meter was 2.1%, including the uncertainty of the V(λ) correction, 2%. Because the measurement distance was as short as 300 mm, it was necessary to use a close-up lens. The close-up lens does not change the accuracy of the LMT 1009 luminance meter, but the reading of the meter should be multiplied by the correction factor F=1.01. The luminance meter was calibrated at NPL.

A ProMetric 1400 CCD imaging photometer was used together with the LMT 1009 luminance meter when measuring the uniformity of the background luminance. The ProMetric 1400 CCD was used to measure luminance at several thousand points simultaneously. The accuracy of the ProMetric 1400 CCD imaging photometer is 3%.

An LMT Pocket lux 2 illuminance meter was used for monitoring the luminance of the hemisphere background during the contrast threshold measurements. The transmittances of the neutral density filters were also measured using the LMT Pocket lux 2 illuminance meter. The error of the linearity of the meter is 0.1%. The measured illuminances were between 0.2...300 lx. The resolution of the LMT Pocket lux 2 illuminance meter is

0.01 lx. Thus the maximum uncertainty of the illuminance measurements caused by the resolution of the LMT Pocket lux 2 illuminance meter was 2.5%.

An Optronic OL-754 spectroradiometer was used for measuring the spectra of the background and the stimulus. The spectroradiometer was calibrated at the Lighting Laboratory using a reference lamp calibrated at the Metrology Research Institute.

3.2.2 Measuring the background luminance

The background luminance levels were adjusted using the LMT 1009 luminance meter with a close-up lens. The meter was placed in the position of the subject's eye and focused on a point 10° left from the fixation point. This was the position of the visual stimulus. The 3° opening in the LMT 1009 luminance meter was used. The sensor of the LMT Pocket lux 2 illuminance meter was placed on the upper part of the modified Goldman perimeter, near the optical fibres. When the luminance level was adjusted, the reading of the illuminance meter was taken. During the contrast threshold measurements, monitoring of the background luminance was conducted using the LMT pocket lux 2 illuminance meter.

Reflections from the subject's face increased background luminances. Using one subject, the background luminance was estimated to be 2 % higher with the subject than without. This was taken into account when adjusting the background luminances during the contrast threshold measurements.

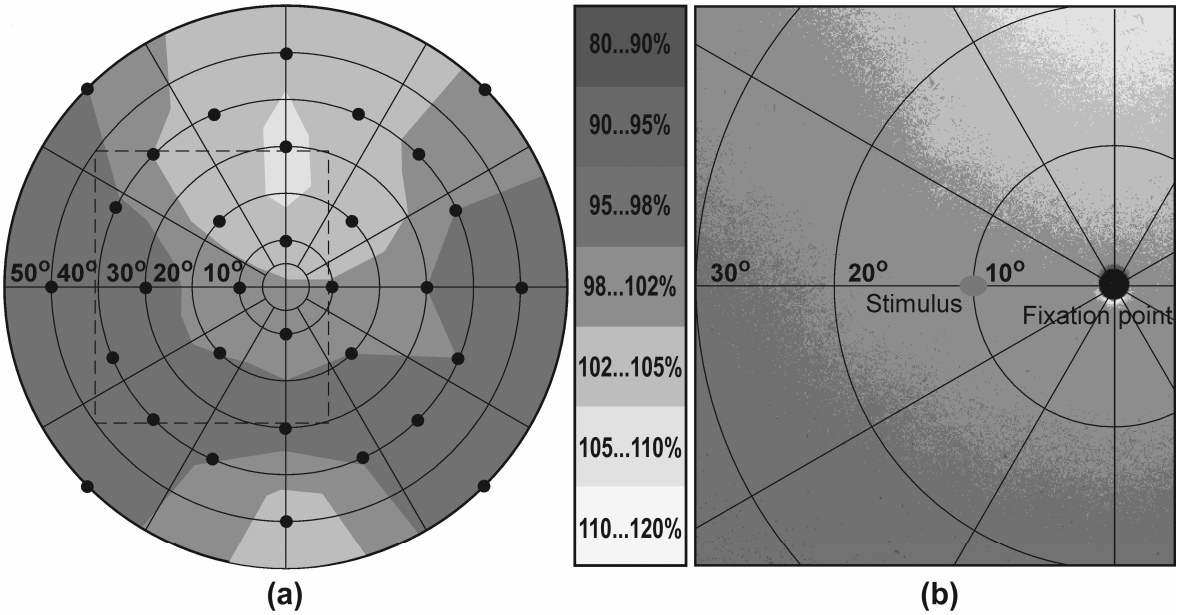

Figure 3. The uniformity of the background luminance. The uniformity of the background luminance in the area ±50° (a). The dots are the points where the background luminance is measured with LMT 1009. The uniformity of the area close to the stimulus (b). The uniformity is measured with ProMetric 1400. The value of 100% is the background luminance value at the position of stimulus.

The uniformity of the background luminance was measured by means of two methods. The ProMetric 1400 CCD imaging photometer was used to measure the luminance distribution of the area around the stimulus, as shown in Figure 3b. The iso-luminance curves were calculated using Matlab. The measurement of the luminance of the whole surface of the hemisphere could not be performed with the ProMetric 1400

CCD imaging photometer because the measurement angle of the photometer is 30°. The luminance distribution of the hemisphere in the area ±50° was calculated by measuring the luminance of the hemisphere at 32 points using the LMT 1009 luminance meter. The corresponding iso-luminance curves were calculated manually. The measurement points are shown in Figure 3a. The area ±50° covered a major part of the visual field. According to visual inspection the uniformity at the angles between ±50... ±90° was adequate. The uniformity of the background luminance was ±2% in the area ±5° around the stimulus and ±1% in the area ±2° around the stimulus. The uniformity of the background luminance was ±10% in the area of ±50° from both sides of the fixation point.

3.2.3 Defining the contrast of the visual stimulus

In this work contrast is defined as

$$C = \frac{\Delta L_{SB}}{L_B} \tag{14}$$

where C is the contrast between the stimulus and the background, L_B is the luminance of the background [cd/m^2], and ΔL_{SB} is the difference between the luminances of the stimulus and the background [cd/m^2].

It was not possible to measure the difference between the luminances of the background and the stimulus ΔL_{SB}, because of the limited accuracy of the LMT 1009 luminance meter using the 1° aperture. Thus the measurement was taken indirectly.

As explained in Chapter 3.1, the amount of light reflected to the stimulus was adjusted using an adjustable gap and neutral density filters. The transmittance of each neutral density filter was measured separately for each stimulus spectrum with the LMT Pocket lux 2 illuminance meter. The optical fibre was pointed at the sensor of the illuminance meter and the illuminance value was recorded. Then each neutral density filter was placed between the optical fibre and the sensor and the illuminance value was recorded. The transmittance of the neutral density filter could be calculated as

$$\tau_{ND} = \frac{E_{ND}}{E_0} \tag{15}$$

where τ_{ND} is the transmittance of the neutral density filter, E_{ND} is the illuminance value with a neutral density filter, and E_0 is the illuminance value without the neutral density filter.

The accuracy of the measurement of the transmittance of the neutral density filter was good, because the measurement was relative and both illuminance values, E_{ND} and E_0, were measured using the same light spectrum. Thus only the uncertainty of the linearity of the LMT pocket lux 2 meter has to be taken into account. A random error of 1.0% is added to the uncertainty estimate in Chapter 3.2.4, because of the possible uncertainties resulting from the placing of the neutral density filter.

The transmittance of the adjustable gap was measured by measuring the luminance of the stimulus using the LMT 1009 luminance meter. The meter was pointed at the stimulus and the background light was turned off. The luminance of the stimulus was measured between 0.1-mm steps of the adjustable gap. No colour filters were used. The

measured luminances were between 0.4...13 cd/m^2, so the sensitivity of the LMT 1009 luminance meter was adequate at a 1° aperture.

The transmittance of the adjustable gap is defined as

$$\tau_{gap} = \frac{L_{gap}(d)}{L_{gap}(4\,mm)} \tag{16}$$

where τ_{gap} is the transmittance of the adjustable gap, $L_{gap}(d)$ is the luminance of the stimulus at the adjustable gap with opening d, d is the opening of the adjustable gap, and $L_{gap}(4\,mm)$ is the luminance of the stimulus at the adjustable gap opening d=4 mm. A polynomichal function was fitted to the measured transmittances of the adjustable gap, τ_{gap}, so it was possible to calculate τ_{gap} when the opening of the adjustable gap, d, was known. The transmittance of the adjustable gap can thus be calculated using Equation (17)

$$\tau_{gap} = 0.5539d^2 + 33.09d + 23.62 \tag{17}$$

where τ_{gap} is the transmittance of the adjustable gap and d is the opening of the adjustable gap. Equation (17) is valid at adjustable gap openings of d=0.8...4 mm. At values of d<0.8 mm a more complicated function would be needed. In the openings of the adjustable gap d=0.5...0.8 mm, the transmittances of the adjustable gap were measured individually for each opening. No openings of the adjustable gap below d=0.5 mm were used.

The value of $L_{gap}(4\,mm)$ in Equation (16), i.e. the luminance of the stimulus at an adjustable gap opening of d=4 mm, was measured using the LMT 1009 luminance meter. The 1° aperture was used and the measurement of the maximum luminance was made for each stimulus spectrum after each contrast threshold measurement session.

When the luminance of the stimulus at an adjustable gap opening of d=4 mm, the transmittance of the neutral density filters used, and the transmittance of the adjustable gap are known, the luminance difference between the background and the stimulus can be calculated using Equation (18)

$$\Delta L_{SB} = L_{gap}(4\,mm) \times \tau_{nd} \times \tau_{gap} \tag{18}$$

where ΔL_{SB} is the luminance difference between the stimulus and the background [cd/m^2], $L_{gap}(4\,mm)$ is the stimulus luminance at the adjustable gap at the position d=4 mm [cd/m^2], τ_{nd} is the transmittance of the neutral density filter used, and τ_{gap} is the transmittance of the adjustable gap.

When the luminance difference between the stimulus and the background is defined, the contrast can be calculated using Equation (14).

3.2.4 Spectral measurements

The spectral measurements were made using an Optronic OL-754 spectroradiometer with an irradiance sensor. In measuring the spectrum of the background, the sensor of the Optronic OL-754 spectroradiometer was placed inside the hemisphere, i.e. the spectrum of the light reflected from the background was measured.

It was not possible to measure the spectrum of the stimulus because the sensitivity of the Optronic OL-754 spectroradiometer was not adequate for the small targets. Thus the background was illuminated using the fibre optic projector and colour filters of the stimulus and the spectrum of the background was measured. The differences in background spectra when the background was illuminated using either the fibre optic projector of the background or the fibre optic projector of the stimulus were negligible.

The neutral density filters could also affect the spectrum of the stimulus. The information on the spectral internal transmittance of the neutral density filters was based on the manufacturer's data and the differences of the transmittances were within ±2% at wavelengths of 400…700 nm. Thus it was assumed that the neutral density filters had no significant effect on the spectra of the stimulus.

Because of these factors it was assumed that the spectra of the background and the stimulus were the same.

3.3 Uncertainties of the luminance and contrast measurements

The contrast of the stimulus defined in Equation (14) includes the background luminance L_B and the luminance difference between the stimulus and the background ΔL_{SB}. The total uncertainty of the contrast of the stimulus is calculated as the square root of the sum of the squares of the uncertainties of each component

$$\delta_C = \sqrt{\delta_B^2 + \delta_{BS}^2} \tag{19}$$

where δ_C is the uncertainty of the contrast of the stimulus, δ_B is the uncertainty of the background luminance, and δ_{BS} is the uncertainty of the difference between the luminances of the stimulus and the background.

The uncertainty of the background luminance consists of the uncertainty of the background luminance measurement, monitoring the background luminance, the stability of the lamp of the fibre optic projector, and the uniformity of the background luminance. The uncertainty of the background luminance δ_B can be calculated as the square root of the sum of the squares of the uncertainties of each component. Each component also has one or more sub-components and the uncertainty of each component can be calculated as the square root of the sum of the squares of the sub-components. The uncertainties are presented in Table 1. The total uncertainty of the background luminance is 3.8%.

The uncertainty of the luminance difference between the stimulus and the background is caused by the uncertainty of the stimulus luminance at the adjustable gap opening d=4 mm, the uncertainty of the transmittance measurement of the neutral density filters, the uncertainty of the transmittance measurement of the adjustable gap, and the stability of the lamp in the fibre optic projector. Each component also has one or more sub-components and the uncertainty of each component can be calculated as the square root of the sum of the squares of the sub-components. The uncertainties are presented in Table 1. The total uncertainty of the luminance difference between the stimulus and background is 3.5%.

The total uncertainty of the measured contrast between the stimulus and the background is 5.2%.

Table 1. The uncertainty estimate of the contrast of the stimulus

Uncertainty of the background luminance measurement	**2.1 %**
Uncertainty of the V(λ)-filter of the LMT 1009 luminance meter	2.0 %
Resolution of the LMT 1009 luminance meter	0.5 %
Resolution of monitoring the background luminance	**2.5 %**
Resolution of the Pocket lux 2 illuminance meter	2.5 %
Stability of the lamp of the fibre optic projector	**2.0 %**
Uniformity of the background luminance	**1.0 %**
Uncertainty of the background luminance (δ_B)	**3.8 %**

Uncertainty of the stimulus luminance at adjustable gap opening d=4 mm	**2.3 %**
Uncertainty of the V(λ)-filter of the LMT 1009 luminance meter	2.0 %
Resolution of the LMT 1009 luminance meter	0.5 %
Focus of the LMT 1009 luminance meter	1.0 %
Effect of the surrounding field	0.3 %
Uncertainty of the transmittance measurement of neutral density filters	**1.0 %**
Uncertainty of the linearity of the LMT Pocket lux 2 illuminance meter	0.1 %
Random error	1.0 %
Uncertainty of the transmittance measurement of the adjustable gap	**1.1 %**
Uncertainty of the linearity and focus of the LMT 1009 luminance meter	0.5 %
Random error	1.0 %
Stability of the lamp of the fibre optic projector	**2.0 %**
Uncertainty of the luminance difference between stimulus and background (δ_{BS})	**3.5 %**

Uncertainty of the contrast of the stimulus ($\delta_C = \sqrt{\delta_B^2 + \delta_{BS}^2}$)	**5.2 %**

4 Measurement methods

4.1 Parameters

4.1.1 Background luminance levels

The average luminance of the road surface is recommended to be between 0.3...2 cd/m^2 [EN 13201]. Eloholma et al [2004] found that luminances at the sides of the road may vary through a wide range. The luminances at the sides of the road can also be lower than 0.3 cd/m^2.

The background luminance levels in the contrast threshold measurements were selected so as to cover the typical luminances found in road lighting conditions. Most of the contrast threshold measurements in this study were taken at the background luminance levels L_B=0.01, 0.1, 1, and 10 cd/m^2, and some were made at the intermediate background luminance levels L_B=0.03, 0.3, and 3 cd/m^2. The background luminance level L_B=20 cd/m^2 was also included, so it was possible to estimate the validity of the photopic spectral luminous efficiency function V(λ) at luminance levels in the photopic luminance region.

With a blue background spectrum it was not possible to reach the background luminance level L_B=10 cd/m^2, so the highest background luminance level in using blue background spectrum was L_B=2.5 cd/m^2.

4.1.2 Eccentricity

The measurements were taken using stimulus eccentricities of 0° and 10°. The eccentricity 0° was used because the photopic spectral luminous efficiency function V(λ) has been defined using a stimulus eccentricity of 0° and because the previous studies [Eloholma et al 1998] indicate that the light spectrum does not affect visual acuity in the mesopic luminance range in foveal vision. In this thesis the aim was to find out if the spectrum of the background light affects the contrast threshold in the mesopic luminance range at an eccentricity of 0°.

An eccentricity of 0° was not included in all the measurements of this study. Especially at low background luminance levels (L_B=0.01...0.1 cd/m^2), it was noticed that it was very difficult for the subject to fixate foveally on the stimulus, which can hardly be seen. When a blue stimulus was used it was noticed that the stimulus would be seen better if the fixation was slightly off-axis. Thus it was not sure that the measurements an eccentricity of 0° really describe foveal vision.

4.1.3 Spectra

In earlier studies contrast thresholds at mesopic luminance levels were studied using spectra which cover the whole visible wavelength region [Eloholma et al 2004, Lewis 1999] and with quasi-monochromatic spectra with a half-bandwidth of 10 nm [Bodrogi 2003]. In this thesis spectral lights with a bandwidth of 100 nm were used, together with white light.

The selected spectra were white, blue, green, and red. These spectra were used in the background and the stimulus. The stimulus was superimposed onto the background. The white light was provided by a 4000-K metal halide lamp and the other spectra were made from white light using coloured filters. The blue light covers the wavelength region λ=400…500 nm, the green light covers the wavelength region λ=500…600 nm, and the red light covers the wavelength region λ=600…700 nm. The white, blue, green, and red

spectra are shown in Figure 4. Because of the limited selection of the coloured filters, the blue and green spectra overlap around the wavelength λ=513 and the green and red spectra overlap around the wavelength λ=584 nm.

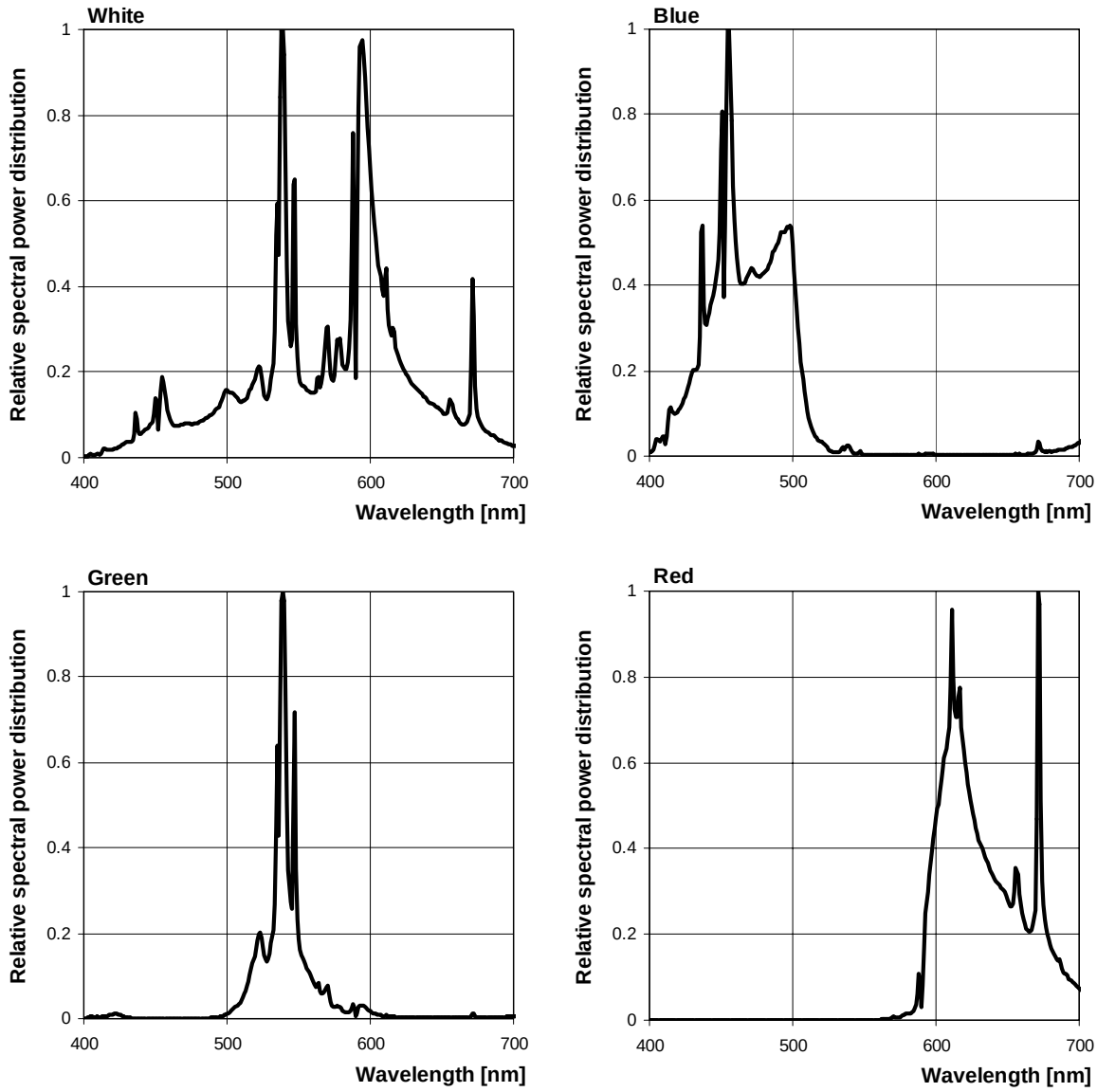

Figure 4. Spectral power distributions of the white, blue, green, and red lights.

4.1.4 Stimulus size

An elliptical stimulus sized 2° horizontally and 1.5° vertically was used in the contrast threshold measurements. The shape of the stimulus was the result of the properties of the modified Goldman perimeter, so it was not possible to use a circular stimulus.

There were also practical reasons for the size of the stimulus. Especially at an eccentricity of 10° and at a background luminance level L_B=0.01 cd/m^2, it would have been difficult for the subject to detect a smaller stimulus. Conversely, the use of a larger stimulus at an eccentricity of 10° could not possibly describe vision exactly at the eccentricity of 10°.

4.1.5 Moving and static stimulus

In the contrast threshold measurements both moving and static stimuli were used. A moving stimulus was used because it was presumable that it would be easier to detect a

moving than a static stimulus, so the accuracy of the measurements would be increased. The moving stimulus was moved elliptically in an area of 4° horizontally and 3° vertically. The speed of the movement was 1 round/1 second.

The moving stimulus was used in the first series of contrast threshold measurements. Later on it was noticed that the movement of the stimulus did not increase the accuracy of the measurements if the subjects were well trained for the measurements.

4.2 Defining the contrast threshold

In defining the contrast threshold the subject's task was to increase the contrast between the stimulus and the background so that it could just be seen and then decrease the contrast between the stimulus and the background so that the stimulus could not be seen any more. This was repeated twice and the absolute threshold was defined as an average of these four measurements.

4.3 Measurement phases

The contrast threshold measurements were conducted during 2002-2004. The measurements were made in seven different phases. The parameters of the different phases are presented in Table 2.

Table 2. The parameters of contrast threshold measurements in Phases I to VII.

	Phase I	Phase II	Phase III	Phase IV	Phase V	Phase VI	Phase VII
Photopic background luminance L_B [cd/m^2]	0.01 0.1 1 10 (2.5*)	0.01 0.1 1	0.01 0.1 1 10	0.01 0.1 1	0.03 0.3 3	10 20	0.01 0.1 1 10
Background spectra	Blue Green Red	Blue Green Red	White	White Blue Green Red	White	White	White
Stimulus spectra	Blue Green Red	Blue Green Red	Blue Green Red	Blue Green Red	Blue Green Red	Blue Green Red	White
Eccentricity	0° 10°	0° 10°	0° 10°	10°	10°	10°	0° 10°
Stimulus presentation	Moving	Moving	Moving Static	Moving Static	Static	Static	Static
Monocular/ binocular vision	Binocular	Binocular	Binocular	Binocular	Binocular	Binocular	Monocular Binocular
Subjects (f = female m = male)	S1m S2m S3m S4m	S5f S6m S7f S8m S9m S10m	S5f S3m S7f S1m S8m	S5f (×5) S1m (×5)	S6m (×5) S8m (×5)	S1m (×5) S5f (×5)	S1m (×5) S5f (×5)

*for blue background spectra background luminance was L_B=2.5 cd/m^2

4.4 Contrast threshold measurements with coloured background

The contrast threshold measurements with blue, green, and red background spectra were made in Phases I, II, and IV. In these measurements the spectra of the background and the stimulus were the same.

In Phase I the contrast threshold measurements were made using a moving stimulus and eccentricities of 0 and 10°. The photopic background levels used were L_B=0.01, 0.1, 1, and 10 cd/m^2 for the red and green background spectra and L_B=0.01, 0.1, 1, and 2.5 cd/m^2 for the blue background spectrum. Four subjects took part in the measurements.

In Phase II the contrast threshold measurements were made using a moving stimulus at eccentricities of 0 and 10°. The photopic background luminance levels used were L_B=0.01, 0.1, and 1 cd/m^2 for all background spectra because it was noticed in Phase I that the contrast threshold does not change between photopic background luminance levels of L_B=1 and 10 cd/m^2. Six subjects took part in the measurements. The measurements started in Phase I were continued in Phase II. Measurements of Phase II were made three months after the measurements of Phase I.

The hypothesis for Phases I and II was that the contrast threshold increases when the photopic background luminance level decreases [Blackwell O.M and Blackwell H.R. 1971]. When the spectral sensitivity of the eye shifts towards to the shorter wavelengths in a case when the photopic background luminance level decreases, it could be assumed that, at lower photopic background luminance levels, the mesopic background luminance within each photopic background luminance level is highest with blue background spectrum, and lowest with red background spectrum. Because of this, the contrast threshold should decrease most with a red background spectrum and least with a blue background spectrum when photopic background luminance decreases. Because there are no rods in the central part of the fovea, the differences in contrast threshold between different background spectra should be found only when contrast thresholds are measured at 10° eccentricity.

In Phase IV the contrast threshold measurements were made using both moving and static stimuli. The photopic background luminance levels were L_B=0.01, 0.1, and 1 cd/m^2. An eccentricity of 10° was used. The contrast threshold measurements were made five times for two subjects.

The hypothesis for Phase IV was the same as for Phases I and II. In addition, it was assumed that lower contrast thresholds can be measured with a moving rather than a static stimulus because a moving stimulus is easier to detect that a static one [Luisov 1980, Goldstein 2002].

4.5 Contrast threshold measurements with white background

The contrast threshold measurements with a white background spectrum and with blue, green, and red stimulus spectra were made in Phases III, IV, V, and VI.

In Phase III the contrast threshold measurements were made using both moving and static stimuli and eccentricities of 0 and 10°. The photopic background luminance levels were L_B=0.01, 0.1, 1 and 10 cd/m^2. Five subjects took part in the measurements.

The hypothesis for Phase III was that contrast threshold increases when background luminance level decreases [Blackwell O.M and Blackwell H.R. 1971]. When the spectral sensitivity of the eye shifts towards the shorter wavelengths in a case when the photopic

background luminance level decreases, the changes in the spectral sensitivity affect the mesopic contrast between the stimulus and the background. Thus, it is assumed that, at lower photopic background luminance levels, the lowest contrast threshold is measured with blue stimulus spectrum, and the highest with red stimulus spectrum. Because there are no rods in the central part of the fovea, the changes in spectral sensitivity should affect the contrast thresholds only when the measurements are made at 10° eccentricity. It is assumed that the lower contrast thresholds are measured with a moving rather than static stimulus because a moving stimulus is easier to detect than a static one [Luisov 1980, Goldstein 2002].

In Phase IV the contrast threshold measurements were made using both moving and static stimuli and using both coloured and white background spectra. The photopic background luminance levels were L_B=0.01, 0.1, and 1 cd/m^2. An eccentricity of 10° was used. The contrast threshold measurements were made five times for two subjects.

The hypothesis for this phase were the same as in Phase III. The goal of Phase IV was to compare the contrast thresholds measured with coloured and white backgrounds, respectively. When measurements are made with a coloured background, the differences in contrast threshold between different spectra are affected only by the different mesopic background luminances. When the background spectrum is white, the changes in the spectral sensitivity of the eye also affect the mesopic contrast between the stimulus and the background. Thus, it may be assumed that the differences in contrast thresholds between different spectra are larger when the measurements are made with a white background spectrum.

In Phase V the contrast threshold measurements were made using a static stimulus at an eccentricity of 10°. The photopic background luminance levels were L_B=0.03, 0.3, and 3 cd/m^2. The goal of this phase was to gain information on the contrast threshold behaviour at photopic background luminance levels which lie between the photopic background luminance levels used in the previous phases. The contrast threshold measurements were taken five times for two subjects. The hypothesis were the same as in Phase III

In Phase VI the contrast threshold measurements were made using a static stimulus at an eccentricity of 10°. In Phase VI the measurements were made at photopic background luminance levels of L_B=10 and 20 cd/m^2 using blue, green, and red stimuli and an eccentricity of 10°. The goal of this phase was to gain information on the contrast threshold behaviour in the photopic luminance range with different stimulus spectra. The contrast threshold measurements were made five times for two subjects. Because the measurements were made at photopic background luminance levels, there should not be a difference between contrast thresholds measured with different stimulus spectra at constant luminance if the spectral luminous efficiency function V(λ) is also valid at 10° eccentricity.

4.6 Contrast threshold measurements with mono- and binocular vision

The contrast threshold measurements were made binocularly, so the adaptation of both eyes was similar and the viewing conditions were natural. The position of the head was adjusted so that the left eye of the subject was fixated straight towards the fixation point, as shown in Figure 2.

In the contrast threshold measurements at an eccentricity of 0° the binocularity was not a problem, because both eyes viewed the stimulus foveally. In the contrast threshold measurements at an eccentricity of 10° the angular position of the stimulus was 10° for the left and 9.5° for the right eye, with the spacing between the eyes assumed to be 60 mm. The positioning of the stimulus was temporal for the left eye and nasal for the right eye. To investigate the possible effects of this, the contrast threshold measurements in Phase VII were made using both monocular and binocular vision. In contrast threshold measurement with monocular vision a baffle was used in front of the right eye. Because of the baffle the stimulus could be seen only with the left eye. The baffle was a 20-mm slide of opal film, whose transmission was 80%. Thus the adaptation level of both eyes was almost the same both in monocular and binocular vision.

A comparison of the mono- and binocular vision was made in Phase VII and the results are presented in Chapter 5.3.2. White background and stimulus spectra were used and the photopic background luminance levels were L_B=0.01, 0.1, 1, and 10 cd/m^2. The contrast threshold was measured at eccentricities of 0 and 10°. The contrast threshold measurements were made five times for two subjects.

4.7 Statistical analysis methods

The statistical analysis of the results was performed using the analysis of variance (ANOVA) and Ducan's Multiple Comparison Test. A probability level of p=0.05 was used. With ANOVA it is possible to find out if there are statistical differences between the compared parameter values, e.g. between different photopic background luminance levels or between different background spectra. ANOVA does not indicate which photopic background luminance level or background spectrum differs from the others. Because of this, Ducan's Multiple Comparison Test was used after ANOVA had shown that significant differences existed. Ducan's Multiple Comparison Test compares several parameter values simultaneously. It was selected because it is more sensitive to differences than e.g. the Bonferroni (All-Pairwise) Multiple Comparison Test, but more conservative than e.g. Fisher's LSD Multiple Comparison Test.

The effect of photopic background luminance on contrast threshold was analysed in Phases I, II, III, IV, V, VI, and VII. The analysis was performed separately for all background and stimulus spectra.

The effect of the background spectrum was analysed in Phases I, II, and IV and the effect of the stimulus spectrum in Phases III, IV, V, and VI. A comparison was made between different background and stimulus spectra within each photopic background luminance level.

The effect of eccentricity was analysed in Phases I, II, III and VII. A comparison was made between different background and stimulus spectra within each photopic background luminance level.

The effect of the movement of the stimulus was analysed in Phases III and IV. A comparison was made between one background or stimulus spectrum within each photopic background luminance level.

An analysis of contrast thresholds measured with a coloured background and a coloured stimulus and with a white background and a coloured stimulus was performed in Phase IV.

The differences between mono- and binocular vision were analysed within each photopic background luminance level in Phase VII.

4.8 Subjects

A total of 10 volunteer subjects took part in the visual tests. The subjects were young, 22 to 32 years old, master's and doctoral students of Helsinki University of Technology.

All the subjects had normal vision and had been examined by an ophthalmologist. Visual acuity was examined at a distance of 5 m (Snellen charts). None of the subjects wore glasses or contact lenses in their daily life or during the tests. The eyes were examined using a Haag-Streit slit lamp biomicroscope with and without a Volk lens and by binocular indirect ophthalmoscopy after the 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).

Some of the subjects took part only in one set of measurements, but two of them (a female aged 24 and a male aged 31) took part in all the measurements. The participation of each subject in different phases can be seen in Table 2.

5 Results of the contrast threshold measurements

5.1 Measurements with coloured background

5.1.1 Results

Contrast threshold measurements with a coloured background were made in Phases I, II, and IV. Figure 5 presents the results of Phases I and II. Figure 5a presents the contrast threshold values measured at an eccentricity of 0° and Figure 5b the contrast threshold values measured at an eccentricity of 10°. The contrast threshold values of Phase II are multiplied by 100 for the sake of the clarity of the figure. Figure 6 presents the results of Phase IV. In Figure 6a the contrast thresholds measured using the moving stimulus are presented and in Figure 6b the contrast thresholds measured using the static stimulus are presented.

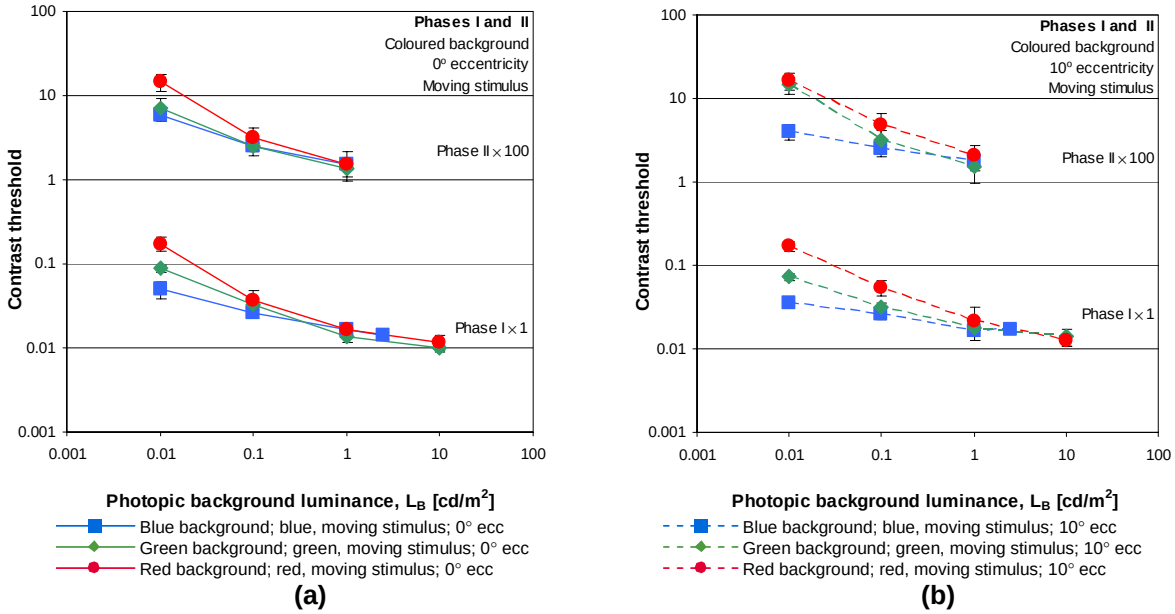

Figure 5. The average contrast thresholds of Phases I and II. The results at an eccentricity of 0° (a) The results at an eccentricity of 10° (b). The background and stimulus spectra were blue, green, and red. Photopic background luminance levels were L_B=0.01, 0.1, 1, and 10 cd/m^2 for green and red spectra and L_B=0.01, 0.1, 1, and 2.5 cd/m^2 for the blue spectrum. A moving stimulus was used. The bars show the standard deviations. The contrast threshold values of Phase II are multiplied by 100.

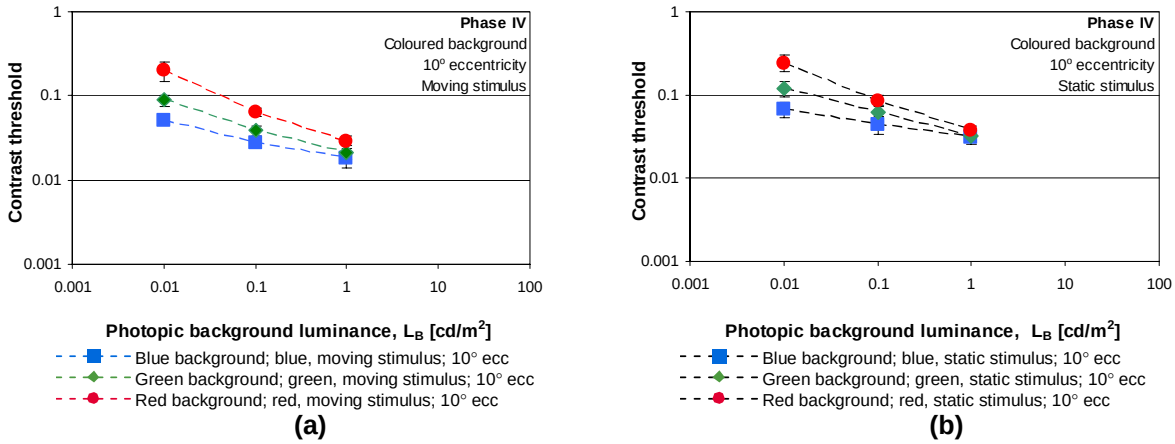

Figure 6. The average contrast thresholds of Phase IV. The results of the moving stimulus (a). The results of the static stimulus (b). The background and stimulus spectra were blue, green, and red. Photopic background luminance levels were L_B=0.01, 0.1, and 1 cd/m^2. An eccentricity of 10° was used. The bars show the standard deviations.

5.1.2 The effect of photopic background luminance

The hypothesis for the effect of photopic background luminance is that the contrast threshold increases when the background luminance level decreases.

In Phase I the statistical analysis shows that the contrast threshold decreases significantly (p-values << 0.05) when the photopic background luminance increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 and from L_B=0.1 cd/m^2 to L_B=1 cd/m^2 at both eccentricities and with all background spectra. The contrast threshold decreases significantly when the photopic background luminance increases from L_B=1 cd/m^2 to L_B=10 cd/m^2 only at an eccentricity of 0° with green and red spectra.

In Phase II the contrast threshold decreases significantly (p-values << 0.05) when the photopic background luminance increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 and from L_B=0.1 cd/m^2 to L_B=1 cd/m^2 at both eccentricities and with every background spectrum.

In Phase IV the contrast threshold decreases significantly when a moving stimulus was used, when the photopic background luminance increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 and from L_B=0.1 cd/m^2 to L_B=1 cd/m^2 with every background spectrum (p-values for blue, green, and red spectra 0.015, 0.001, and 0.001 respectively). When a static stimulus was used, the statistical analysis shows that the contrast threshold decreases significantly when the photopic background luminance increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 and from L_B=0.1 cd/m^2 to L_B=1 cd/m^2 with green and red background spectra (p-values 0.017 and 0.003). With a static stimulus and a blue background spectrum no significant differences in the contrast threshold were found between the photopic background luminance levels L_B=0.01... 1 cd/m^2.

In summary it can be said that the contrast threshold decreases when the photopic background luminance level increases. The same effect was found in the study of Blackwell O.M and Blackwell H.R. [1971]. In the contrast threshold measurements in Phases I, II, and IV the contrast thresholds increased more with a red than a blue background spectrum when photopic background luminance levels decreased. This indicates that the mesopic luminance of the background decreases more with a red than a blue background spectrum and confirms that the spectral sensitivity of the eye shifts towards shorter wavelengths.

5.1.3 The effect of background spectrum

When the background and the stimulus have the same spectrum, the hypothesis is that the contrast threshold increases most with a red background spectrum and least with a blue background spectrum when the contrast threshold is measured at 10° eccentricity.

In Phase I the statistical analysis shows that background and stimulus spectra have a significant effect (p-values << 0.05) on the contrast threshold at a photopic background luminance level L_B=0.01 cd/m^2 at eccentricities of 0 and 10°. The contrast threshold is highest when the background spectrum is red and lowest when the background spectrum is blue. At a photopic background luminance level L_B=0.1 cd/m^2 significant differences between different stimulus spectra can be found only at an eccentricity of 10°. The contrast threshold is highest when the background spectrum is red and lowest when the background spectrum is blue. At the photopic background luminance levels

L_B=1 and 10 cd/m^2 no significant differences in contrast threshold between different background spectra could be found.

In Phase II the background and stimulus spectra have a significant effect (p-values << 0.05) on contrast threshold at the photopic background luminance level L_B=0.01 cd/m^2 at eccentricities of 0 and 10°. At an eccentricity of 0° the contrast threshold is highest when the spectrum of the background is red and lowest when the background spectrum is green or blue. At an eccentricity of 10° the contrast threshold is highest when the background spectrum is red and lowest when the background spectrum is blue. At the photopic background luminance level L_B=0.1 cd/m^2 significant differences can be found only at an eccentricity of 10° when the contrast threshold is highest with a red background spectrum and lowest with a blue background spectrum. At the photopic background luminance level L_B=1 cd/m^2 no significant differences in contrast threshold between different background spectra could be found.

In Phase IV the background and stimulus spectra have a significant effect (p-values << 0.05) on the contrast threshold at the photopic background luminance level L_B=0.01 cd/m^2 when a moving stimulus was used. At this photopic background luminance level the contrast threshold is highest when the background spectrum is red and lowest when the background spectrum is blue. At the photopic background luminance level L_B=0.1 cd/m^2 the contrast threshold is highest when the background spectrum is red and lowest when the background spectrum is green or blue. At the photopic background luminance level L_B=1 cd/m^2 the contrast threshold is highest when the background spectrum is red. When a static stimulus was used the statistical analysis showed that the background and stimulus spectra have a significant effect (p-values << 0.05) on contrast thresholds at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2. At these photopic background luminance levels the contrast threshold is highest when the background spectrum is red and lowest when the background spectrum is blue. At the photopic background luminance level L_B=1 cd/m^2, using a static stimulus, no significant differences in contrast thresholds between stimulus spectra were found.

In summary it can be said that when the photopic background luminance level decreases from L_B=10 cd/m^2 to L_B=0.01 cd/m^2 the differences between contrast thresholds measured with different background spectra also increase. With a decreasing photopic background luminance level, the contrast threshold measured with a red background spectrum becomes higher compared to the contrast threshold measured with a blue background spectrum.

In these measurements the spectrum of the background and the stimulus were the same and thus the photopic and mesopic contrast between the stimulus and the background remained the same. In the measurements presented in this chapter differences between the contrast thresholds measured with different background spectra were found at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2, even though the photopic background luminances were the same for each background spectrum. It is known that the contrast threshold decreases when the photopic background luminance decreases [Blackwell O.M and Blackwell H.R. 1971]. Because of this it could be assumed that the mesopic background luminances were different with

different background spectra. The lowest contrast thresholds were measured with a blue background spectrum. This confirms that the mesopic luminance is highest with a blue background spectrum at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2 and the spectral sensitivity of the eye shifts towards shorter wavelengths when the photopic background luminance level decreases from L_B=10 cd/m^2 to L_B=0.01 cd/m^2.

5.1.4 The effect of eccentricity

The hypothesis for the effect of eccentricity is that the changes in spectral sensitivity affect the contrast threshold only when the measurements are made at 10° eccentricity.

In Phase I the statistical analysis shows that the contrast threshold is significantly higher at an eccentricity of 10° than at an eccentricity of 0° when the background spectrum is blue (p-value 0.005) and the photopic background luminance level is L_B=2.5 cd/m^2. With a red background spectrum and at the photopic background luminance level L_B=0.1 cd/m^2 the contrast threshold is significantly higher at an eccentricity of 10 than at 0° (p-value 0.042). At other photopic background luminance levels no significant differences between eccentricities of 0 and 10° could be found.

In Phase II the contrast threshold is significantly higher at an eccentricity of 0 than at 10° when the background spectrum is blue (p-value 0.006) and the photopic background luminance level is L_B=0.01 cd/m^2. With a red background spectrum and at the background luminance levels L_B=0.1 and 1 cd/m^2 the contrast threshold is significantly higher at an eccentricity of 10 than 0° (p-values 0.016 and 0.031).

Because there are no rods in the central part of the fovea, changes in spectral sensitivity in the mesopic luminance range are expected only in the extra-foveal parts of the retina. Thus it was expected that at the lower photopic background luminance levels L_B=0.01 and 0.1 cd/m^2 differences between contrast thresholds would be found between the eccentricities of 0 and 10°. However, only a few significant differences between contrast thresholds measured at eccentricities of 0 and 10° could be found at the lower photopic background luminance levels L_B=0.1 and 0.01 cd/m^2 in Phases I and II. In Figure 5 it can be seen that the contrast threshold increases most with red and least with a blue background spectrum at eccentricities of both 0 and 10° when the photopic background luminance level decreases. Thus it could be said that the spectral sensitivity of the eye also shifts towards shorter wavelengths at an eccentricity of 0° when the photopic background luminance level decreases.

One reason for the similarity of the results of the contrast threshold measurements at eccentricities of 0 and 10° might be the measurement method. In the measurements a moving stimulus was used. The total area where the stimulus was visible was 3 × 4°. This was larger than the area of the central part of the fovea, so rods also took part in the vision in the measurements at an eccentricity of 0°.

Another reason for the similarity of the results at eccentricities of 0 and 10° might be that fixation is difficult at an eccentricity of 0°. In peripheral vision fixation is easy, as the subject can fixate on the central point of the perimeter. In the measurements at an eccentricity of 0° there was no marked fixation point and, especially at lower photopic background luminance levels, it is not sure that the subject detects the stimulus using only the fovea. In fact, at low photopic luminance levels the stimuli can be seen better

using slightly off-axis than pure foveal vision. So it is possible that the subject also used extra foveal vision during the 0°-eccentricity measurements.

5.1.5 The effect of the movement of the stimulus

The hypothesis for the effect of the stimulus movement is that the contrast threshold is higher when measurements are made using a static stimulus.

In Phase IV the statistical analysis shows that the contrast threshold is significantly higher (p-values << 0.05) when a static stimulus is used, compared to a moving stimulus at all the photopic background luminance levels L_B=0.01, 0.1, and 1 cd/m^2. The standard deviations were smaller when a moving stimulus was used because a moving stimulus is easier to detect than a static stimulus [Luisov 1980, Goldstein 2002].

5.1.6 Conclusions

The changes in the contrast threshold as a function of photopic background luminance level confirm that when the photopic background luminance level decreases from L_B=1 cd/m^2 to L_B=0.01 cd/m^2 the spectral sensitivity of the eye shifts towards the shorter wavelengths. This was found with the measurements at eccentricities of both 0 and 10°. Lewis [1999] found the same kind of effect with a different experimental arrangement. In his study sinusoidal gratings were used as a stimulus and the light sources used were an incandescent lamp, high- and low-pressure sodium lamps, a mercury lamp, and a metal halide lamp. For the measurements of this thesis background and stimulus spectra with a 100-nm bandwidth were used.

It was also found that the behaviour of the contrast threshold and thus the changes in the spectral sensitivity were almost identical at eccentricities of 0 and 10°. Because of this it could be said that the changes in the spectral sensitivity affect the visibility of targets sized over 3°.

The measurements with moving and static stimuli indicate that a moving stimulus is easier to detect.

5.2 Measurements with white background

5.2.1 Results

Contrast threshold measurements with a white background were made in Phases III, IV, V, and VI. In Figure 7 the results of the contrast threshold measurements of Phases III, IV, and V at an eccentricity of 10° are presented. Figure 7a presents the contrast threshold values measured with a static stimulus and Figure 7b the contrast threshold values measured with a moving stimulus. The contrast threshold values of Phase IV are multiplied by 100 and the contrast threshold values of Phase V by 10,000 for the sake of the clarity of the figure.

Figure 8 presents the results of the contrast threshold measurements made in Phase III at an eccentricity of 0°. Figure 8a presents the contrast thresholds measured using a static stimulus and Figure 8b the contrast thresholds measured using a moving stimulus.

Figure 9 presents the results of the contrast threshold measurements made in Phase VI.

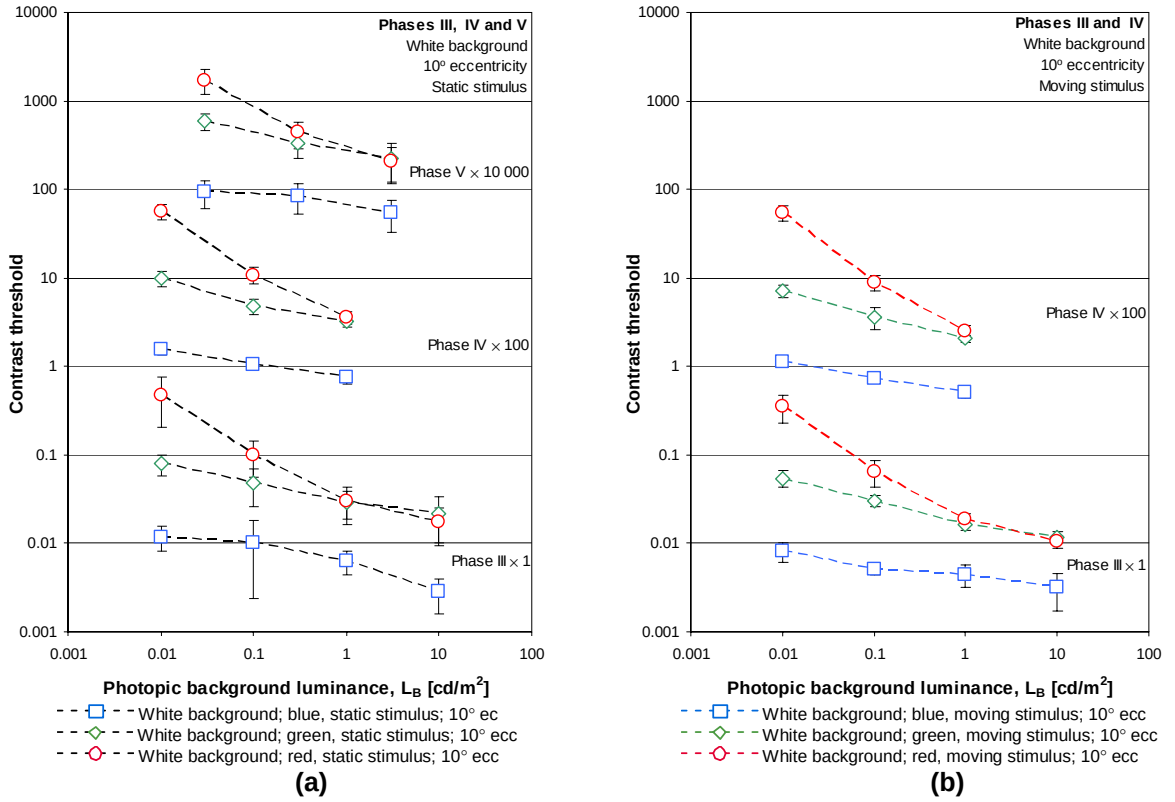

Figure 7. The average contrast thresholds of Phases III, IV, and V. The results at an eccentricity of 10° with a static stimulus (a) The results at an eccentricity of 10° with a moving stimulus (b). The background spectrum was white and the stimulus spectra were blue, green, and red. Photopic background luminance levels were L_B=0.01, 0.1, 1, and 10 cd/m^2 in Phase III, L_B=0.01, 0.1, and 1 cd/m^2 in Phase IV, and L_B=0.03, 0.3, and 3 cd/m^2 in Phase V. The bars show the standard deviations. The contrast threshold values of Phase IV are multiplied by 100 and the contrast threshold values of Phase V by 10000.

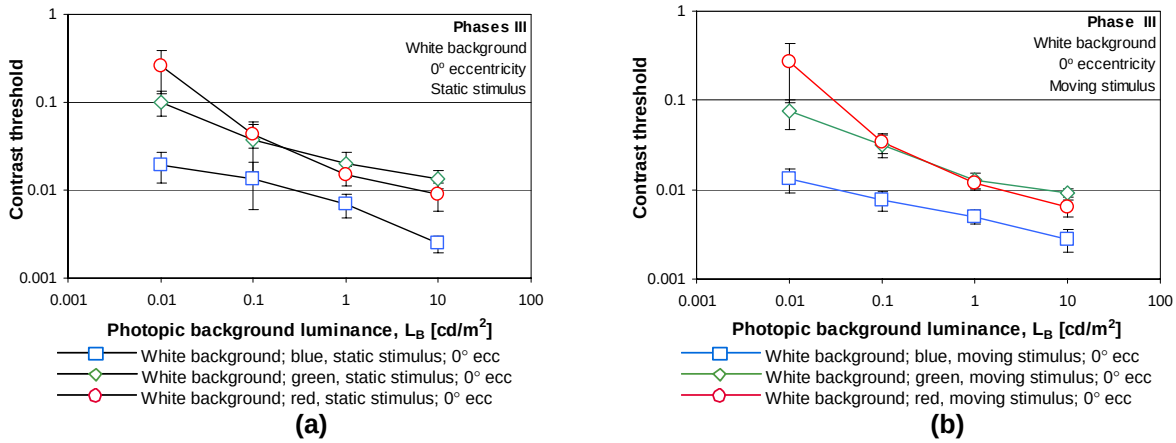

Figure 8. The average contrast thresholds of Phase III. The results at an eccentricity of 0° with a static stimulus (a). The results at an eccentricity of 0° with a moving stimulus (b). The background spectrum was white and the stimulus spectra were blue, green, and red. Photopic background luminance levels were L_B=0.01, 0.1, 1, and 10 cd/m^2. The bars show the standard deviations.

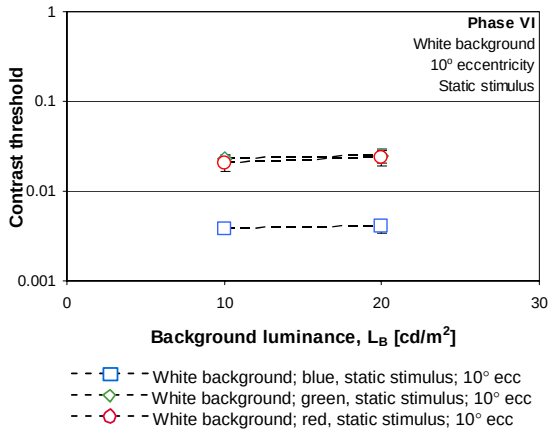

Figure 9. The average contrast thresholds of Phase VI. The background spectrum was white, the stimulus spectra were blue, green, and red, and photopic background luminance levels were L_B=10 and 20 cd/m^2. The bars show the standard deviations.

5.2.2 The effect of photopic background luminance

The hypothesis for the effect of photopic background luminance is that the contrast threshold increases when the background luminance level decreases.

In Phase III the statistical analysis shows that the contrast threshold decreases significantly at an eccentricity of 10° (p-values << 0.05) when the photopic background luminance increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2, from L_B=0.1 cd/m^2 to L_B=1 cd/m^2, and from L_B=1 cd/m^2 to L_B=10 cd/m^2 when both moving and static stimuli were used and when the stimulus spectrum was green or red. With a blue stimulus spectrum the contrast threshold decreased when the photopic background luminance increased from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 only when a moving stimulus was used (p-value 0.001). A significant decrease in the contrast threshold could be found between the photopic background luminance levels L_B=0.01 cd/m^2 and L_B=1 cd/m^2 and L_B=0.1 cd/m^2 and L_B=10 cd/m^2, both with a static and moving stimulus and with all stimulus spectra.

In Phase III the contrast threshold decreases significantly at an eccentricity of 0° (p-values << 0.05) when the photopic background luminance increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2, from L_B=0.1 cd/m^2 to L_B=1 cd/m^2, and from L_B=1 cd/m^2 to L_B=10 cd/m^2 when both a moving and static stimulus were used and when the stimulus spectrum was blue or red. With a green stimulus spectrum a significant decrease in contrast threshold could be found between the photopic background luminance levels L_B=0.01 cd/m^2 and L_B=1 cd/m^2, both with static and moving stimuli. With a green stimulus spectrum the contrast threshold decreased when the photopic background luminance increased from L_B=1 cd/m^2 to L_B=10 cd/m^2 only when a moving stimulus was used (p-value 0).

In Phase IV the contrast threshold decreases significantly at an eccentricity of 10° (p-values from 0.004 to 0.012) when the photopic background luminance level increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 and from L_B=0.1 cd/m^2 to L_B=1 cd/m^2 with a moving stimulus with all stimulus spectra. With a static stimulus the contrast threshold decreases significantly when the photopic background luminance level increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 and from L_B=0.1 cd/m^2 to L_B=1 cd/m^2 with blue and red stimuli (p-values 0.012 and 0.003). With a green stimulus spectrum and with a static

stimulus the contrast threshold decreases significantly when the photopic background luminance level increases from L_B=0.01 cd/m^2 to L_B=0.1 cd/m^2 (p-value 0.015).

In Phase V the contrast threshold decreases significantly (p-values << 0.05) when the photopic background luminance level increases from L_B=0.03 cd/m^2 to L_B=0.3 cd/m^2 and from L_B=0.3 cd/m^2 to L_B=3 cd/m^2 with all stimulus spectra.

In Phase VI there are no significant changes in the contrast thresholds between the photopic background luminance levels L_B=10 and 20 cd/m^2 with any stimulus spectrum.

In summary it can be said that the contrast threshold increased when the photopic background luminance level decreased. The spectra of the background and the stimulus were different, so the photopic and mesopic contrasts between the stimulus and the background were different. When the photopic background luminance decreased from L_B=10 cd/m^2 to L_B=0.01 cd/m^2 the contrast threshold increased more with a red stimulus spectrum than with a blue stimulus spectrum at eccentricities of both 0 and 10°. This means that when the photopic background luminance level decreased a greater difference in luminance between the stimulus and the background was needed for a red than a blue stimulus to make the stimulus detectable at eccentricities of both 0 and 10°. This confirms that the spectral sensitivity of the eye shifts towards shorter wavelengths when the photopic background luminance decreases.

5.2.3 The effect of the stimulus spectrum

The hypothesis for the effect of the stimulus spectrum is that the contrast threshold increases most with a red stimulus spectrum and least with a blue when the contrast threshold is measured at 10° eccentricity.

In Phase III the statistical analysis showed that at an eccentricity of 0° the stimulus spectrum had a significant effect (p-values << 0.05) on the contrast threshold at the photopic background luminance level L_B=0.01 cd/m^2. The contrast threshold was highest when the stimulus spectrum was red and lowest when the stimulus spectrum was blue. This was true for both static and moving stimuli. At the photopic background luminance level 0.1 cd/m^2 the contrast threshold was lower with a blue stimulus than with green and red stimuli with both moving and static stimuli. At the photopic background luminance level L_B=1 cd/m^2 the contrast threshold was lower with a blue stimulus than with green and red stimuli when a moving stimulus was used and lowest with a blue and highest with a green stimulus spectrum when a static stimulus was used. At the photopic background luminance level L_B=10 cd/m^2 the contrast threshold was lowest with a blue stimulus spectrum and highest with a green stimulus with both moving and static stimuli.

In Phase III the stimulus spectrum has a significant effect at an eccentricity of 10° (p-values << 0.05) on the contrast threshold at the photopic background luminance levels L_B=0.01 cd/m^2 and L_B=0.1 cd/m^2. The contrast threshold is highest when the stimulus spectrum is red and lowest when the stimulus spectrum is blue. This was true for both static and moving stimuli. At the photopic background luminance levels L_B=1 cd/m^2 and L_B=10 cd/m^2 the contrast threshold is lower with a blue stimulus spectrum than with green and red stimulus spectra. There was no significant difference between contrast thresholds measured with green and red stimuli. This was true for both static and moving stimuli.

In Phase IV the stimulus spectrum has a significant effect (p-values << 0.05) on the contrast threshold at the photopic background luminance levels L_B=0.01 cd/m^2 and L_B=0.1 cd/m^2. The contrast threshold is highest when the stimulus spectrum is red and lowest when the stimulus spectrum is blue. This was true for both static and moving stimuli. At the photopic background luminance level L_B=1 cd/m^2 the contrast threshold is lower with a blue stimulus than with green and red stimuli. There was no significant difference between the contrast thresholds measured with green and red stimuli. This was true for both static and moving stimuli.

In Phase V the stimulus spectrum has a significant effect (p-values << 0.05) on the contrast threshold at the photopic background luminance levels L_B=0.03, 0.3, and 3 cd/m^2. The contrast threshold is highest when the stimulus spectrum is red and lowest when the stimulus spectrum is blue.

In Phase VI there is a significant difference between the contrast threshold values measured with blue, green, and red stimuli at the photopic background luminance levels L_B=10 and 20 cd/m^2 (p-values << 0.05). The contrast threshold value is lowest with a blue and highest with a red stimulus spectrum.

Because the spectra of the background and the stimulus were different, the mesopic and photopic contrasts between the stimulus and the background were not the same. Thus the differences in contrast thresholds between stimuli with different spectra at the same photopic background luminance level indicate that the spectral sensitivity of the eye differs from the photopic spectral luminous efficiency function V(λ). At the photopic background luminance levels L_B=0.01, 0.03, 0.1, and 0.3 cd/m^2 the contrast threshold was highest when the stimulus spectrum was red and lowest when the stimulus spectrum was blue. This indicates that the blue stimulus looked brighter against the white background than did the red stimulus and the spectral sensitivity of the eye was shifted towards shorter wavelengths.

At the photopic background luminance levels L_B=1, 10, and 20 cd/m^2 the contrast threshold measured with a blue stimulus spectrum is lower than the contrast threshold measured with green or red stimulus spectra. This indicates that in peripheral vision the spectral sensitivity of the eye does not follow the photopic spectral luminous efficiency function V(λ) even if the photopic background luminance levels are within the photopic luminance range (L_B=10 or 20 cd/m^2).

The differences in contrast thresholds between the different stimulus spectra at 0° eccentricity at background luminance levels L_B=0.01 and 0.1 cd/m^2 might be caused by the uncertainty of the contrast threshold measurements described in Chapter 5.1.4. At background luminance levels L_B=1 and 10 cd/m^2 with a static stimulus, and at background luminance level L_B=10 cd/m^2 with a moving one, it was found that the contrast threshold was highest with a green stimulus. This might indicate that the photopic spectral luminous efficiency function V(λ) does not describe the spectral sensitivity of the eye perfectly at the fovea when the contrast threshold is used as a visual task. This is suggested because the photopic spectral luminous efficiency function V(λ) is based on brightness matching and flicker photometry measurements. In order to confirm this, more accurate contrast threshold measurement methods at 0° eccentricity are needed.

5.2.4 The effect of the movement of the stimulus

The hypothesis for the effect of the stimulus movement is that the contrast threshold is higher when measurements are made using a static stimulus.

In Phase III the statistical analysis shows that the contrast threshold is significantly higher with a static stimulus than a moving stimulus at an eccentricity of 0° with a green stimulus at the photopic background luminance levels L_B=0.01, 1, and 10 cd/m^2 (p-values 0.019, 0.002, and 0.01 correspondingly) and with a red stimulus at the photopic background luminance level L_B=10 cd/m^2 (p-value 0.011). At an eccentricity of 10° the contrast threshold is significantly higher with a static than with a moving stimulus with green stimulus spectra at the photopic background luminance level L_B=1 cd/m^2 (p-value 0.011).

In Phase IV the contrast threshold is significantly higher (p-values << 0.05) with a static than a moving stimulus at the photopic background luminance levels L_B=0.1 and 1 cd/m^2 for all stimulus spectra. At the photopic background luminance level L_B=0.01 cd/m^2 the contrast threshold is significantly higher (p-values << 0.05) with a static than a moving stimulus in both the blue and green stimulus spectra.

In summary it can be said that the average contrast thresholds were lower when the contrast threshold was measured with a moving stimulus, even if the differences were not always statistically significant. This indicates that a moving stimulus is easier to detect than a static stimulus.

The movement of the stimulus had a stronger effect on the contrast threshold in Phase IV than in Phase III. One reason for this might be that the measurements in Phase IV were made five times with two trained subjects and those in Phase III once with five subjects. The use of two trained subjects in Phase IV led to smaller deviations in the contrast threshold in Phase IV than in Phase III. Thus the differences could be better detected statistically in Phase IV.

5.2.5 The effect of the eccentricity

The hypothesis for the effect of the eccentricity is that the changes in spectral sensitivity affect the contrast threshold when measurements are made at 10° eccentricity.

In Phase III the statistical analysis shows that with a blue stimulus spectrum and at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2 the contrast threshold is significantly higher (p-values 0.0048 and 0.0166 correspondingly) at an eccentricity of 0° than at an eccentricity of 10° when a moving stimulus was used.

With a green stimulus spectrum the contrast threshold is higher (p-value 0.047) at an eccentricity of 0° than at an eccentricity of 10° at the photopic background luminance level L_B=0.01 cd/m^2 when a moving stimulus was used. At the photopic background luminance levels L_B=1 and 10 cd/m^2 the contrast threshold was higher at an eccentricity of 10° than at an eccentricity of 0° (p-values << 0.05). When a static stimulus was used the contrast threshold was higher at an eccentricity of 10° than at an eccentricity of 0° (p-value 0.0379) at the photopic background luminance levels L_B=1 and 10 cd/m^2.

With a red stimulus spectrum the contrast threshold was higher at an eccentricity of 10° than at an eccentricity of 0° at the photopic background luminance levels L_B=0.1, 1, and 10 cd/m^2 when both moving and static stimuli were used (p-values << 0.05)

The results show that the contrast threshold behaves almost identically as a function of photopic background luminance level at eccentricities of both 0 and 10°. Statistically significant differences were found, but the differences between contrast thresholds were small. This indicates that changes in spectral sensitivity also have an effect on visibility at an eccentricity of 0° when the visual target is sized 2°. One reason for this result might be the inaccuracy of the measurement method, as described in Chapter 5.1.3.

5.2.6 Conclusions

In the measurements of Phases III, IV, V, and VI presented in this chapter the background spectrum was white and the spectra of the stimuli were blue, green, and red. Because the spectra of the stimulus and the background were different, the mesopic and photopic contrasts between the stimulus and the background were different.

In the measurements of Phases III, IV, and V, presented in this chapter, the contrast thresholds increased when the photopic background luminance level decreased. The effect was stronger with red and green stimulus spectra than with a blue stimulus spectrum at eccentricities of both 0 and 10°. Differences between contrast thresholds with different stimulus spectra were found at all photopic background luminance levels, but the differences increased when the photopic background luminance level decreased. The contrast thresholds were lower with a blue stimulus spectrum than with a red stimulus spectrum. This indicates that the spectral sensitivity of the eye shifted towards shorter wavelengths.

At the photopic background luminance levels L_B=10 and 20 cd/m^2 the contrast threshold was lower with a blue than a green or red stimulus spectrum. One reason for this might be that in the photopic luminance range the off-axis parts of the retina are more sensitive to short wavelengths than the fovea. The definition of luminance is based on the photopic spectral luminous efficiency function V(λ), which describes the spectral sensitivity of the eye in 2° foveal vision. The difference in spectral sensitivity of different parts of the retina can be seen by comparing the spectral luminous efficiency function V(λ) and spectral luminous efficiency function for a 10° field $V_{10}(\lambda)$ in Figure 1. The $V_{10}(\lambda)$ has higher spectral sensitivity values in the blue part of the spectrum, in comparison to the V(λ). The results confirm that the spectral luminous efficiency function V(λ) does not describe the spectral sensitivity of the eye in the peripheral parts of the retina, even if the photopic background luminance levels are in the photopic luminance range.

5.3 The contrast threshold measured with coloured and white backgrounds

5.3.1 Results

In Phase IV the contrast threshold measurements were made using both coloured and white background spectra. The measurements were made five times for two subjects. The measurements were made during the same session using a white and coloured background. The results of Phase IV are shown in Figure 10. Figure 10a shows the contrast threshold values measured with a static stimulus and Figure 10b shows the contrast threshold values measured with a moving stimulus. The contrast thresholds measured with a white background are multiplied by 100 for the sake of the clarity of the figure.

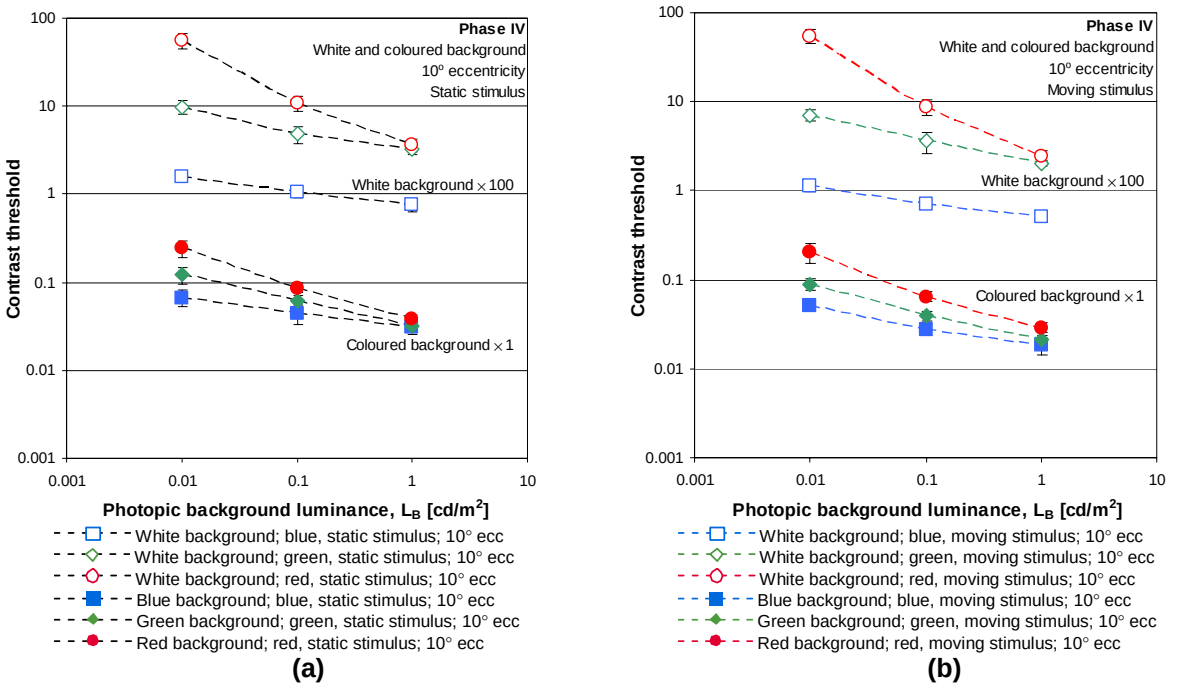

Figure 10. The average contrast thresholds in Phase IV. The results at an eccentricity of 10° with a static stimulus (a). The results at an eccentricity of 10° with a moving stimulus (b). The background spectra were white, blue, green, and red and the stimulus spectra were blue, green, and red. The photopic background luminance levels were L_B=0.01, 0.1, and 1 cd/m^2. The bars show the standard deviations. The contrast threshold values of the results with a white background are multiplied by 100.

5.3.2 The effect of the background and stimulus spectra

The hypothesis for the effect of the background and stimulus spectra is that the changes in spectral sensitivity have a larger effect on the contrast threshold when measurements are made with a white background and white stimulus than when they are made with a coloured background and coloured stimulus.

The statistical analysis showed that with a blue stimulus spectrum the contrast thresholds were higher with a blue background spectrum than with a white background spectrum at the photopic background luminance levels L_B=0.01, 0.1 and 1 cd/m^2, both for static and moving stimuli. With a green stimulus spectrum the contrast thresholds were higher with a green background spectrum than with a white background spectrum at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2 for a static stimulus and at the photopic background luminance level L_B=0.01 cd/m^2 for a moving stimulus. With a red stimulus spectrum the measured contrast threshold is higher with a white background spectrum than with a red background spectrum at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2 for both static and moving stimuli.

5.3.3 Conclusions

When the background and the stimulus had the same spectrum, the changes in the spectral sensitivity of the eye did not have an effect on the mesopic contrasts between the background and the stimulus, only on the mesopic background and stimulus luminances. Because the contrast threshold was lower with a blue background spectrum than a red background spectrum it can be assumed that the mesopic background luminance was higher with a blue background spectrum than a red background spectrum. This confirms

that when the photopic background luminance decreased, the spectral sensitivity of the eye shifted towards shorter wavelengths.

In case of a white background spectrum and blue, green, or red stimulus spectra the mesopic luminance of the background was always the same within one photopic background luminance level. Because the coloured stimulus was superimposed onto the background, the difference between the mesopic luminance of the stimulus and the mesopic luminance of the background was dependent on the spectrum of the stimulus. Thus the changes in the spectral sensitivity of the eye directly affected the mesopic contrast between the stimulus and the background. When the spectral sensitivity of the eye was shifted towards shorter wavelengths, a larger luminance difference between the red stimulus and white background was needed for the stimulus to be detectable than was the case with the blue stimulus and white background.

It was found that the differences between contrast thresholds measured with different stimulus spectra are larger with a white than with a coloured background. This indicates that changes in the mesopic contrast between the stimulus and the background have a stronger effect on the contrast threshold than changes in the mesopic background luminance.

The difference between contrast thresholds measured with a blue stimulus and green and red stimuli is also larger with a white than a coloured background at the photopic background luminance level L_B=1 cd/m^2. This indicates that the photopic spectral luminous efficiency function V(λ) does not describe the spectral sensitivity of the eye at an eccentricity of 10° at the photopic luminance level L_B=1 cd/m^2, which is near the lower limit of the photopic luminance range. This property of the photopic spectral luminous efficiency function V(λ) should be taken into consideration when calculating the contrast of coloured stimuli against a white background.

5.4 Mono- and binocular contrast threshold measurements

5.4.1 The results

In Phase VII contrast threshold measurements were made to find out if there were differences in the contrast threshold when the measurements were made monocularly or binocularly. The results are shown in Figure 11. Figure 11a shows the results at an eccentricity of 0° and Figure 11b shows the results at an eccentricity of 10°.

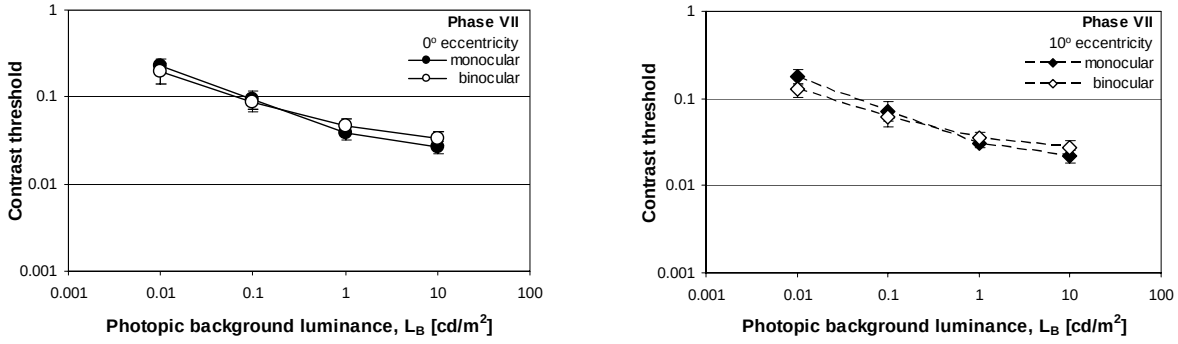

Figure 11. The average contrast thresholds of Phase VII. a) The results at an eccentricity of 0 °. b) The results at an eccentricity of 10 °. Both monocular and binocular vision were used. Photopic background luminance levels were L_B=0.01, 0.1, 1, and 10 cd/m^2; the background and stimulus spectra were white. The bars show the standard deviations.

5.4.2 The effect of photopic background luminance

The statistical analysis shows that the contrast threshold decreases when the photopic background luminance level increases from L_B=0.01 to L_B=0.1 cd/m^2, from L_B=0.1 to L_B=1 cd/m^2, and from L_B=1 to L_B=10 cd/m^2 (p-values $<<$ 0.05). This was true at eccentricities of both 0 and 10° and for both monocular and binocular vision.

5.4.3 The effect of eccentricity

The statistical analysis shows that the contrast threshold is significantly higher at an eccentricity of 0° that at an eccentricity of 10° at every photopic background luminance level, L_B=0.01, 0.1, 1, and 10 cd/m^2 and both in mono- and binocular vision (p-values $<<$ 0.05).

5.4.4 The differences between mono- and binocular vision

The statistical analysis shows that the contrast threshold is significantly higher in binocular vision than monocular vision at the photopic background luminance level L_B=10 cd/m^2 at an eccentricity of 0° (p-value 0.010). At an eccentricity of 10° the contrast threshold is higher at the photopic background luminance level L_B=0.01 cd/m^2 in monocular vision (p-value 0) and the contrast threshold is higher in binocular vision at the photopic background luminance levels L_B=1 and 10 cd/m^2 (p-values 0.001 and 0.000).

5.4.5 Conclusions

The goal of the measurements of this phase was to find out if the results of the previous phases would have been different if the measurements had been made with monocular vision instead of binocular vision. The results of Phase VII indicate that with an eccentricity of 0° the contrast threshold is the same for monocular and binocular vision at the photopic background luminance levels L_B=0.01...1 cd/m^2 at which most of the contrast threshold measurements of this thesis were made. At an eccentricity of 10° the effect of monocular/binocular vision on the contrast threshold is dependent on the photopic background luminance level. At the low photopic background luminance level L_B=0.01 cd/m^2 the measured contrast thresholds are higher in monocular vision and at the higher photopic background luminance levels L_B=1 and 10 cd/m^2 the measured contrast threshold is higher in binocular vision. Thus it could be said that at 10° the contrast threshold measured with binocular vision cannot be generalised to monocular vision.

The measurements of this phase were made with two subjects. Because of the experimental set-up, the monocular measurements were made using the left eye for both subjects. A better way to compare contrast thresholds in monocular and binocular vision could have been to make the measurements using the leading eye of the subject in monocular measurements. In these measurements it was not found out which eye was the leading eye.

The effect of the eccentricity on the contrast threshold was clearer in Phase VII than in the previous phases. In Phase VII the contrast threshold was always higher at an eccentricity of 0°. One reason for this might be that the white stimulus was easier to detect than a coloured stimulus. Another reason might be that the white spectrum used consisted of all wavelengths and so the difference between the mesopic and photopic luminance of the background was small. Fixation could also be easier at an eccentricity of 0° when the stimulus and the background were white.

6 Applying results to the existing models for mesopic spectral sensitivity

6.1 Applied models

In this chapter the results of this thesis are applied to Palmer's first model [Palmer 1968], the X model [Rea et al 2004], and the MOVE model [Eloholma and Halonen 2005]. Palmer's model was the first heterochromatic brightness matching-based model and the MOVE model and X model are the latest performance-based models.

The calculations were performed for the contrast threshold data obtained at an eccentricity of 10° using the coloured and white background spectra and a static stimulus.

The results of Phase VI were also applied to the peripheral spectral luminous efficiency function developed by Orreveteläinen [2005].

6.2 Calculations with the MOVE and X models

Although the MOVE model [Eloholma and Halonen 2005] and X model [Rea et al 2004] are based on different equations, their use is similar. With both models it is possible to calculate the mesopic luminance when the photopic and scotopic luminances are known. The outputs of both models are the mesopic luminance and the weighting factor for calculating the mesopic spectral luminous efficiency function from the photopic spectral luminous efficiency function $V(\lambda)$ and scotopic spectral luminous efficiency function $V'(\lambda)$.

When a coloured background and a coloured stimulus with the same spectra were used in the contrast threshold measurements, the mesopic contrast between the background and the stimulus was independent of the spectral sensitivity of the eye and thus independent of the spectral luminous efficiency function used. In the case of a coloured background the mesopic luminances of the background were calculated using the photopic and scotopic luminances of the background as input values in the MOVE model and X model using Equations (11) and (7). The contrast thresholds of Phases I, II, and IV are presented as a function of mesopic background luminance in Figures 12, 13, and 14.

When a white background and a coloured stimulus were used, the mesopic contrast between the background and the stimulus changed when the spectral sensitivity of the eye changed. Using Equation (7) for the X model and Equation (11) for the MOVE model the mesopic background luminances were calculated for each photopic background luminance level. Then, using the parameter 'X' from Equation (6) for the X model and the parameter 'x' from Equation (10) for the MOVE model, it was possible to calculate the mesopic spectral luminous efficiency functions given by both models. With the mesopic spectral luminous efficiency functions it was possible to calculate the mesopic luminance for the difference between the photopic luminances of the stimulus and the background. From these the mesopic contrast between the stimulus and the background was calculated separately for each measured contrast threshold value. The mesopic contrast thresholds are presented as a function of photopic background luminance in Figures 16, 17, and 18.

6.3 Calculations with Palmer's model

With Palmer's model the mesopic luminance can be calculated using the large-field photopic luminance and scotopic luminance as input values. The experiments on which Palmer's model is based on were performed using the 5, 15, and 45° field sizes. The value of the parameter M_{P1} in the model (Equation (2)) is dependent on the field size used. In the calculation of this thesis the value of M_{P1}=0.0628, which was a value for M_{P1} for the 15° field size, is used because, according to Palmer [1968], it is probably applicable to any field larger than 10°.

When a coloured background and a coloured stimulus with the same spectra were used, the mesopic background luminance was calculated using Equation (2). The contrast thresholds in Phases I, II, and IV are presented as a function of mesopic background luminance in Figures 12, 13, and 14.

When a white background and a coloured stimulus were used, the mesopic background luminances for each photopic background luminance level were calculated using Equation (2). The luminance difference, in terms of the mesopic luminance between the background and the stimulus, was calculated using Equation (2). From these the mesopic contrast between the stimulus and the background was calculated separately for each measured contrast threshold value. The mesopic contrast thresholds are presented as a function of photopic background luminance in Figures 16, 17, and 18. These calculations were different with Palmer's model than with the X model and MOVE model, because it was not possible to calculate the mesopic spectral luminous efficiency function with Palmer's model.

6.4 Comparison of the models for mesopic spectral sensitivity with a coloured background

Figures 12a, 13a, and 14a present the contrast thresholds measured in Phases I, II, and IV as a function of mesopic background luminance calculated using the MOVE model, X model, and Palmer's model. When the mesopic background luminances are calculated using the X model the contrast thresholds are multiplied by 100 and when the mesopic background luminances are calculated using Palmer's model the contrast thresholds are multiplied by 10,000 for the sake of the clarity of the figure. Figure 12b, 13b, and 14b present the contrast threshold measured in Phases I, II and IV as a function of photopic background luminance.

All the models applied for mesopic spectral sensitivity give equally good estimations for the mesopic background luminance when contrast threshold is used as a visual task. An ideal model for mesopic spectral sensitivity would describe the mesopic luminances of the background with different spectra and at different photopic background luminance levels, so that the measured contrast thresholds were set on the same curve. It can be seen from Figures 12, 13, and 14 that none of the models does this perfectly. There is no analytical method to compare the models with each other. With these results it is not possible to say which of these three models is the best model for spectral sensitivity in the mesopic luminance range.

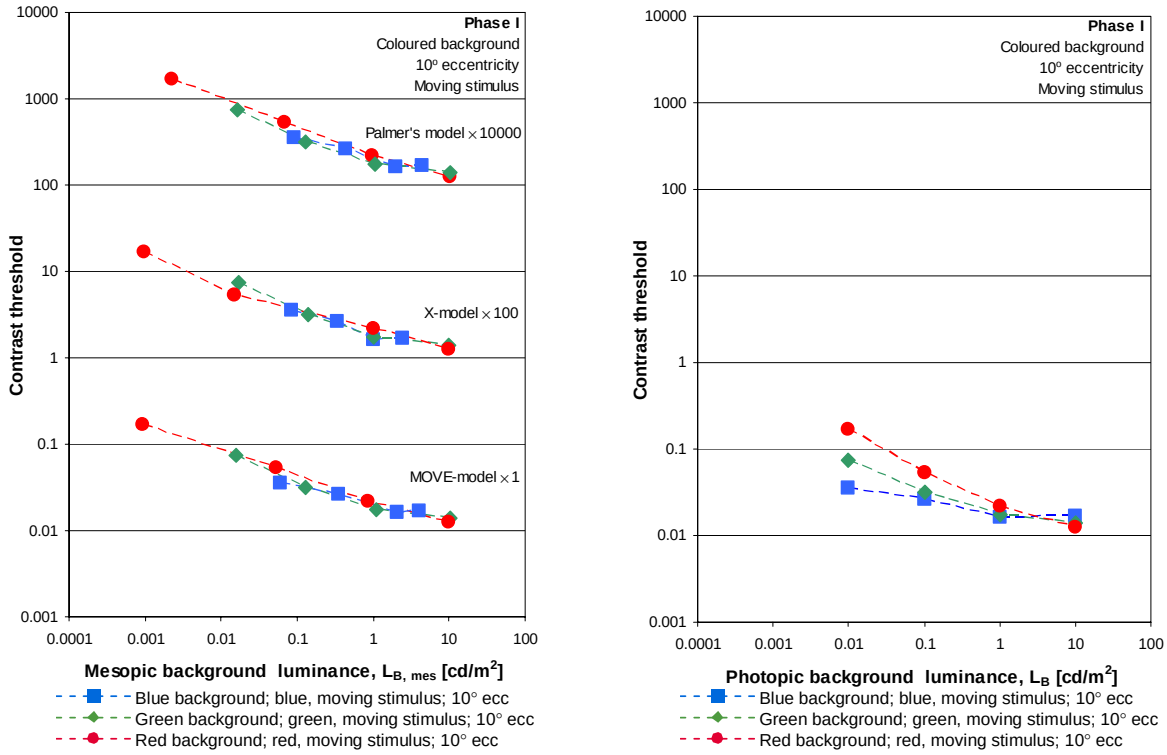

Figure 12. The contrast threshold measured in Phase I as a function of mesopic background luminance calculated using the MOVE model, X model, and Palmer's model (a). The results are multiplied by 1, 100, and 10,000 respectively. The contrast threshold measured in Phase I as a function of photopic background luminance (b)

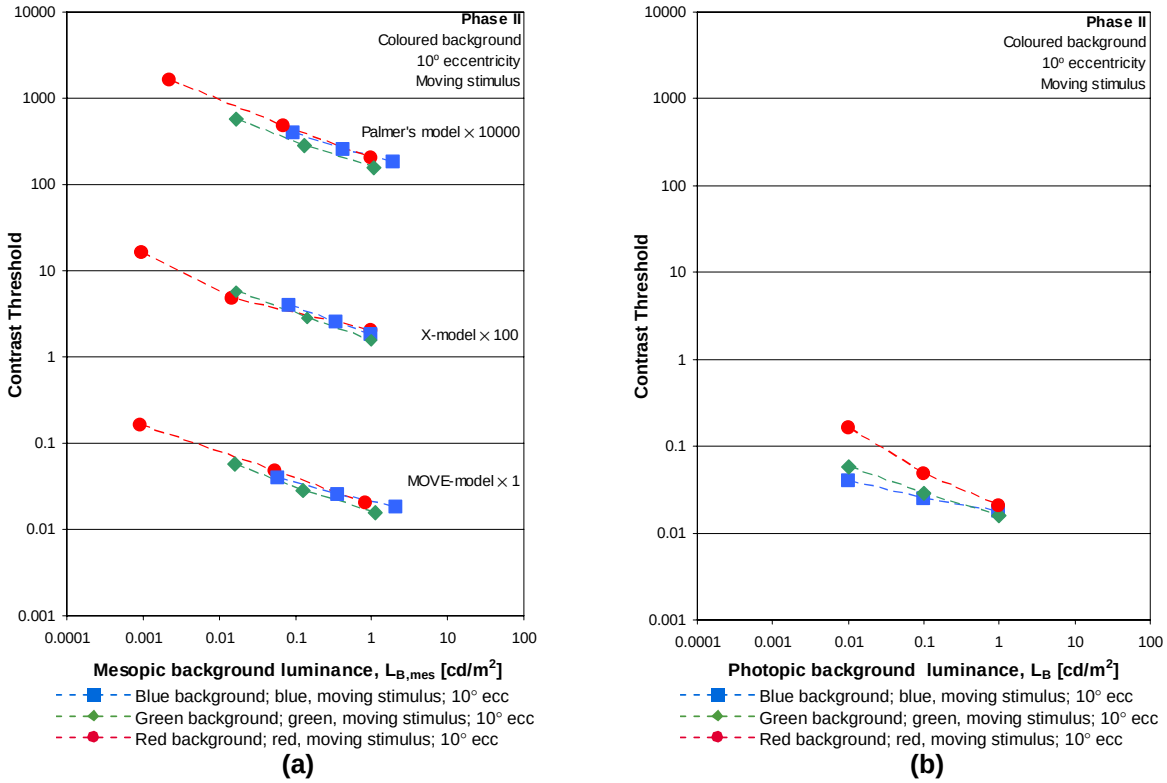

Figure 13. The contrast threshold measured in Phase II as a function of mesopic background luminance calculated using the MOVE model, X model, and Palmer's model (a). The results are multiplied by 1, 100, and 10,000, respectively. The contrast threshold measured in Phase II as a function of photopic background luminance (b).

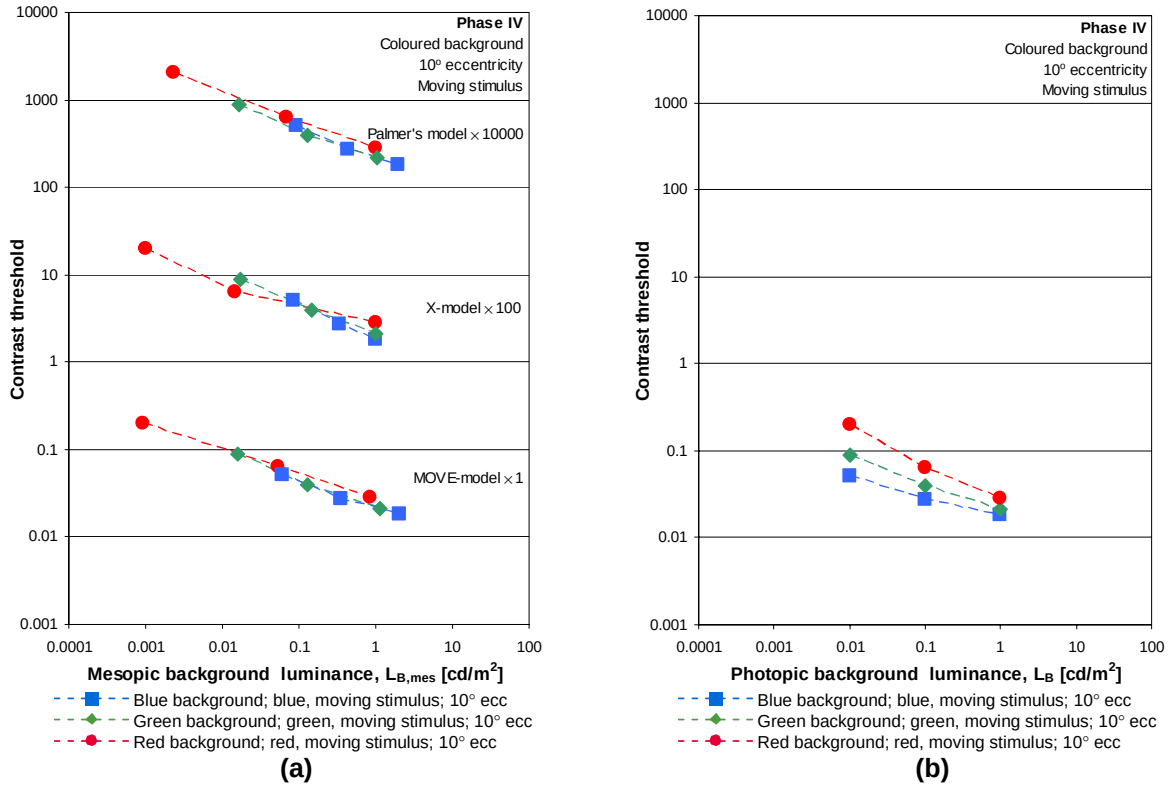

Figure 14. The contrast threshold measured in Phase IV as a function of mesopic background luminance calculated using the MOVE model, X model, and Palmer's model (a). The results are multiplied by 1, 100, and 10,000 respectively. The contrast threshold measured in Phase IV as a function of photopic background luminance (b).

In order to make a reliable comparison between the different models for mesopic spectral sensitivity using a background and stimulus with the same spectrum the experimental setup should be arranged differently. Instead of using the same photopic luminances in the background with different spectra, the same mesopic luminance, calculated using the applied models for mesopic spectral sensitivity, should be used. When the mesopic luminance levels of the background are the same within each background spectrum, the contrast thresholds measured with different background spectra within one mesopic background luminance level should be the same. Then e.g. the standard deviation between the contrast thresholds measured with different background spectra within one mesopic background luminance level could be calculated in order to estimate the quality of the model. A large standard deviation between the contrast thresholds measured with different background spectra within the same mesopic background luminance level would indicate that the applied model for mesopic spectral sensitivity does not describe the spectral sensitivity in the mesopic luminance range perfectly.

In Figure 15a the mesopic luminances of a background with blue, green, and red spectra at the photopic luminance levels L_B=0.01...10 cd/m^2 are presented. In Figure 15b the ratio of mesopic luminance to photopic luminance with blue, green, and red spectra at the photopic luminance levels L_B=0.01...10 cd/m^2 is presented.

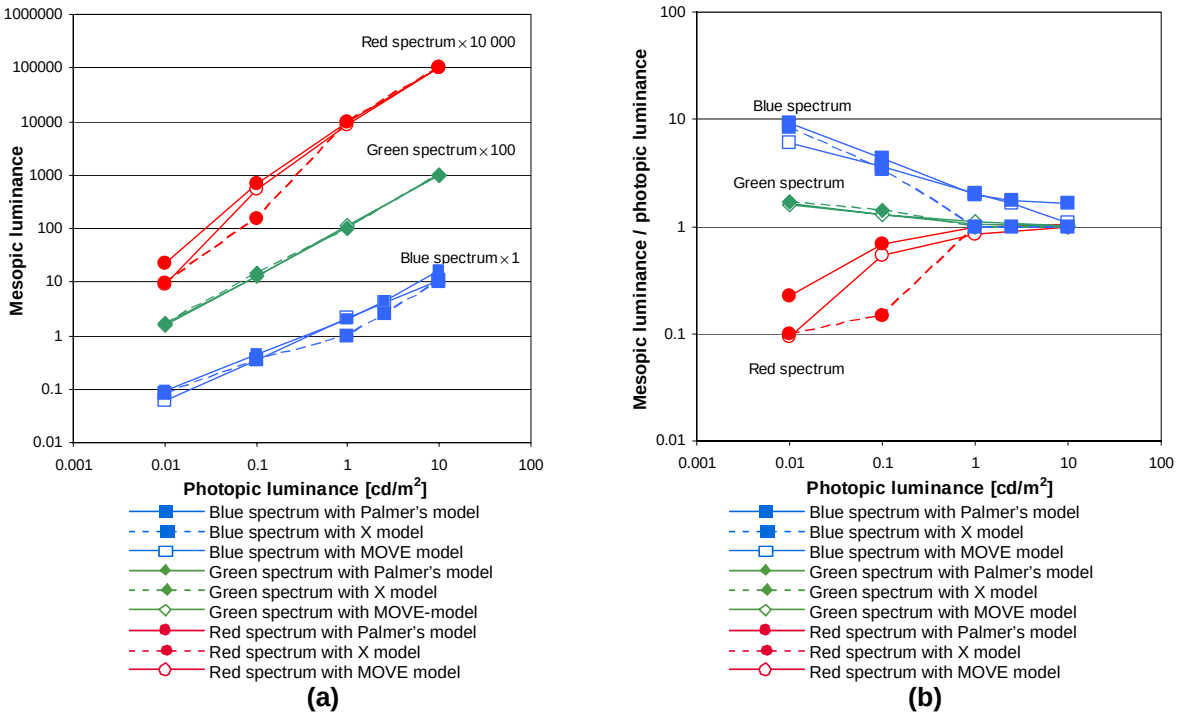

Figure 15. Mesopic luminances calculated with Palmer's model, the X model, and the MOVE model for blue, green, and red background spectra (a). The mesopic luminances for green background spectra are multiplied by 100 and mesopic luminances for red background spectra by 10,000. The ratio of calculated mesopic luminance and photopic luminance (b).

For the green background spectrum the differences between mesopic luminances calculated with Palmer's model, the X model, and the MOVE model are small. The S/P ratio of the green spectrum is only 1.7, compared to S/P ratios of 11 for blue and 0.092 for red spectra. Because the mesopic luminances calculated using the MOVE model and X model are dependent on the S/P ratio, it is logical that an S/P ratio near 1 gives almost equal mesopic luminances even if the calculation method of the model is different. In Palmer's model the large-field photopic luminance and scotopic luminance were used when calculating the mesopic luminance. If the S/P ratio is calculated using the large-field photopic luminance and scotopic luminance, it is still 1.7 for a green background spectrum. Because of this, it is not possible to find the differences between the models with a green spectrum.

For the red background spectrum at the photopic background luminance level L_B=0.01 cd/m^2, Palmer´s model gives the highest mesopic luminance. At the photopic background luminance level L_B=0.1 cd/m^2 Palmer´s model gives the highest and the X model gives the lowest mesopic luminance for the red background spectrum. For the blue background spectrum the differences between mesopic luminances calculated using Palmer's model, the X model, and the MOVE model are smaller at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2 than with the red spectrum. At the photopic background luminance levels L_B=1 and 2.5 cd/m^2 the X model gives the lowest mesopic luminance for the blue background spectrum.

Palmer's model was based on measurements made using a bipartite field at an eccentricity of 0°. Thus more cones took part in vision than in the measurements which are the basis of the MOVE model and the X model were made at eccentricities of 10, 12, and 15°. Because of this the long wavelengths of the red spectrum affected the mesopic

luminances calculated using Palmer's model more than they affected the mesopic luminances calculated using the MOVE model or X model. In the blue spectrum the difference between Palmer's model and the other two models is not so large. The reason might be that the S/P ratio of the blue spectrum is so high that the different weighting between photopic or large-field photopic and scotopic luminances in different models does not have a strong effect on the mesopic luminance.

One difference between the X model and the other two models can be seen from Figure 15. The X model assumes that mesopic luminance is equal to photopic luminance above photopic luminance levels of 0.6 cd/m^2. Because of this, the ratio of photopic luminance and mesopic luminance calculated using the X model changes significantly between the photopic luminance levels 0.1 and 1 cd/m^2.

6.5 Comparison of the models for mesopic spectral sensitivity with white background

Figures 16a, 17a, and 18a present the mesopic contrast threshold calculated by applying the MOVE model, X model, and Palmer's model to the contrast thresholds measured in Phases III, IV, and V as a function of photopic background luminance. The contrast thresholds calculated using the X model are multiplied by 100 and the contrast thresholds calculated using Palmer's model by 10,000 for the sake of the clarity of the figure. Figures 16b, 17b, and 18b present the contrast threshold (V(λ)-weighted) measured in Phases III, IV, and V as a function of photopic luminance background luminance.

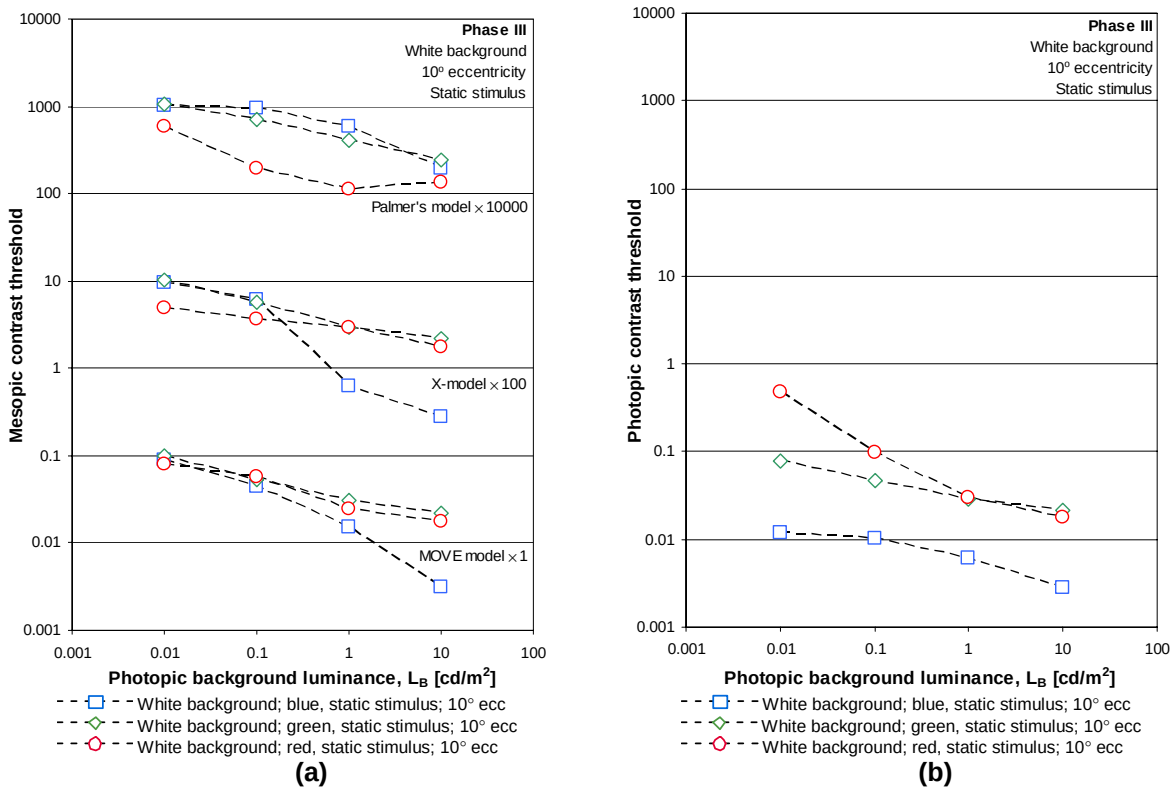

Figure 16. The mesopic contrast threshold calculated by applying the MOVE model, X model, and Palmer's model to the contrast threshold measured in Phase III (a). The results are multiplied by 1, 100, and 10,000 respectively. The results of the measurement of photopic contrast thresholds in Phase III (b).

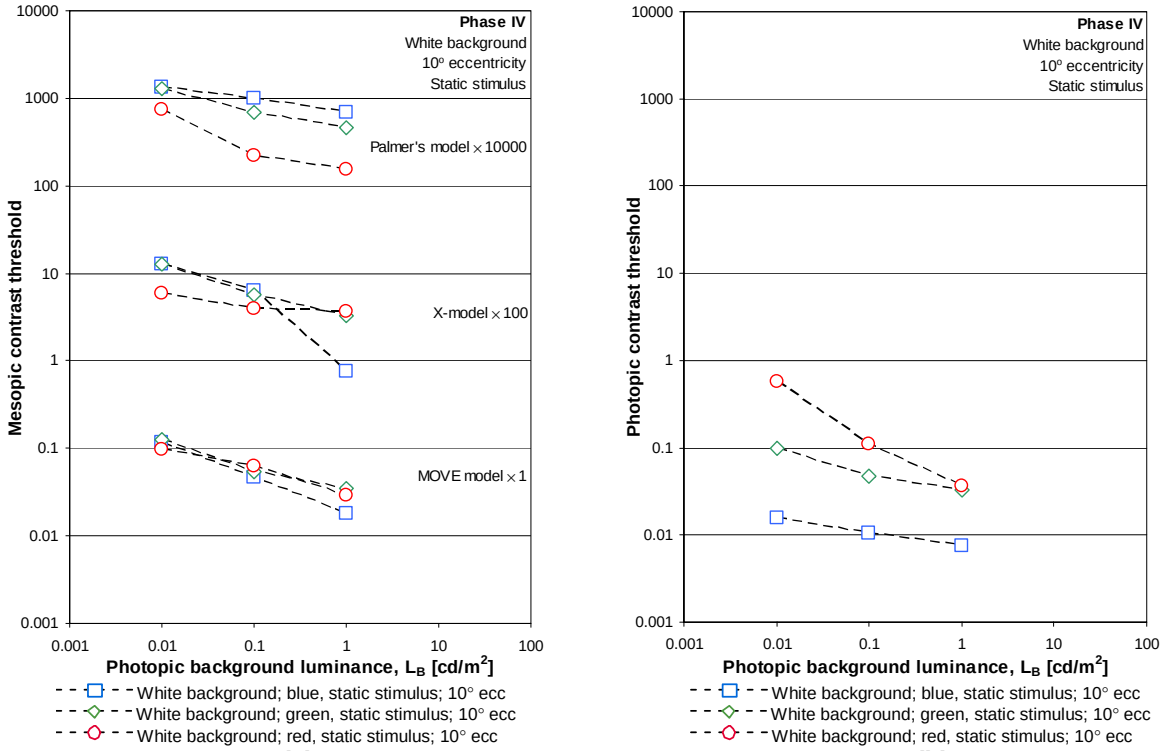

Figure 17. The mesopic contrast threshold calculated by applying the MOVE model, X model, and Palmer's model to the contrast thresholds measured in Phase IV (a). The results are multiplied by 1, 100, and 10,000 respectively. The results of the measurement of photopic contrast thresholds in Phase IV (b).

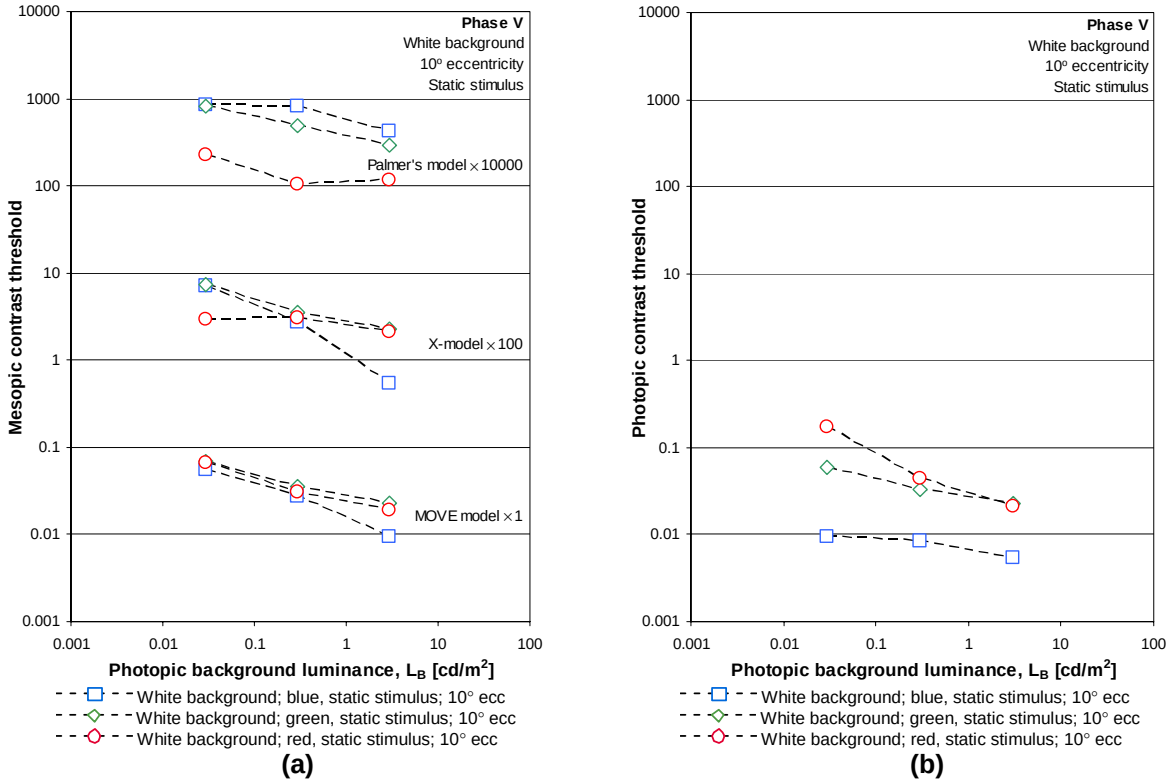

Figure 18. The mesopic contrast thresholds calculated by applying the MOVE model, X model, and Palmer's model to the contrast threshold measured in Phase V (a). The results are multiplied by 1, 100, and 10,000 respectively. The results of the measurement of photopic contrast thresholds in Phase V (b).

By using the models for mesopic spectral sensitivity it should be possible to define the mesopic luminance in such a way that the performance of the visual task within one mesopic luminance level is independent of the light spectrum. In this study the contrast threshold was used as a visual task. Thus the models for mesopic spectral sensitivity should define the mesopic contrast thresholds in such a way that within the same photopic background luminance they are independent of the stimulus spectrum used.

When comparing the models, the standard deviations of the mesopic contrast thresholds with different stimulus spectra were used as an estimate of the quality of the model. This was possible because the mesopic luminances of the background were the same for each stimulus spectrum within one photopic background luminance level. It was supposed that a small standard deviation between mesopic contrast thresholds within the same photopic background luminance level with different stimulus spectra indicates that the model used for mesopic spectral sensitivity gives a good estimate of the mesopic contrast. A good estimate of the mesopic contrast threshold indicates that the model gives a good estimate of the mesopic luminances of the stimulus and the background.

In Figure 19 the standard deviations of the mesopic contrast thresholds calculated using Palmer's model, the X model, and the MOVE model and the measured photopic contrast thresholds of Phases III, IV, and V are shown. At the photopic background luminance levels L_B=0.01...3 cd/m^2 the MOVE model gives the smallest standard deviation for the mesopic contrast thresholds. The standard deviations of the mesopic contrast thresholds calculated with the X model and Palmer's model are of the same order of magnitude at the photopic background luminance levels L_B=0.01, 0.03, 1, and 3 cd/m^2. At the photopic background luminance levels L_B=0.1 and 0.3 cd/m^2 the standard deviations of the mesopic contrast thresholds calculated with the X model are higher than the standard deviations calculated with Palmer's model. At the photopic background luminance level L_B=10 cd/m^2 Palmer's model gives the lowest standard deviation and the standard deviations of the mesopic contrast threshold calculated with the MOVE model and X model are of the same order of magnitude. The uncertainty of the contrast threshold estimated in Chapter 3.3 is negligible compared to the standard deviations between the mesopic contrast thresholds within one photopic background luminance level.

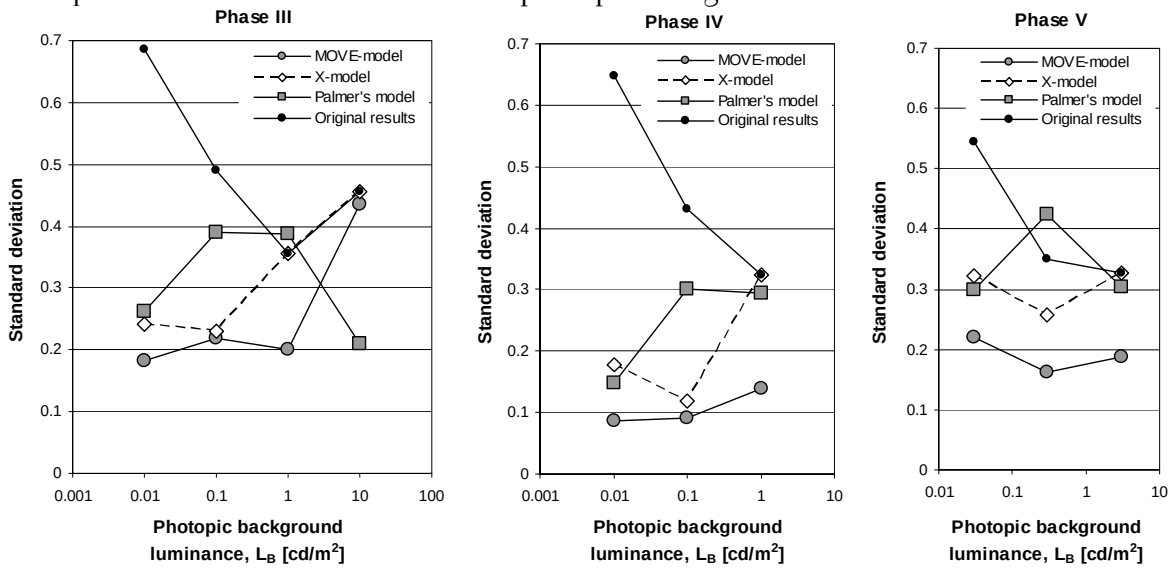

Figure 19. The standard deviations of the photopic contrast threshold measured in Phases III, IV, and V and the standard deviations of the mesopic contrast thresholds calculated using the three different models for mesopic spectral sensitivity

The standard deviations of the photopic contrast thresholds are higher than the standard deviations of the mesopic contrast thresholds at the photopic background luminance levels L_B=0.01 and 0.1 cd/m^2. At the photopic background luminance level L_B=1 cd/m^2 in Phase III and at L_B=0.3 cd/m^2 in Phase V the standard deviations of the mesopic contrast thresholds calculated using Palmer's model are higher than the standard deviations of the photopic contrast thresholds. At the photopic background luminance levels L_B=1, 3 and 10 cd/m^2 the mesopic contrast threshold calculated using the X model is equal to the photopic contrast thresholds because the X model defines the mesopic luminance only at the photopic luminance levels <0.6 cd/m^2.

In conclusion it can be said that the MOVE model gives the best estimates of the mesopic contrast threshold at the photopic background luminance levels L_B=0.01...3 cd/m^2. At the photopic background luminance level L_B=10 cd/m^2 Palmer's model gives the best estimate of the mesopic contrast threshold.

6.6 Calculations with peripheral spectral luminous efficiency function

The contrast threshold values measured in Phase VI can be applied to the model for spectral sensitivity in peripheral vision developed by Orreveteläinen [2005]. Using Equation (12) the contrast threshold values can be defined using the peripheral spectral luminous efficiency function $V_{per}(\lambda)$. These are known as peripheral contrast thresholds.

Figure 20a shows the contrast thresholds measured in Phase VI and Figure 20b and Figure 20c show the peripheral contrast thresholds calculated from the results of Phase IV as a function of photopic background luminance. Because a white background and a coloured stimulus were used, the contrast between the background and the stimulus was dependent on the spectral luminous efficiency function used. It was supposed that the model is optimal if the peripheral contrast thresholds within the same photopic background luminance level are independent of the spectrum of the stimulus. The standard deviations between the peripheral contrast thresholds measured with different stimulus spectra within one photopic background luminance level are used as an indicator of the quality of the model.

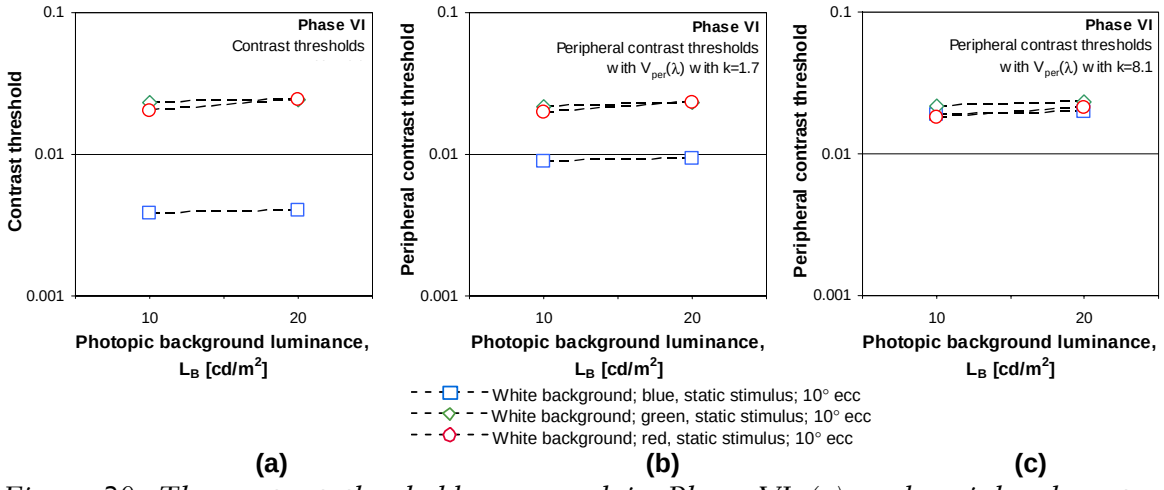

Figure 20. The contrast thresholds measured in Phase VI (a) and peripheral contrast threshold calculated using spectral luminous efficiency function $V_{per}(\lambda)$ with k values k=1.7322 (b) and k=8.1 (c).

The standard deviations of the photopic contrast thresholds at the photopic background luminance levels L_B=10 and 20 cd/m^2 are 0.0105 and 0.0117. When the contrast thresholds are calculated using the peripheral spectral luminous efficiency function $V_{per}(\lambda)$ with k=1.7322, the standard deviations of the peripheral contrast threshold at the photopic background luminance levels L_B=10 and 20 cd/m^2 are 0.0068 and 0.0078 correspondingly. k=1.7322 was the k-value which was optimised in Orreveteläinen's [2005] study. The minimum standard deviations for the peripheral contrast threshold at the photopic background luminance levels L_B=10 and 20 cd/m^2 are reached when the value k=8.1 is given for the parameter k. Then the standard deviations of the peripheral contrast thresholds at the photopic background luminance levels L_B=10 and 20 cd/m^2 are 0.0020 and 0.0012 correspondingly.

There are two possible explanations as to why the minimum standard deviations are reached using a different k-value than that optimised in Orreveteläinen's [2005] study. First, the spectra of the stimuli used were different. Orreveteläinen used narrow-band LEDs as a light source for the stimulus and in this thesis the bandwidth of the stimulus spectra was 100 nm. Secondly, the visual task was different. In Orreveteläinen's study reaction time was used as a visual task and Orreveteläinen's model was applied to the contrast threshold measurements of this thesis.

As a conclusion of calculations with a peripheral spectral luminous efficiency function, it can be said that models based on the measurements of reaction time do not necessarily describe the spectral sensitivity when contrast threshold is used as a visual task. This result is in accordance with the results of Viénot and Chiron [1995], who found that, when the spectral sensitivity function is based on flicker photometry, the transition from the scotopic domain to the photopic is more abrupt than when the sensitivity function is based on brightness matching.

6.7 Conclusion of the models for mesopic spectral sensitivity

The measurements that form the basis of the models were made using different parameters. Palmer's model [Palmer 1968] is based on measurements made with several quasi-monochromatic lights with a half-bandwidth of 30 nm. Stimuli sized 5, 15, and 45° were presented at an eccentricity of 0°. The X model [Rea et al 2004] is partly based on measurements made using high-pressure sodium lamp and metal halide lamp spectra [He et al 1997] and partly on measurements with five quasi-monochromatic light spectra with a half-bandwidth of 10 nm for the left eye and the light of a low-pressure sodium lamp light for the right eye [He et al 1998]. The stimulus eccentricities were 15 and 12° respectively. The MOVE model [Eloholma and Halonen 2005] is based on measurements made with both quasi-monochromatic light spectra with a 10-nm bandwidth, narrow-band spectra with 15...40-nm bandwidth and broadband light spectra with a stimulus at an eccentricity of 10°. The effects of the different parameters of the measurements on the basis of the models used could partly explain the differences between the models.

The models are also based on different visual tasks. Palmer's model [Palmer 1968] is based on brightness matching measurements, the X model [Rea et al 2004] is partly based on monocular reaction time measurements [He et al 1997] and partly on binocular simultaneity measurements [He et al 1998], and the MOVE model [Eloholma and Halonen 2005] is based on the contrast threshold, reaction time, and visual acuity measurements. When

applying the results of this thesis to the model of Orreveteläinen [2005], it was found that a model for spectral sensitivity based on reaction time measurements does not necessarily describe the vision when the model is applied to the results of the contrast threshold measurements. Thus the different visual tasks that form the basis of the models used could partly explain the differences found between the models. On the basis of the measurements of this thesis it is not possible to say what the effect is of the visual task on the basis of the model for spectral sensitivity to the mesopic luminance given by the model.

One difference between the models used for mesopic spectral sensitivity is that they define the limits of mesopic luminance range differently. Palmer's model is a weighted mean of scotopic and large-field photopic luminance, as can be seen from Equation (3). The weighting factor 'a_P' gets a value a_P=0.01 at the large-field photopic luminance value L_{10}=4.3 cd/m^2. This means that above the large-field photopic luminance level L_{10}=4.3 cd/m^2 the effect of the scotopic luminance on mesopic luminance is less than 1% and the mesopic luminance is almost equal to the large-field photopic luminance. The MOVE model is also a weighted mean of scotopic luminance and photopic luminance, as can be seen from Equation (8). The parameter 'x' gets a value x=0.99 at the photopic luminance level L_P=11.9 cd/m^2. The X model is a weighted mean of scotopic luminance and photopic luminance levels below L_P=0.6 cd/m^2 and above this the mesopic luminance is defined as being equal to the photopic luminance. This causes abrupt changes in the mesopic contrast thresholds between the photopic background luminance levels L_B=0.1 and 1 cd/m^2 when mesopic contrast thresholds are calculated using the X model.

When the mesopic background luminances and mesopic contrast thresholds were defined using Palmer's model [Palmer 1968], the X model [Rea et al 2004], and the MOVE model [Eloholma and Halonen 2005], the differences between the mesopic contrast threshold with different background and stimulus spectra were smaller than the differences between photopic contrast thresholds with different background and stimulus spectra. All the models used give better estimates of the mesopic background luminance or mesopic contrast threshold than the spectral luminous efficiency function V(λ). When the background spectrum is white and the stimulus spectrum is blue, green, or red, the MOVE model gives the best estimate of the mesopic luminance at photopic background luminance levels L_B=0.01...3 cd/m^2.

7 Conclusions

The results of this thesis confirmed that when the photopic background luminance level decreases from L_B=10 cd/m^2 to L_B=0.01 cd/m^2 the contrast threshold increases at stimulus eccentricities of both 0 and 10°. It was found that the contrast threshold increased least with blue and most with red background spectra when the background and stimulus had the same spectrum. When the background was white the contrast threshold increased least with blue and most with red stimulus spectra. The results show that the spectral sensitivity of the eye is shifted towards shorter wavelengths when photopic background luminance levels decrease from L_B=10 to L_B=0.01 cd/m^2.

The contrast threshold measurements at the photopic background luminance levels L_B=10 and 20 cd/m^2 showed that contrast thresholds were lower with a blue stimulus spectrum than with green or red stimulus spectra, even within the same photopic background luminance level. This indicates that the photopic spectral luminous efficiency function V(λ) does not describe the spectral sensitivity of the eye at an eccentricity of 10°, even in the photopic luminance range.

The new idea in this thesis was that the contrast threshold measurements were made both with a white background and blue, green, and red stimuli and with blue, green and red backgrounds and blue, green, and red stimuli. It was found that the differences between the contrast thresholds measured with different stimulus and background spectra were larger when the measurements were made with a coloured stimulus and a white background. Thus it can be said that the changes in the spectral sensitivity of the eye affect the visibility of a low-contrast stimulus more if the stimulus is coloured and the background is white than if the stimulus and the background have the same spectrum. It can also be said that in mesopic conditions a low-contrast blue stimulus can be seen better than a low-contrast red stimulus in peripheral vision.

Lighting conditions comparable to the experimental set-up of this thesis can be found in road lighting conditions. There are visual targets which have the same spectrum as the background and visual targets which have a different spectrum than the background. Pedestrians, animals etc. which are illuminated by the road lighting have the same spectrum as the background, which is e.g. the road surface. Coloured traffic signs which are illuminated by the headlights of the car, reflectors worn by a pedestrian, or flashing lights and warning signals related to road construction work are examples of visual targets whose spectra usually differ from their background spectrum.

The results of the contrast threshold measurements were applied to three existing models for mesopic spectral sensitivity. It was found that all the models considered describe the spectral sensitivity at an eccentricity of 10° at the photopic background luminance levels L_B=0.01...10 cd/m^2 better than the photopic spectral luminous efficiency function V(λ), when the contrast threshold is used as a visual task. However, none of the models used describes the mesopic luminance or mesopic contrast threshold perfectly.

It was found that the MOVE model [Eloholma and Halonen 2005] describes the mesopic contrast threshold best at the photopic background luminance levels L_B=0.01...3 cd/m^2 when a white background and a coloured stimulus were used. The MOVE model is based on contrast threshold, reaction time, and visual acuity measurements.

A model for peripheral spectral sensitivity [Orreveteläinen 2005] was applied to the results of the contrast threshold measurements of this thesis. It was found that Orreveteläinen's model [2005], which is based on reaction time measurements, does not describe the spectral sensitivity when contrast threshold is used as a visual task. Thus it could be said that the quality of the models for spectral sensitivity should be validated using different visual tasks than those the model is based on. If the model for spectral sensitivity were based on measurements with different visual tasks, it would increase the reliability of the model.

In this thesis it was also found that the results of the contrast threshold measurements are different when the measurements are made monocularly or binocularly at an eccentricity of 10°. The difference between the contrast threshold measured with monocular or binocular vision depends on photopic background luminance and eccentricity. In mesopic conditions, e.g. in the case of road lighting, vision is binocular. Thus it could be said that the model for mesopic spectral sensitivity should be based on measurements made with binocular vision.

8 Author's contribution

The author designed the used measurement systems and measurement methods. The measurement system was constructed by the author or under the supervision of the author. The parameters of the contrast threshold measurement were jointly agreed by the Steering Committee of the MOVE project. The contrast threshold measurement were performed or supervised by the author. The analysis of the results and the conclusions were made by the author.

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