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CIE

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 1

CIE 16x:2005

UDC: 612.84
535.66

Descriptor: Physiological optics, vision
Colorimetry

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The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 38 countries and one geographical area and of 4 associate members.

The objectives of the CIE are :

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
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4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
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3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
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Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in 38 Ländern und einem geographischen Gebiet und aus 4 assoziierten Mitgliedern.

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2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 1-36 of Division 1 "Vision and Colour" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-36 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

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The following members of TC 1-36, "Fundamental chromaticity diagram with physiologically significant axes" took part in the preparation of this technical report. The committee comes under Division 1 "Vision and Colour".

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CONTENTS

FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 1

SUMMARY

CIE established, in 1991, the Technical Committee TC 1-36 with the following Terms of Reference: "Establish a fundamental chromaticity diagram of which the co-ordinates correspond to physiologically significant axes".

Part I of the report is limited to the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1° to 10°.

The report starts with the choice of the 10° Colour Matching Functions (CMFs) of Stiles and Burch (1959). Then, following the ideas put forward by Stockman and Sharpe (2000), by application of König's hypothesis, and using the most modern data on the spectral sensitivity functions of dichromats, it is followed by the derivation of the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane for a 10° viewing field, the so called "cone fundamentals".

Next, by correcting these functions for the absorption of the ocular media and the macular pigment, and taking into account the optical densities of the cone visual pigments, all for a 10° viewing field, the low density absorbance functions of these pigments were derived.

Using these low density absorbance functions one can derive, taking the absorption of the ocular media and the macula, and taking into account the densities of the visual pigments for a 2° viewing field, the 2° cone fundamentals.

Using the same procedure one can derive cone fundamentals for every viewing angle between 1° and 10°.

Effects of age can also be incorporated by application of the relationship of the absorption of the lens as a function of age.

Tables are given, with intervals of 5 nm, of

- 10° cone fundamental sensitivity functions, both in terms of energy and quanta;
- optical density of the macular pigment;
- optical density of lens and other ocular media;
- the photopigment low density absorbance spectra;
- 2° cone fundamental sensitivity functions, both in terms of energy and quanta;
- maximal optical density of the macular pigment as a function of field size;
- the optical density of lens and other ocular media as a function of age;
- the maximal values of the optical density of the visual pigments as a function of field size.

DIAGRAMME FONDAMENTAL DE CHROMATICITE AVEC DES AXES PHYSIOLOGIQUES – PARTIE 1

RESUME

La CIE a établi, en 1991, le comité technique TC 1-36 de la Division 1 Vision et couleur avec le mandat suivant : "Etablir un diagramme fondamental de chromaticité dont les coordonnées correspondent à des axes physiologiquement significatifs". La partie I du rapport est limitée au choix d'un ensemble de fonctions colorimétriques et à l'évaluation des fondamentales de cônes pour l'observateur normal, pour un champ visuel allant de 1° à 10°.

Le rapport commence par le choix des fonctions colorimétriques 10° (CMFs) de Stiles et de Burch (1959). Puis, selon les idées proposées par Stockman et Sharpe (2000), en appliquant l'hypothèse de König et en s'appuyant sur les données les plus modernes des fonctions de sensibilité spectrale des dichromates, on dérive les fonctions de sensibilité spectrale des cônes sensibles aux grandes (L), aux moyennes (M) et aux courtes (S)

longueurs d'onde, mesurées dans le plan de la cornée pour un champ visuel de 10°, que l'on nomme "fondamentales de cônes" pour 10°.

Ensuite, en corrigeant ces fonctions de l'absorption des milieux oculaires et du pigment maculaire, et en tenant compte de la densité optique des pigments visuels des cônes, toutes valeurs établies pour un champ visuel de 10°, on dérive les fonctions d'absorbance spectrale relative pour une faible concentration de ces photopigments. A l'aide de ces fonctions d'absorbance spectrale relative pour une faible concentration de photopigment, on peut calculer, en tenant compte de l'absorption des milieux oculaires, du pigment maculaire, et de la densité optique des pigments visuels des cônes, toutes valeurs établies pour un champ visuel de 2°, les fondamentales de cônes pour 2°.

Par le même procédé, on peut dériver des fondamentales de cônes pour tout angle visuel entre 1° et 10°.

L'effet de l'âge peut également être incorporé en appliquant la relation de l'absorption du cristallin en fonction de l'âge.

Des tables donnent, avec un intervalle de 5 nm,

- les fonctions de sensibilité des fondamentales de cônes pour 10°, en termes d'énergie et de quanta;
- la densité optique du pigment maculaire;
- la densité optique du cristallin et autres milieux oculaires transparents;
- les spectres d'absorbance relative pour une faible concentration des photopigments;
- les fonctions de sensibilité des fondamentales de cônes pour 2°, en termes d'énergie et de quanta;
- la densité optique maximale du pigment maculaire en fonction du diamètre du champ visuel;
- la densité optique du cristallin et autres milieux oculaires transparents;
- la valeur maximale de la densité optique des pigments visuels en fonction du diamètre du champ visuel.

GRUNDLEGENDE FARBTAFEL MIT PHYSIOLOGISCHEN ACHSEN – TEIL 1

ZUSAMMENFASSUNG

Im Jahre 1991 richtete die Internationale Beleuchtungskommission (CIE) das technische Komitee TC 1-36 ein mit folgendem Auftrag: "Schaffung einer grundlegenden Farbtafel deren Koordinaten physiologisch bedeutsamen Achsen entsprechen".

Teil I des vorliegenden Berichts beschränkt sich auf die Auswahl eines geeigneten Satzes von instrumentellen Spektralwertfunktionen und die Bereitstellung von spektralen Sehzapfen-Grundfunktionen für den Normalbeobachter, Funktionen, die für einen Sehwinkelbereich von 1° bis 10° gelten sollen.

Der Bericht beginnt mit der Wahl der 10°-Gesichtsfeld-Spektralwerte von Stiles und Burch (1959). Basierend auf den Ideen von Stockman und Sharpe (2000), werden die Königsche Hypothese, und die modernsten zahlenmäβigen Ergebnisse über die spektralen Empfindlichkeitsfunktionen der Dichromaten verwendet und die spektralen Empfindlichkeitsfunktionen der langwelligen (L), mittelwelligen (M) und kurzwelligen (S) Sehzapfen abgeleitet, präkorneal für ein 10°-Gesichtsfeld gemessen, die sogenannten "Sehzapfen-Grundfunktionen".

Danach werden aus diesen 10°-Gesichtsfeld-Grundfunktionen die spektralen inneren dekadische Extinktionswerte (die "spektrale Absorbanz") für verdünnte Sehzapfenpigment-Konzentrationen abgeleitet, indem - für ein 10°-Gesichtsfeld - die Absorption der okularen Medien und des Makulapigments berücksichtigt und die optische Dichte der Sehzapfenpigmente in Anrechnung gestellt wird. Mit Hilfe dieser "verdünnten" spektralen Absorbanz-Funktionen kann man 2°-Gesichtsfeld-Grundfunktionen nun dadurch herleiten,

daβ man für ein Gesichtsfeld sowohl die Absorption der okularen Medien und des Makulapigments als auch die optische Dichte der Sehzapfenpigmente berücksichtigt.

Nach dem gleichen Verfahren kann man Sehzapfen-Grundfunktionen für jeden Gesichtswinkel zwischen 1° und 10° ableiten.

Auch Auswirkungen des Lebensalters können durch die Beachtung der altersabhängigen Linsenabsorption einbezogen werden.

Es sind Tabellen angefügt, die in Intervallen von 5 nm u.a. folgendes erhalten:

- 10° Sehzapfen-Grundfunktionen, sowohl leistungs- als auch quantenfluβ-bezogen;
- optische Dichte des Makulapigments;
- optische Dichte der Linse und der übrigen okularen Medien;
- Absorbanz-Spektren für Sehpigmente geringer Dichte;
- 2° Sehzapfen- Grundfunktionen, sowohl leistungs- als auch quantenfluβbezogen;
- maximale optische Dichte des Makulapigments als Funktion der Gesichtsfeldgröβe;
- optische Dichte der Linse und der übrigen okularen Medien als Funktion des Lebensalters;
- maximale Dichte-Werte der Sehpigmente als Funktion der Gesichtsfeldgröβe.

1. INTRODUCTION

1.1 History

In 1931 CIE widened the scope of the photometric standard observer with the addition of colorimetric properties based on experimental studies by Wright (1928-1929) and by Guild (1931). Both of these studies were in terms of relative intensities, so that their final colour matching functions could only be defined after calibration with the photopic luminous efficiency function, $V(\lambda)$, which was established in 1924 by the CIE (CIE, 1926). This function had its problems though, because in the short wavelength region, the values were a compromise due to large differences between the results of various experiments. But even if the 1924 $V(\lambda)$ function had been faultless: this method presupposes a linear relation between photometry and colorimetry which needs not to be true and is not required to define colorimetric properties (Estévez, 1979).

A quarter of a century later Stiles and Burch determined a purely colorimetric database in a pilot study with ten observers (Stiles and Burch, 1955). The CIE, at its Zürich Session (CIE, 1955), did not consider the discrepancies between the CIE 1931 Standard Observer (CIE, 1931) and these 2° pilot data large enough to warrant a change in the standard data for practical colorimetry. Only a set of 10° colour-matching functions was derived to supplement the 2° existing colorimetric data basis (CIE, 1964).

However, vision researchers felt a need for an improved colorimetric observer as a common basis for their fundamental research. Other studies have since provided a great deal of additional information in terms of cone system action spectra. As there seems to be considerable convergence of ideas, it was appropriate to try to define a Modified Colorimetric Observer, in parallel to the Modified Photometric Observer, $V_M(\lambda)$, as published by the CIE (CIE, 1990). To that purpose CIE established, in 1991, the Technical Committee TC 1-36 with the following Terms of Reference: "Establish a fundamental chromaticity diagram of which the co-ordinates correspond to physiologically significant axes". The TC saw as its first task to "make the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1° to 10°". Further it saw as its task to consider age as a variable.

This report describes the underlying ideas, the methods, and the results, in terms of colour matching functions, receptor action spectra, photopigment action spectra for the eye media, etc. Colorimetric plots, one most similar to the CIE 1931 (x,y)-chromaticity diagram, in particular for those interested in its practical significance, and one in terms of cone system excitations, in particular for those interested in fundamental research, are also presented. All data were tabulated, with 5 nm spacing, and where necessary, in terms of both energy and quanta. All conclusions and recommendations are summarised in a final chapter, together with the prospects of further work.

1.2 Procedure

We call "cone fundamentals" the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane.

The derivation of cone fundamental sensitivity functions has a long history, starting with Helmholtz. Many attempts have been made since then. It should be recognised, however, that for deriving cone fundamental sensitivity functions from psycho-physical, the committee is mainly influenced, as far as the way of data is concerned, by the work of Vos and Walraven (1971), by Smith and Pokorny (1975), by Stockman, MacLeod and Johnson (1993), and finally by Stockman, Sharpe and Fach (1999) and Stockman and Sharpe (2000).

The committee agreed to accept the derivation as described in the latter two papers, in which the findings of the other mentioned papers are incorporated, and to accept, with the exception of some details, their data as recommendation to be used for fundamental research on colour vision. The committee agreed because it considers the choice of Stockman, Sharpe and Fach as:

- the best experimental database of colorimetric properties;
- the most reliable linear transformation of the colour matching functions $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$ and $\bar{b}_{10}(\lambda)$ to cone system action spectra $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$. Here König's interpretation of dichromacy as due to the complete loss of one cone system, is a necessary starting point, together with the current view that only the L- and M-systems notably contribute to luminance. Direct experimental action spectra, either from electrophysiological studies, or from psychophysical studies, or derived from dichromatic luminosity functions is considered as an additional evidence and a tool for validation rather than a primary input.
- the best modifying data of the intervening eye media on the spectra, so that the transformation from external (incident at the cornea) to internal (efficient for photopigment isomerisation) action spectra can be made;
- the way to bridge the gap between small-field and wide-field colorimetric properties by the thinning out of the macular pigment towards the periphery and by the subtle change in the action spectra due to a reduced effective optical density of the visual photopigments toward the periphery as appropriate.

Further:

- agreement was sought on a possible link with luminosity functions, which were already defined by the CIE. In the 10° case the $\bar{y}_{10}(\lambda)$ of the CIE1964 observer, which is based on the work of Stiles and Burch (1959) as well as of Speranskaya (1959), was chosen, but for the 2° case the proposal by Stockman and Sharpe to define the luminosity function, on quantum basis, as the addition of the appropriate proportions of $\bar{l}_{10}(\lambda)$ and $\bar{m}_{10}(\lambda)$ was followed, rather than e.g. choosing $V(\lambda)$ of 1924 or $V_M(\lambda)$;
- agreement was sought on the best transformation to a system similar to CIE 1931 *XYZ*, and a proposal was formulated for a corresponding Fundamental Chromaticity Diagram. In line with the generally accepted null luminosity from the S-system, a Luther-MacLeod-Boynton diagram was constructed in terms of *S/(L+M)* versus *L/(L+M)* (Luther 1927, MacLeod, Boynton, 1979),
- finally, all data were tabulated, with 5 nm spacing, and where necessary, in terms of both energy and quanta. Tables with 1 nm and 0,1 nm spacing can be found on the Website http://www.cvrl.ac.uk.

1.3 Restrictions

Since observers, even within the same age bracket, may differ, a fundamental observer must be a theoretical construct based on averages. Any "real observer" will be different from the "TC 1-36 Modified Colorimetric Observer".

The starting functions are average colour-matching functions from a large sample (about 50 observers). An important inter-observer source of variability is the polymorphism of the photopigments, showing up in the small, probably hereditary, variations of a few nanometers in λ_{peak} of the cone fundamentals. Additional parameters such as the lens optical density, or macular pigment optical density, are given as average figures. Where relevant, the inter-observer variability will be dealt with as a separate remark at the appropriate chapter.

The relative spectral optical density of the macular pigment is assumed to remain the same at any eccentricity, although it is recognized that there exists a variability of the Lutein/Zeaxanthin (L/Z) ratio over the retina. It would not be surprising if the ratio would vary among observers, and that its distribution versus eccentricity would vary as well. Although the Lutein/Zeaxanthin (L/Z) ratio in the macular pigment changes with eccentricity on the retina, the differences are considered not large enough to apply these for the calculations of the absorption by the macular pigment. Where relevant, the inter-observer variability will be dealt with as a separate remark in the appropriate chapter.

As a consequence of these inter-individual variations the accuracy of the tabulated values does not reflect actual accuracy. The number of decimals was chosen such that [ΔSensitivity/$\Delta\lambda$] values can be safely used as representing differential quotients [dSensitivity/dλ] values in model calculations on for instance wavelength discrimination.

Finally, in order to keep this document manageable the committee has been rather restrictive in arguing our choices on literature data on spectral absorption and sensitivity. The detailed arguments should then be taken from the original publications. Whenever such a choice is made, it is marked as a recommendation and indicated in bold letters.

1.4 Structure of the report

The report contains three parts. After the general introduction (Chapter 1), which also includes a list of definitions and symbols, Part I, composed of Chapters 2 to 5, deals with the derivation of the cone fundamentals from the colour mixture functions and data tables in Chapter 6.

Chapter 2 deals with the derivation of the CIE 10° Modified Colorimetric Observer. Chapter 3 is concerned with the derivation of the spectral absorbance functions of the three cone visual pigments. Chapter 4 deals with the derivation of the CIE 2° Modified Colorimetric Observer.

Chapter 5 deals with the way a colorimetric observer can be derived for any field of view between 1° and 10° and for any age, from the CIE 10° Modified Colorimetric Observer.

Chapter 6, finally, presents the tables pertaining to Part I.

Part II consists of chapters dealing respectively with the significance of the obtained results for photometry, and with the presentation of the results in terms of 2-dimensional chromaticity diagrams.

Part III consists of the summaries, the conclusions, and recommendations.

1.5 Definitions and symbols

Terms used in this report are defined according to the definition in the International Lighting Vocabulary (CIE, 1987).

The term cone fundamentals, however is not defined, and this committee recommends adding the following definition to the ILV.

Cone fundamentals or fundamental colour-matching functions

The spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-), and short-wave sensitive (S-) cones, measured in the corneal plane.

Symbols are respectively for spectral sensitivity functions:

$\bar{l}_{\mathrm{fs}}(\lambda)$, $\bar{m}_{\mathrm{fs}}(\lambda)$ and $\bar{s}_{\mathrm{fs}}(\lambda)$ when expressed in terms of energy, and

$\bar{l}_{\mathrm{q,fs}}(\lambda)$, $\bar{m}_{\mathrm{q,fs}}(\lambda)$ and $\bar{s}_{\mathrm{q,fs}}(\lambda)$ when expressed in terms of quanta,

the "*fs*" indicating the field size.

Note 1. For the 2° data the "2" is usually omitted.

For example:

$\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ when expressed in terms of energy, and

$\bar{l}_{\mathrm{q}}(\lambda)$, $\bar{m}_{\mathrm{q}}(\lambda)$ and $\bar{s}_{\mathrm{q}}(\lambda)$ when expressed in terms of quanta for a 2° field size; and

$\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ when expressed in terms of energy, and

$\bar{l}_{q,10}(\lambda)$, $\bar{m}_{q,10}(\lambda)$ and $\bar{s}_{q,10}(\lambda)$ when expressed in terms of quanta for a 10° field size.

Note 2. The functions are usually presented normalized such that the maximum value of each is unity.

Note 3. It is recommended that the terms cone fundamentals or fundamental colour-matching functions are used to specify the spectral sensitivity functions measured in the corneal plane. The use of the terms "fundamentals" or "fundamental response curves" is advised against, because these terms are sometimes used in other meanings.

2. CONE FUNDAMENTAL SENSITIVITY FUNCTIONS FOR THE 10° OBSERVER

2.1 Task definition

We call "cone fundamentals" the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane. The cone fundamentals are a linear transformation of the colour-matching functions (CMFs) of the observer.

The task in this chapter, the derivation of the cone fundamental sensitivity functions for the young adult 10° field size observer, means the definition of the parameters in the following equations:

$$\begin{aligned}
\bar{l}_{10}(\lambda) &= l_R \cdot \bar{r}_{10}(\lambda) + l_G \cdot \bar{g}_{10}(\lambda) + l_B \cdot \bar{b}_{10}(\lambda) \\
\bar{m}_{10}(\lambda) &= m_R \cdot \bar{r}_{10}(\lambda) + m_G \cdot \bar{g}_{10}(\lambda) + m_B \cdot \bar{b}_{10}(\lambda) \qquad (2.1) \\
\bar{s}_{10}(\lambda) &= s_R \cdot \bar{r}_{10}(\lambda) + s_G \cdot \bar{g}_{10}(\lambda) + s_B \cdot \bar{b}_{10}(\lambda)
\end{aligned}$$

in which $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ are the cone fundamental sensitivity functions, and $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$ and $\bar{b}_{10}(\lambda)$ the colour-matching functions both at corneal level.

Since we are interested only in relative values – we will normalise all spectral sensitivity functions to peak height one – it is only the ratio $l_R : l_G : l_B$, etc. which matters.

2.2 Basic assumptions

2.2.1 The colour matching functions (CMFs)

After a careful examination of the colour-matching data, the recommendation by Stockman and Sharpe (2000) has been followed to adopt the choice of the large field 10° CMFs of Stiles and Burch (1959), based upon matching data using mixtures of 645,2 nm (R), 526,3 nm (G), and 444,4 nm (B). It constitutes the most comprehensive set of CMF-data, which were measured directly, by a large number of subjects (49 subjects from 25500 cm^{-1} to 14000 cm^{-1}, and by 9 subjects from 15000 cm^{-1} to 12133 cm^{-1}), were not contaminated by photometric adjustment, and have not been modified by other CIE committees (see Table 6.1). However, the values of $\bar{b}_{10}(\lambda)$ beyond 505 nm show such a large spread, that they (see Fig 2.1) should be disregarded. The values beyond 505 nm are derived from other psychophysical data, (see Section 2.3.2.)

It is recommended to use as the colour-matching data for the 10° visual field the 10° CMFs of Stiles and Burch (1959), excluding the values of $\bar{b}_{10}(\lambda)$ beyond 505 nm (See Table 6.1 in terms of energy, and Fig. 2.1).

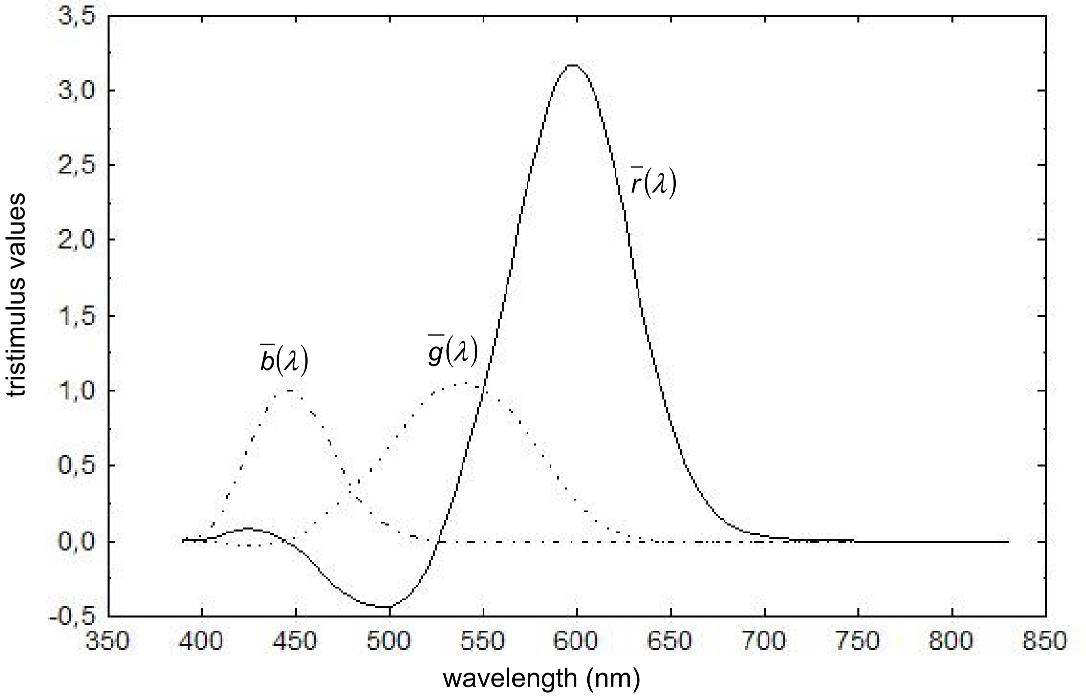

Fig. 2.1. The Stiles-Burch colour matching functions.

2.2.2 *The König hypothesis*

The theoretical basis for deriving cone fundamentals is the König hypothesis, which postulates that dichromatic vision is a reduced form of trichromatic vision where one cone system is missing and the two others are left unchanged in spectral sensitivity. This hypothesis has been confirmed many times since, both by retinal densitometry (Rushton, 1964; Rushton, Powell and White, 1973) and on the basis of psychophysical arguments (Vos and Walraven, 1971).

Consequently, the cone fundamentals should reflect the spectral sensitivity of the visual system measured in the case of

- dichromacy;
- foveal tritanopia;
- cone response isolation.

Several estimates have been constructed from CIE standard observer colour matching functions. Every attempt has contributed to an improved prediction of the cone fundamentals.

Stockman and Sharpe (2000) used all three methods, and came to a proposal, which reflects present knowledge.

The mentioned basic assumptions are further elaborated in Section 2.3.

2.3 The 10° cone fundamentals

2.3.1 *L_{10}- and M_{10}-cone fundamentals, and the S_{10}-cone fundamental from 390 nm to 505 nm*

If we are concerned only about the relative cone spectral sensitivity, the transformations for

$\bar{l}_{10}(\lambda)$ and $\bar{m}_{10}(\lambda)$ simplify to:

$$(l_R / l_B) \cdot \bar{r}_{10}(\lambda) + (l_G / l_B) \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = \mathrm{k_l} \cdot \bar{l}_{10}(\lambda) \qquad (2.2)$$

$$(m_R / m_B) \cdot \bar{r}_{10}(\lambda) + (m_G / m_B) \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_m \cdot \bar{m}_{10}(\lambda) \quad (2.3)$$

where k_l and k_m are scaling constants.

According to Stockman and Sharpe (2000) the following numerical data hold:

$$2{,}846201 \cdot \bar{r}_{10}(\lambda) + 11{,}092490 \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_l \cdot \bar{l}_{10}(\lambda) \quad (2.4)$$

$$0{,}168926 \cdot \bar{r}_{10}(\lambda) + 8{,}265895 \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_m \cdot \bar{m}_{10}(\lambda) \quad (2.5)$$

Where the S-cones are virtually insensitive to long-wavelength light, s_R is taken to be zero. This leads to

$$(s_R / s_B) \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_s \cdot \bar{s}_{10}(\lambda) \quad (2.6)$$

in which k_s is a scaling constant.

According to Stockman and Sharpe (2000) the following numerical data hold for the wavelength region 390 nm to 505 nm.

$$0{,}0106 \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_s \cdot \bar{s}_{10}(\lambda) \quad (2.7)$$

2.3.2 S_{10}-cone fundamental beyond 505 nm

Due to the poor accuracy of the $\bar{b}_{10}(\lambda)$-values for wavelengths beyond 505 nm, a better estimation for deriving the $\bar{s}_{10}(\lambda)$ is obtained indirectly from other psychophysical experiments (Stockman and Sharpe, 2000). A Gaussian expansion (see Chapter 4) is used to fit the experimental results collected on a 2° field (Stockman, Sharpe and Fach, 1999) and readjusted back to 10°, using the same assumptions as those described in Chapter 4.

2.3.3 L_{10}-, M_{10}- and S_{10}-cone fundamentals

It is recommended to use the following formulas for transformation from CMFs to the L_{10}-, M_{10}- and S_{10}-cone fundamentals (the latter only in the wavelength region of 390 nm to 505 nm), normalised to 1 at the maximum values (see Tables 6.2 and 6.3).

$$\bar{l}_{10}(\lambda) = 0{,}192325269 \cdot \bar{r}_{10}(\lambda) + 0{,}749548882 \cdot \bar{g}_{10}(\lambda) + 0{,}0675726702 \cdot \bar{b}_{10}(\lambda)$$

$$\bar{m}_{10}(\lambda) = 0{,}0192290085 \cdot \bar{r}_{10}(\lambda) + 0{,}940908496 \cdot \bar{g}_{10}(\lambda) + 0{,}113830196 \cdot \bar{b}_{10}(\lambda) \quad (2.8)$$

$$\bar{s}_{10}(\lambda) = 0{,}0105107859 \cdot \bar{g}_{10}(\lambda) + 0{,}991427669 \cdot \bar{b}_{10}(\lambda) \text{ (390 nm to 505 nm region)}$$

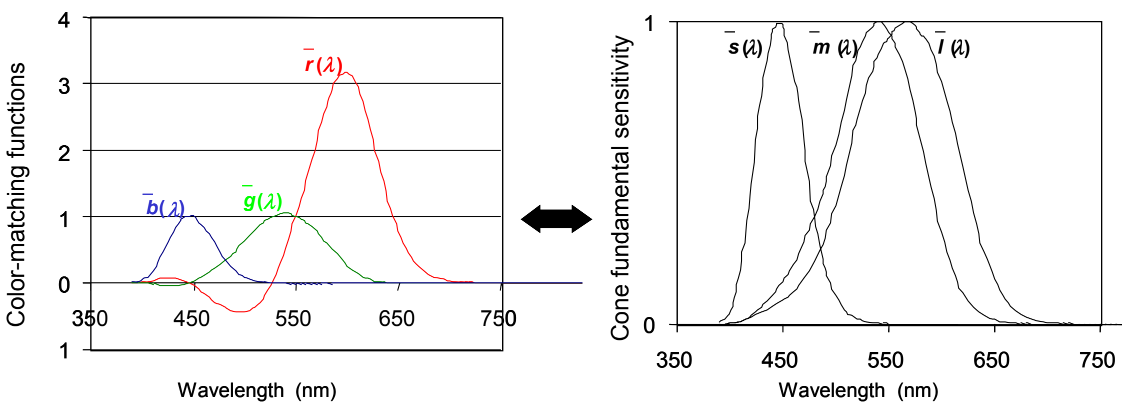

Fig. 2.2. Illustration of the transformation from colour matching functions to cone fundamentals in terms of energy. The transformation is carried out by using Eq. 2.2.

For the wavelength region beyond 505 nm this course is complemented by the tabulated values given in Tables 6.2 and 6.3. These values are derived from the Gaussian expansion of the 2° data as given in Chapter 4.

2.3.4 Transformation of cone fundamentals in terms of energy to cone fundamentals in terms of quanta.

The 10° L-, M-, and S-cone fundamentals in terms of energy $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ are given in Table 6.2.

To convert the 10° L-, M-, and S-cone fundamentals in terms of energy $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ to cone fundamentals in terms of quanta, respectively $\bar{l}_{q,10}(\lambda)$, $\bar{m}_{q,10}(\lambda)$ and $\bar{s}_{q,10}(\lambda)$, one should multiply values presented in Table 6.2 by $1/\lambda$ and re-normalise at the nearest 0,1 nm to the maximum values. Results are given in Table 6.3.

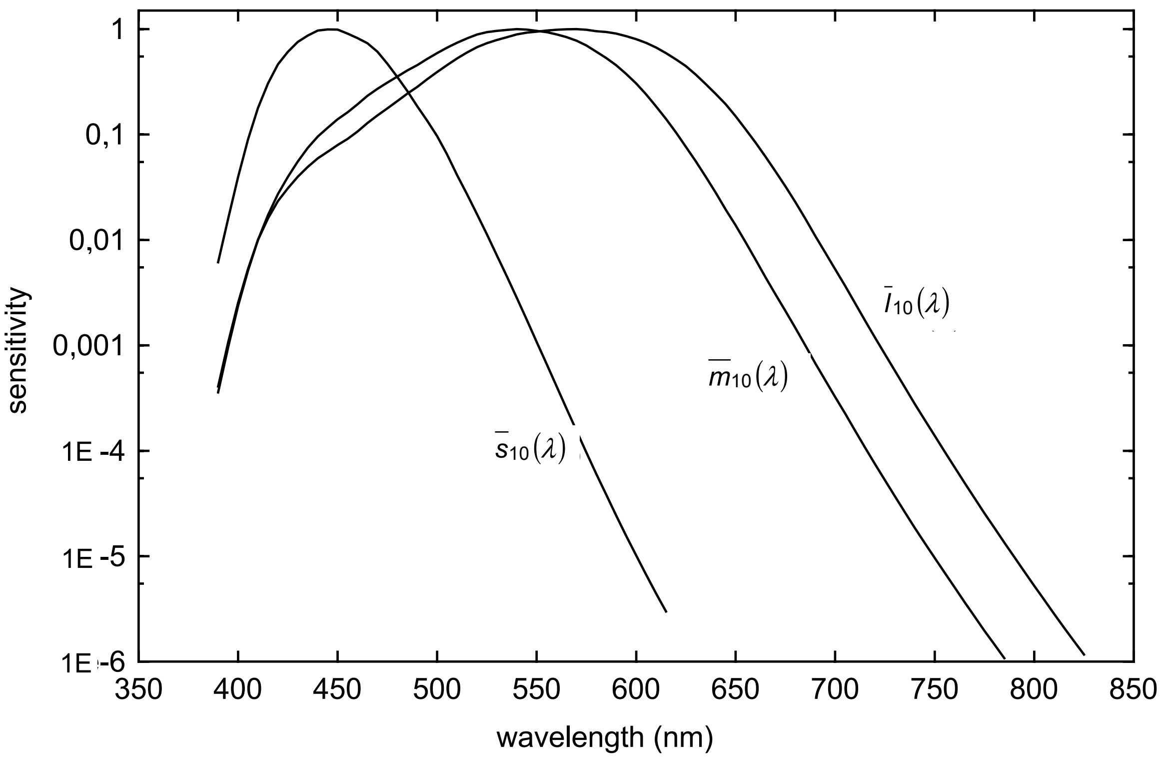

Fig. 2.3. The 10° L-,M-, and S-cone fundamentals in terms of energy $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$, normalised to 1 at the maximum, as given in Table 6.2.

3. DERIVATION OF THE PHOTOPIGMENT ABSORPTION SPECTRA

3.1 Task definition

In Chapter 2 the 10° cone fundamental sensitivity functions, as the most reliable basic set of data, were derived. In order to derive compatible cone fundamentals for other field sizes, from 1° to 10°, it is necessary to make an intermediate step via the photopigment absorption spectra. That requires knowledge of the spectral absorption characteristics of the intermediate inert pigments in the ocular media.

It is therefore necessary to know:

- the absorption spectrum by the macular pigment;
- the absorption spectrum by the lens and other pre-retinal media.

By correcting the cone fundamental sensitivity functions by these absorption spectra one obtains the cone spectral absorption functions.

In order to derive the absorption functions of the visual pigments the self-screening in the outer segments of the photoreceptors has to be taken into account. The self-screening results in narrowing of the photopigment spectral absorptivity (or absorptance for an infinitely low density) compared to the cone spectral absorptance.

N.B. CIE defines Absorptance as the ratio of the absorbed radiant or luminous flux to the incident flux in the given conditions (CIE 17.4-1987, 845-04-75).

The task in this chapter is to carry out these corrections in order to derive the photopigment absorption spectra. The case of low-density absorbance is a special case, which is the basis for calculations to derive the absorptance at any given density. Therefore the chapter concludes with the low-density absorbance spectra of the three cone pigments.

3.2 The spectral optical density $D_{\tau,\mathrm{macula}}(\lambda)$ of the macular pigment as a function of wavelength.

Stockman and Sharpe have recently reviewed the abundant literature on the spectral absorption of the macular pigment. Differences between the various sources are rather small, and the committee agrees with the choices made by Stockman and Sharpe.

The macular pigment optical density has its maximum around 460 nm (see Fig. 3.1). Although its amount varies considerably among observers, the maximum optical density of 0,095 for a 10° visual field diameter is a representative average.

It is therefore recommended to use as the optical density values for the macular pigment the $D_{\tau,\mathrm{macula}}(\lambda)$ values as determined by Stockman and Sharpe (2000) and to adopt the maximum density of 0,095 at 460 nm as a representative average for field diameter of 10°, see Table 6.4, 3rd column.

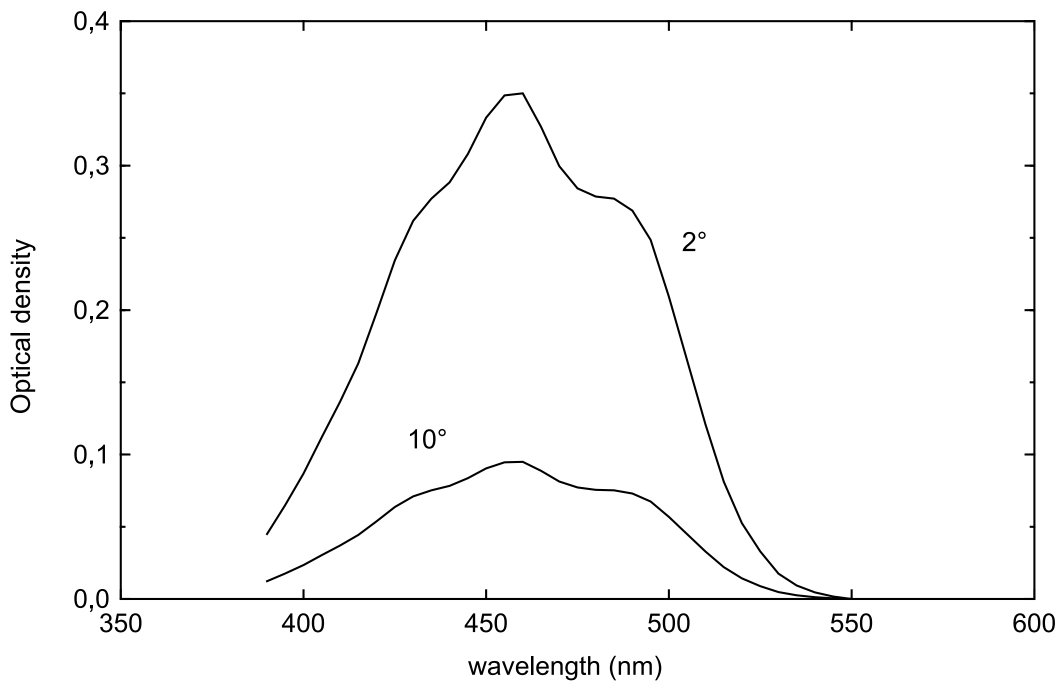

Fig 3.1. The optical density $D_{\tau,\mathrm{macula}}(\lambda)$ of the macular pigment for a 2° field size, and for a 10° field size.

3.3 The spectral optical density $D_{\tau,ocul}(\lambda)$ as a function of wavelength of the lens and other ocular media

The absorptance in the anterior eye media does not show any dependence upon field size, as light to all parts of the retina has to pass the same media. It is at its highest at very short wavelengths. The main absorptive agent is the lens pigmentation, which is known to drastically increase with age (see Chapter 5).

It is recommended to use for the absorption by the lens and other ocular media the $D_{\tau,ocul}(\lambda)$ values as given by Stockman and Sharpe (2000), see Table 6.5.

3.4 The peak optical density $D_{\tau,max}$ of the visual pigments in the outer segments of the photoreceptors

If the low density spectral absorbance, normalized to unity peak value is $A_{i,0}(\lambda)$, and $D_{\tau,max}$ is the peak axial optical density of the photopigment in the outer segment then the absorptance spectrum $\alpha_i(\lambda)$ is (i refers to internal):

$$\alpha_i(\lambda) = 1 - 10^{[-D_{\tau,max} A_{i,0}(\lambda)]} \quad (3.1)$$

This implies a broadening of the cone spectral absorptance relative to the low-density photopigment spectral absorptance when the optical density $D_{\tau,max}$ becomes sufficiently high.

Conversely, it is possible to recover the low-density spectral absorbance template of the pigment from the spectral absorptance of a given element the peak optical density of which is known (Lamb, 1995). If the cone absorptance or normalised cone spectral sensitivity in terms of quanta and normalized at peak value is $\alpha_i(\lambda)$ and the peak optical density is $D_{\tau,max}$, then the low-density spectral absorbance $A_{i,0}(\lambda)$ of the pigment is

$$A_{i,0}(\lambda) = {}^{10}\log[1 - \alpha_i(\lambda) \cdot (1 - 10^{(-D_{\tau,max})})] / (-D_{\tau,max}) \quad (3.2)$$

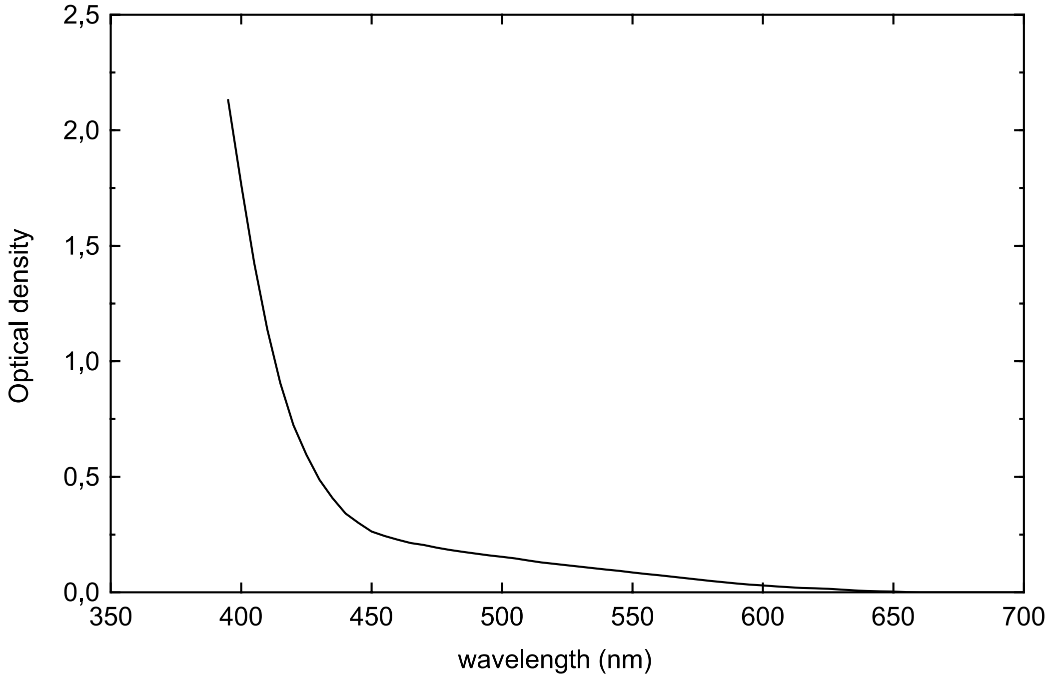

Fig. 3.2. The optical density $D_{\tau,ocul}(\lambda)$ of the lens and other ocular media.

Stockman and Sharpe (2000) derived the values for the peak optical densities $D_{\tau,max}$ of the visual pigments as given in Table 6.6.

It is recommended to use as the peak optical density of the visual pigments in the outer segments of the photoreceptors the $D_{\tau,max}$ values as given by Stockman and Sharpe (2000), see Table 6.6.

3.5 The low density spectral absorbance of the visual pigments

The L-, M- and S-pigment absorbance functions are now derived by correcting the cone fundamentals by the absorption of the ocular media and the macular pigment. If $D_{\tau,\text{macula}}(\lambda)$ is the optical density template for the macular pigment, then the transmission is

$$\tau_{\text{macula}}(\lambda) = 10^{-D_{\tau,\text{macula}}(\lambda)}$$

If $D_{\tau,\text{ocul}}(\lambda)$ is the optical density template for the lens and other ocular media, then the transmission is

$$\tau_{\text{ocul}}(\lambda) = 10^{-D_{\tau,\text{ocul}}(\lambda)}$$

The cone absorptance spectra in terms of quanta are given by the cone fundamental sensitivity in terms of quanta divided by the transmittance at every wavelength, and therefore:

$$\alpha_{\text{il},10}(\lambda) = \bar{l}_{\text{q},10}(\lambda) \;/\; [\tau_{\text{macula}}(\lambda) \cdot \tau_{\text{ocul}}(\lambda)]$$

$$\alpha_{\text{im},10}(\lambda) = \bar{m}_{\text{q},10}(\lambda) \;/\; [\tau_{\text{macula}}(\lambda) \cdot \tau_{\text{ocul}}(\lambda)] \qquad (3.3)$$

$$\alpha_{\text{is},10}(\lambda) = \bar{s}_{\text{q},10}(\lambda) \;/\; [\tau_{\text{macula}}(\lambda) \cdot \tau_{\text{ocul}}(\lambda)]$$

The low density spectral absorbance of the visual pigments is given by

$$A_{\text{i},0(\text{L-pigment})}(\lambda) = {}^{10}\log\,[1- \alpha_{\text{il},10}(\lambda) \cdot (1-10^{(-D_{\tau,\max,\text{l}})})] \;/\; (-D_{\tau,\max,\text{l}})$$

$$A_{\text{i},0(\text{M-pigment})}(\lambda) = {}^{10}\log\,[1- \alpha_{\text{im},10}(\lambda) \cdot (1-10^{(-D_{\tau,\max,m})})] \;/\; (-D_{\tau,\max,\text{m}}) \qquad (3.4)$$

$$A_{\text{i},0(\text{S-pigment})}(\lambda) = {}^{10}\log\,[1- \alpha_{\text{is},10}(\lambda) \cdot (1-10^{(-D_{\tau,\max,\text{s}})})] \;/\; (-D_{\tau,\max,\text{s}})$$

Following this procedure, and using the data as recommended in 3.2, 3.3 and 3.4 Stockman and Sharpe arrived at the values of the low optical density spectral absorbance as given in Fig. 3.3 and Table 6.6.

It is recommended to use as the low density absorbance spectra $A_{\text{i},0(\text{L-pigment})}(\lambda)$, $A_{\text{i},0(\text{M-pigment})}(\lambda)$, and $A_{\text{i},0(\text{S-pigment})}(\lambda)$ those as given by Stockman and Sharpe (2000), see Table 6.6.

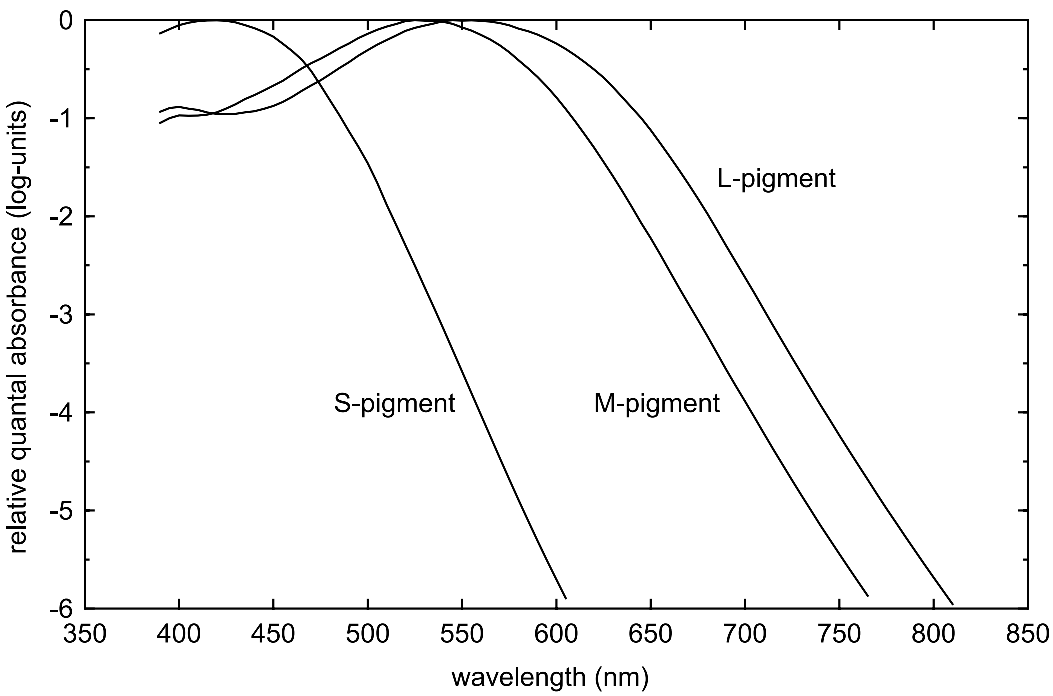

Fig. 3.3. The low density absorbance spectra of the visual pigments.

4. CONE FUNDAMENTAL SENSITIVITY FUNCTIONS FOR THE 2°-OBSERVER

4.1 Task definition

The task in this chapter is to define the cone fundamental sensitivity functions for the 2° Modified CIE Standard Observer, and to indicate how these are derived from the photopigment low density absorbance functions.

Although several data sets of colour-matching functions for 2° fields are available from which 2° cone fundamentals could be theoretically derived, the committee has recognised that these data suffer from small errors. A reconstructed set of 2° cone fundamentals based on modern knowledge of colour vision, in particular an accurate set of 10° cone fundamentals, is to be preferred. Here we follow the suggestion of Stockman and Sharpe (2000).

In this chapter the cone fundamental sensitivity functions are derived from the photopigment absorbance functions (see Chapter 3) by correcting for:

- the absorption by the macular pigment for the 2° field size;
- the absorption by the lens and other ocular media;

and by taking care of

- the specific values for the peak densities of the visual pigments for the 2° field size.

4.2 The 2° spectral optical density $D_{\tau,\mathrm{macula}}(\lambda)$ of the macular pigment

The relative optical density spectrum for the macular pigment is assumed to be independent of eccentricity.

A maximum optical density at 460 nm of 0,35 for a 2° visual field diameter is a representative average. Stockman and Sharpe have recently reviewed the abundant literature on the spectral absorption of the macular pigment. Differences between the various sources are rather small, and the committee agrees with the choices made by Stockman and Sharpe (2000).

It is therefore recommended to use as the spectral optical density values for the macular pigment the $D_{\tau,\mathrm{macula}}(\lambda)$ values as determined by Stockman and Sharpe (2000) and to adopt the maximum optical density of 0,35 at 460 nm as a representative average for field diameter of 2°, see Table 6.4, second column.

4.3 The spectral optical density $D_{\tau,\mathrm{ocul}}(\lambda)$ of the lens and other ocular media

The absorption in the lens and other ocular media is independent of field size, as light to the central parts of the retina has to pass the same media. It is at its highest at very short wavelengths.

It is recommended to use as the absorption by the lens and other ocular media the $D_{\tau,\mathrm{ocul}}(\lambda)$ values as given by Stockman and Sharpe (2000), see Table 6.5.

4.4 The peak optical densities $D_{\tau,\mathrm{max,l}}$, $D_{\tau,\mathrm{max,m}}$ and $D_{\tau,\mathrm{max,s}}$ of the visual pigments in the outer segments of the photoreceptors

The shape of the spectral absorption functions of the cone visual pigments depends on their peak optical density (Beer's law).

Stockman and Sharpe (2000) derived the values $D_{\tau,\mathrm{max,l}}$, $D_{\tau,\mathrm{max,m}}$ and $D_{\tau,\mathrm{max,s}}$ for the peak optical densities of the visual pigments as given in the following table.

Table 4.4.1. Peak densities $D_{\tau,\max,l}$, $D_{\tau,\max,m}$ and $D_{\tau,\max,s}$ of the visual pigments.

	2°	10°
L-cones	0,5	0,38
M-cones	0,5	0,38
S-cones	0,4	0,3

It is recommended to use as the peak optical density of the visual pigments (2°) the values $D_{\tau,\max,l}$, $D_{\tau,\max,m}$ and $D_{\tau,\max,s}$ as given by Stockman and Sharpe (2000).

4.5 The reconstructed cone fundamental sensitivity functions for the 2° observer

The cone fundamental sensitivity functions for the CIE 2° cone fundamental observer are reconstructed through the following steps for every cone type:

The low density spectral absorbance $A_{i,0}(\lambda)$ of the visual pigment is given in log-values in Table 6.6.

The peak optical densities $D_{\tau,\max}$ of the visual pigments is given in Section 4.4.

The fraction of the incident light at the retinal level absorbed in the cones, or the cone absorptance spectra in terms of quanta, is:

$$\begin{aligned} \alpha_{i,l}(\lambda) &= 1 - 10^{[-D_{\tau,\max,l} \cdot A_{i,0(\text{L- pigment})}(\lambda)]} \\ \alpha_{i,m}(\lambda) &= 1 - 10^{[-D_{\tau,\max,m} \cdot A_{i,0(\text{M- pigment})}(\lambda)]} \\ \alpha_{i,s}(\lambda) &= 1 - 10^{[-D_{\tau,\max,s} \cdot A_{i,0(\text{S- pigment})}(\lambda)]} \end{aligned} \tag{4.1}$$

The quantal fraction of the incident light at the corneal level absorbed in the cones, i.e. the cone fundamental sensitivity in terms of quanta is given by the cone absorptance spectra in terms of quanta multiplied by the transmittance at every wavelength:

$$\begin{aligned} \bar{l}_q(\lambda) &= \alpha_{i,l,2}(\lambda) \cdot \tau_{\text{macula}}(\lambda) \cdot \tau_{\text{ocul}}(\lambda) \\ \bar{m}_q(\lambda) &= \alpha_{i,m,2}(\lambda) \cdot \tau_{\text{macula}}(\lambda) \cdot \tau_{\text{ocul}}(\lambda) \\ \bar{s}_q(\lambda) &= \alpha_{i,s,2}(\lambda) \cdot \tau_{\text{macula}}(\lambda) \cdot \tau_{\text{ocul}}(\lambda) \end{aligned} \tag{4.2}$$

To convert 2° cone fundamental sensitivity functions $\bar{l}_q(\lambda)$, $\bar{m}_q(\lambda)$ and $\bar{s}_q(\lambda)$ in terms of quanta into 2° cone fundamental sensitivity functions $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ in terms of energy one should multiply by λ and renormalize at the nearest 0,1 nm to the maximum values, respectively at 570,2 nm, 542,8 nm, 442,1 nm.

On the basis of the above field parameter values, the data tabulated in Table 6.7 result, after normalising to peak values 1, for the 2° cone fundamental sensitivity functions. Essentially the same data are reproduced in Table 6.8 in terms of log quantal sensitivity functions, by multiplying the Table 6.7 values by $1/\lambda$, renormalizing to peak values 1, and taking log-values.

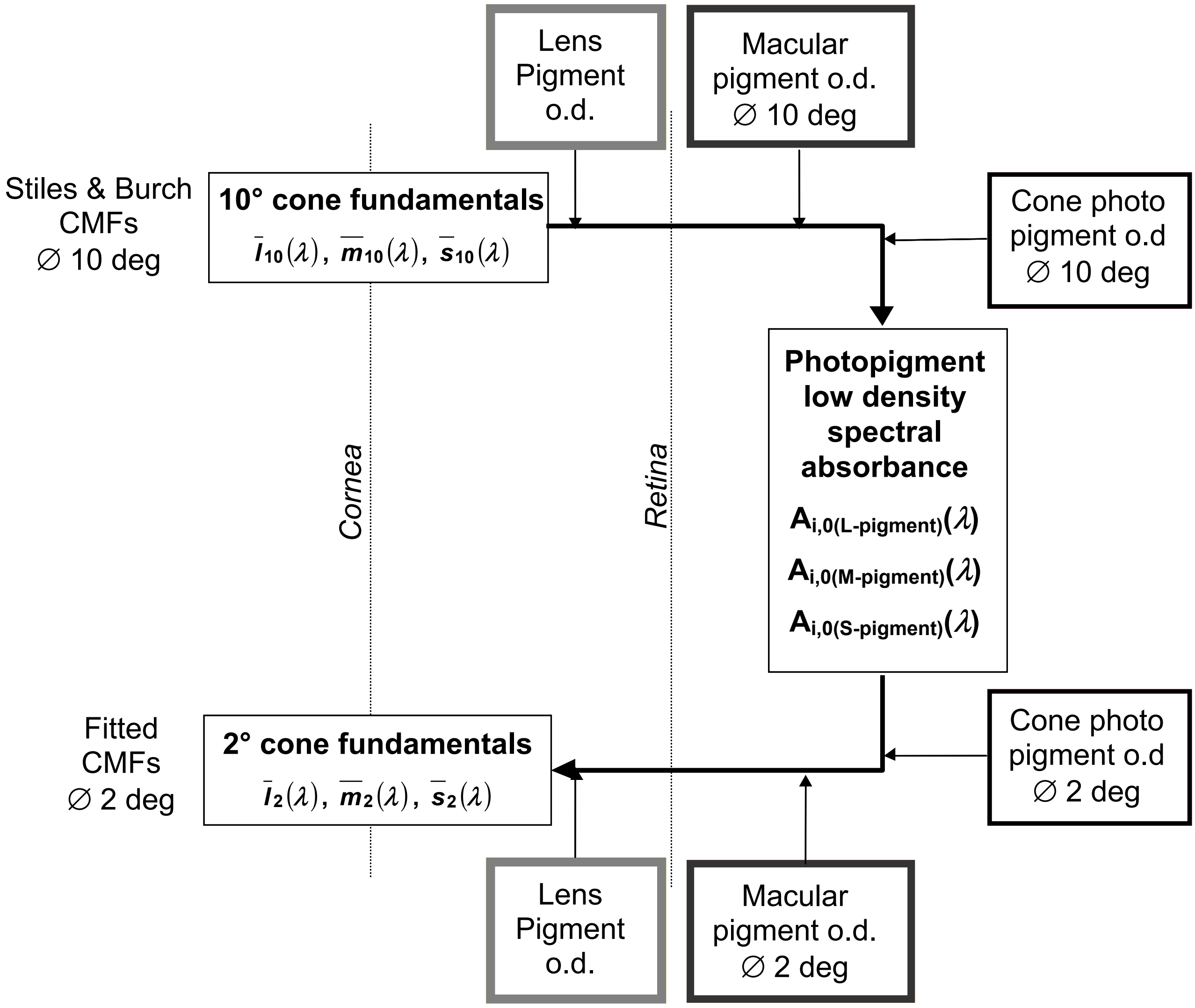

Fig. 4.1. Schematic representation of the derivation of the 2° cone fundamentals from the 10° cone fundamentals.

It is recommended to use as the cone fundamental sensitivity functions for the 2° observer in term of energy $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$, and in terms of quanta $\bar{l}_q(\lambda)$, $\bar{m}_q(\lambda)$ and **$\bar{s}_q(\lambda)$ those as given by Stockman and Sharpe (2000), see respectively Tables 6.7 and 6.8.**

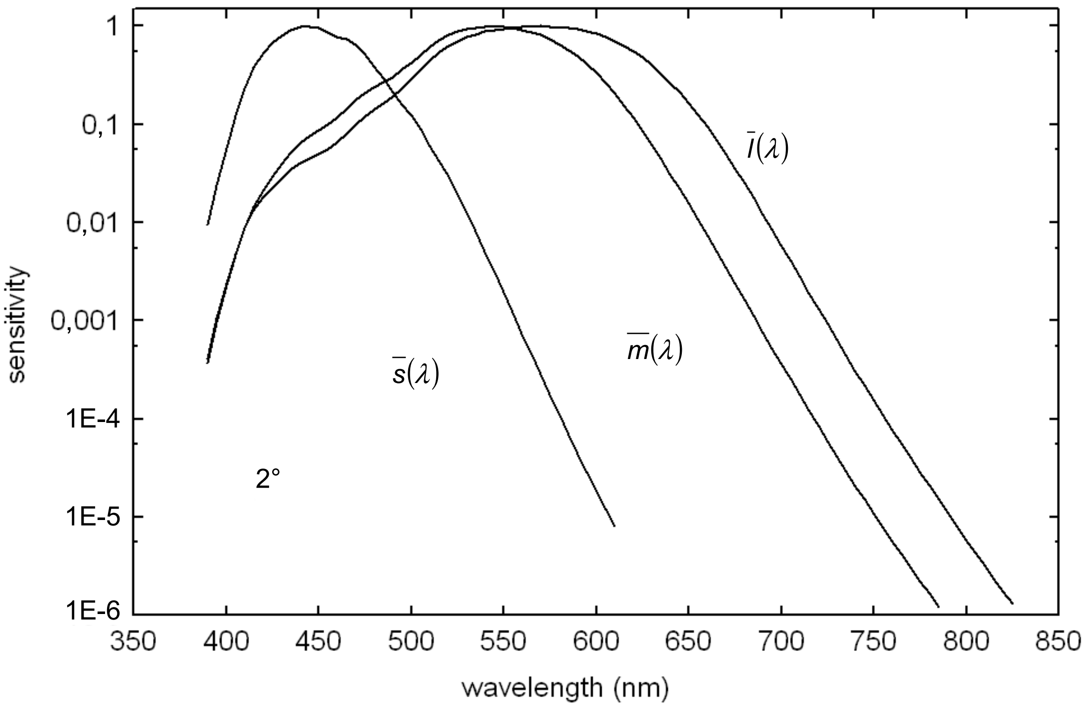

Fig. 4.2. The cone fundamentals for 2° viewing field.

4.6 The S-cone fundamental beyond 505 nm

As mentioned in Chapter 2, the values of the S-cone fundamental beyond 505 nm are based on the present general knowledge of long wavelength slopes for visual pigments. Stockman and Sharpe (2000) have chosen to adjust the S-cone 2° cone fundamental sensitivity curve prior to convert it to S-cone 10° cone fundamental sensitivity curve.

An empirical Gaussian function was used to smooth and combine the data available from 505 to 615 nm, and to extrapolate the function from 615 nm to 830 nm.

$$\log \bar{s}_q(\lambda) = a + b \cdot \exp\{-0{,}5 \cdot [(x - c) / d]^2\}$$

in which $\bar{s}_q(\lambda)$ is the sensitivity on quantal basis, and $x = (1/\lambda)$ expressed in cm^{-1}.

Subsequently, small macular pigment distortions were applied to correct that function between 510 nm and 550 nm.

Fitting $\bar{s}_q(\lambda)$ with the Gaussian function and the coefficients

a = -9,187942456; b = 8,441473743; c = 20940,689; and d = 3691,342401

allows to extrapolate the S-cone fundamental sensitivity curve on quantal base (see Table 6.8) for the 2° observer up to 830 nm.

5. A FIELD SIZE AND AGE DEPENDENT OBSERVER

5.1 Task definition

So far CIE has standardized colour mixture data for 2° and 10°. Originally, the CIE has opted for only standardizing for a 2° field, a rod free area thus restricting measurements to cone vision.

Later came the need to standardize for larger areas because in practice the effective field of view is often much larger than 2°. A field size of 10° was chosen, with the proviso that the luminance of the test field was high enough to avoid rod intrusion.

A full range from 1° to 10° is desirable to fill the need for people not to be bound to these two field sizes in their settings.

Moreover, almost all experimental work in the past has been done by young adult subjects, while presently the social concern has clearly shifted to include a more aged population. For these reasons this chapter generalizes the standard observer to a field size and age dependent observer. To derive the properties of this observer it is necessary to define the field size dependence of the effective macular pigment optical density, and of the visual pigment densities. One can safely assume that the absorption by the lens and other ocular media is not dependent upon field size. The main difference between the aged and the young in this respect is the difference in absorption in the ocular media, in particular the lens. Of minor influence are the dependencies on age of the absorption by the macular pigment, and of the densities of the visual pigments.

The task in this chapter is to generalize the standard observers for 10° and 2°, as described in preceding chapter, to a field size and age dependent observer.

5.2 Procedure

The cone fundamentals for every field size from 1° to 10° can be derived in the same way as the cone fundamentals for the 2°-observer are derived from the photopigment low density absorbance functions of the dilute pigment (see Chapter 4).

But next to the knowledge of

- the relative optical density of the macular pigment;
- the relative optical density of the lens and other ocular media;
- the relative low optical density absorbance spectra of the photo pigments

it is needed to know:

- the peak optical density of the macular pigment for field sizes from 1° to 10°;
- the dependence of the absorption by the macular pigment on age;
- the absorption by the lens and other ocular media for field sizes from 1° to 10°;
- the dependence of the absorption by the lens and other ocular media on age;
- the peak densities of the visual pigments for field sizes from 1° to 10°;
- the dependence of the peak densities of the visual pigments on age.

5.3 The peak optical density $D_{\tau,\text{max,macula}}$ of the macular pigment as a function of field size *fs* (1°-10°)

The relative spectral optical density of the macular pigment is assumed to remain the same at any eccentricity. Therefore only the effective peak optical density of the macular pigment has to be known as a function of field size. The optical density values at 460 nm for 2° and 10° are known, see Chapters 2 and 4, and Table 6.4. There is evidence, as given by Moreland and Alexander (1997) that the dependence of the $D_{\tau,\text{max,macula}}$ can be described by an exponential function. Therefore the relationship can be described by

$$D_{\tau,\text{max,macula}} = 0{,}485 \cdot e^{(-fs/6{,}132)}$$

in which *fs* is the field size in degrees. This formula leads to values of 0,35 and 0,095 at 2° and 10°, respectively.

It is recommended to use as the maximal optical density values for the macular pigment the values (at 460 nm) as a function of field size *fs* (1° to 10°) according to (see Table 6.9):

$$D_{\tau,\mathrm{max,macula}} = 0{,}485 \cdot e^{(-fs/6{,}132)} \quad (5.1)$$

5.4 The dependence of the absorbance by the macular pigment on age

Only a few studies are devoted to the dependence of the absorbance by the macular pigment on age (Werner et al., 1987; Bone et al., 1988; Sheng-Fu Chen,Yin Chang and Jia-Cheng Wu, 2001, Ciulla et al., 2001; Broekmans et al., 2002). None of these studies showed a strong dependence. The most recent study (Zagers and van Norren, 2004) shows that the dependence is insignificant.

Consequently, it is assumed that the absorbance by the macular pigment is not dependent on age.

5.5 The spectral optical density $D_{\tau,\mathrm{ocul}}(\lambda)$ of the lens and other ocular media for field sizes from 1° to 10°

Since light reaching this central part of the retina has virtually the same way to pass through the same optical media, the spectral optical density $D_{\tau,\mathrm{ocul}}(\lambda)$ of the lens and other ocular media would in any way depend on the field size.

5.6 The spectral optical density $D_{\tau,\mathrm{ocul}}(\lambda)$ of the lens and other ocular media as a function of age

Table 6.10 presents the function $D_{\tau,\mathrm{ocul}}(\lambda)$ for an average 32-yr-old observer (the average age of the Stiles and Burch observers), with a small pupil (< 3 mm), according to Stockman, Sharpe and Fach (1999), as used for the calculations in Chapters 3 and 4.

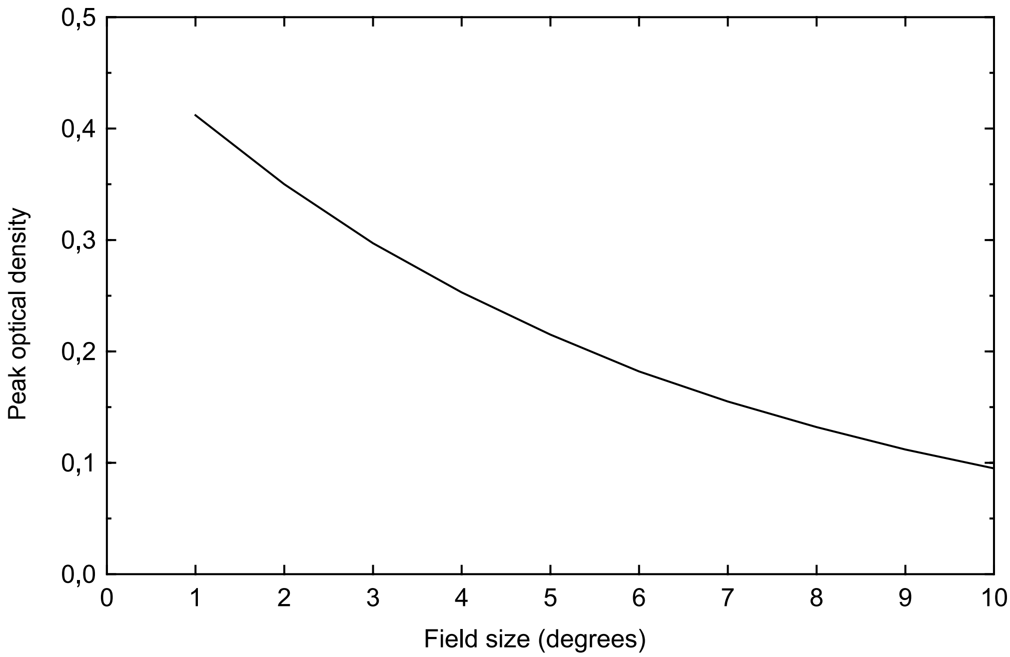

Fig 5.1. The peak optical density (at 460 nm) of the macular pigment as a function of field size.

These functions can be separated into two components: $D_{\tau,\mathrm{ocul}}1(\lambda)$ represents portion affected by aging after age 20, and $D_{\tau,\mathrm{ocul}}2(\lambda)$ represents portion stable after age 20. (After Pokorny, Smith and Lutze, 1987).

The optical density of the lens of an average observer may be estimated by:

$D_{\tau,\text{ocul}}(\lambda) = D_{\tau,\text{ocul}}1(\lambda) \cdot [1 + 0{,}02(A-32)] + D_{\tau,\text{ocul}}2(\lambda)$, for an average observer between the ages of 20 and 60; and

$D_{\tau,\text{ocul}}(\lambda) = D_{\tau,\text{ocul}}1(\lambda) \cdot [1{,}56 + 0{,}0667(A-60)] + D_{\tau,\text{ocul}}2(\lambda)$ for an average observer over the age of 60, where A is the observer's age.

It is recommended to calculate the optical density $D_{\tau,\text{ocul}}(\lambda)$ of the lens and other ocular media by the following Equations:

$D_{\tau,\text{ocul}}(\lambda) = D_{\tau,\text{ocul}}1(\lambda) \cdot [1 + 0{,}02(A-32)] + D_{\tau,\text{ocul}}2(\lambda)$, for an average observer between the ages of 20 and 60; and

$D_{\tau,\text{ocul}}(\lambda) = D_{\tau,\text{ocul}}1(\lambda) \cdot [1{,}56 + 0{,}0667(A-60)] + D_{\tau,\text{ocul}}2(\lambda)$ for an average observer over the age of 60

in which $D_{\tau,\text{ocul}}1(\lambda)$ and $D_{\tau,\text{ocul}}2(\lambda)$ are the values as a function of age as given in Table 6.10, where A is the observer's age.

5.7 The peak optical density of the visual pigments $D_{\tau,\text{max}}$ as a function of field size (1° to 10°)

The peak optical density values $D_{\tau,max}$ for 2° and 10° are known, see Table 6.6.

According to Pokorny and Smith (1976) the dependence on field size of the $D_{\tau,\text{max}}$ can be described by an exponential function with an asymptotic value.

It is recommended to use as the maximal optical density values for the three different cone-types:

$$\begin{aligned} D_{\tau,\text{max (L-cones)}} &= 0{,}38 + 0{,}54 \cdot e^{(-fs/1{,}333)} \\ D_{\tau,\text{max (M-cones)}} &= 0{,}38 + 0{,}54 \cdot e^{(-fs/1{,}333)} \\ D_{\tau,\text{max (S-cones)}} &= 0{,}30 + 0{,}45 \cdot e^{(-fs/1{,}333)} \end{aligned} \qquad (5.2)$$

in which *fs* is the field size in degrees.

This formula leads to values of 0,5 and 0,38 at 2° and 10° respectively for the L- and M-cones, and of 0,4 and 0,3 at 2° and 10° respectively for the S-cones, see Table 6.11.

5.8 The peak optical density $D_{\tau,\text{max}}$ of the visual pigments as a function of age

Recent experiments (Swanson and Fish, 1996, Zagers and van Norren, 2004) suggest that the peak optical density of the visual pigments decrease gradually as a function of age.

In view of the scarce data, which indicate that these changes are small, this dependence is for the present neglected.

5.9. The cone fundamentals for field sizes 1° to 10° and age between 20 and 80 years

The cone fundamentals for every field size from 1° to 10° are reconstructed through the following steps for every cone type:

The low-optical density spectral absorptances $A_{i,0}(\lambda)$ of the pigments are given in log-values in Table 6.6.

The peak optical densities $D_{\tau,\text{max}}$ of the visual pigments are calculated according to the equations as given in Section 5.7.

The fraction of the incident light at the retinal level absorbed in the cones or the cone absorptance spectra are then given by

$$\alpha_{i,l}(\lambda) = 1 - 10^{[-D_{\tau,max(L\text{-}cones)}\, A_{i,0(L\text{-}pigment)}(\lambda)]}$$
$$\alpha_{i,m}(\lambda) = 1 - 10^{[-D_{\tau,max(M\text{-}cones)}\, A_{i,0(M\text{-}pigment)}(\lambda)]} \quad (5.3)$$
$$\alpha_{i,s}(\lambda) = 1 - 10^{[-D_{\tau,max(S\text{-}cones)}\, A_{i,0(S\text{-}pigment)}(\lambda)]}$$

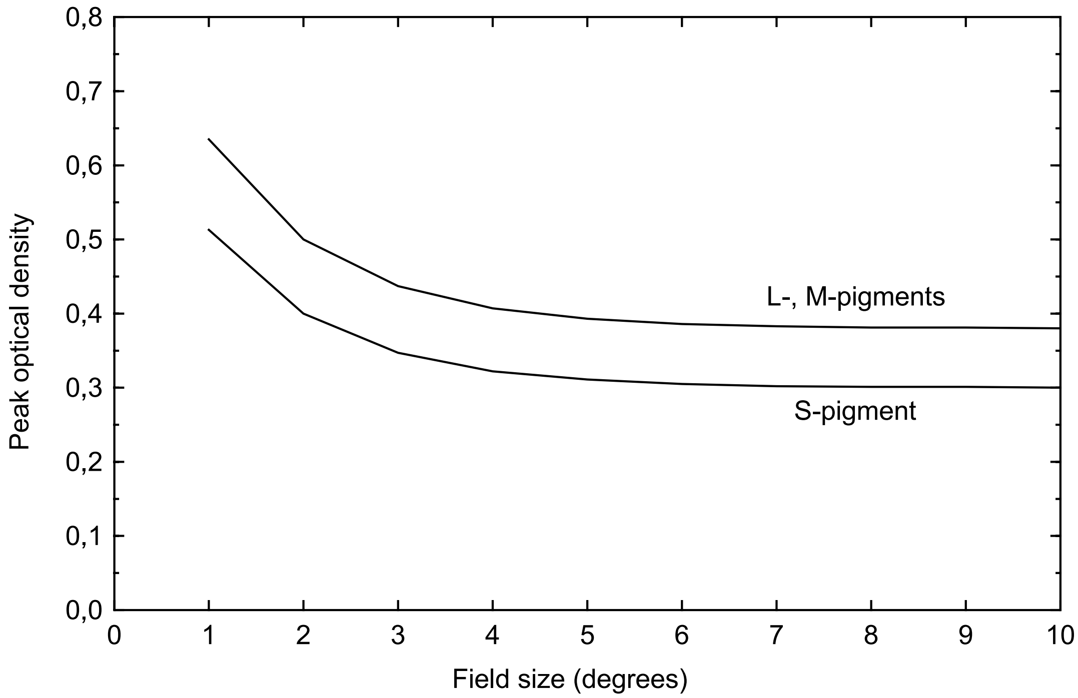

Fig. 5.2. The peak optical density of the visual pigments as a function of field size.

The fraction of the incident light at the corneal level absorbed in the cones, i.e. the cone fundamental sensitivity curve is given by the cone absorptance spectra multiplied by the transmittance at every wavelength:

$$\bar{l}(\lambda) = \alpha_{i,l}(\lambda) \cdot 10^{[-D_{\tau,\,max,macula} \cdot D_{macula,relative}(\lambda) - D_{\tau,ocul}(\lambda)]}$$
$$\bar{m}(\lambda) = \alpha_{i,m}(\lambda) \cdot 10^{[-D_{\tau,\,max,macula} \cdot D_{macula,relative}(\lambda) - D_{\tau,ocul}(\lambda)]} \quad (5.4)$$
$$\bar{s}(\lambda) = \alpha_{i,s}(\lambda) \cdot 10^{[-D_{\tau,\,max,macula} \cdot D_{macula,relative}(\lambda) - D_{\tau,ocul}(\lambda)]}$$

To convert cone fundamental sensitivity functions $\bar{l}_{fs,q}(\lambda)$, $\bar{m}_{fs,q}(\lambda)$ and $\bar{s}_{fs,q}(\lambda)$ in terms of quanta, in which *fs*, the field size in degrees, is a value between 1 and 10, into cone fundamental sensitivity functions $\bar{l}_{fs}(\lambda)$, $\bar{m}_{fs}(\lambda)$ and $\bar{s}_{fs}(\lambda)$ in terms of energy, one should multiply by λ and renormalize at the nearest 0,1 nm to the maximum values.

On the basis of the above field parameter values, and the data tabulated in Table 6.4, the relative optical density of the macular pigment $D_{macula,relative}(\lambda)$, (Table 6.10) the optical density $D_{\tau,ocul}(\lambda)$ of lens and other ocular media as a function of age, and (Table 6.6) the relative low-optical density spectral absorbance $A_{i,0}(\lambda)$ of the pigments the cone fundamental sensitivity functions for any field size and any age can be derived.

6. TABLES

Table 6.1 The 10° CMFs of Stiles and Burch (1959) in terms of energy.

These CMFs are measured directly, by 49 subjects from 25500 cm^{-1} to 14000 cm^{-1} (392,2 nm to 714,3 nm) with primary stimuli at 22450 cm^{-1}, 19000 cm^{-1} or 17000 cm^{-1} and 15420 cm^{-1}, and by 9 subjects from 15000 cm^{-1} to 12133 cm^{-1} (666,7 nm to 824,2 nm), with primary stimuli at 21250 cm^{-1}, 17000 cm^{-1} and 14250 cm^{-1}.

λ(nm)	$\bar{r}_{10}(\lambda)$	$\bar{g}_{10}(\lambda)$	$\bar{b}_{10}(\lambda)$
390	1,5000E-03	-4,0000E-04	6,2000E-03
395	3,8000E-03	-1,0000E-03	1,6100E-02
400	8,9000E-03	-2,5000E-03	4,0000E-02
405	1,8800E-02	-5,9000E-03	9,0600E-02
410	3,5000E-02	-1,1900E-02	1,8020E-01
415	5,3100E-02	-2,0100E-02	3,0880E-01
420	7,0200E-02	-2,8900E-02	4,6700E-01
425	7,6300E-02	-3,3800E-02	6,1520E-01
430	7,4500E-02	-3,4900E-02	7,6380E-01
435	5,6100E-02	-2,7600E-02	8,7780E-01
440	3,2300E-02	-1,6900E-02	9,7550E-01
445	-4,4000E-03	2,4000E-03	1,0019E+00
450	-4,7800E-02	2,8300E-02	9,9960E-01
455	-9,7000E-02	6,3600E-02	9,1390E-01
460	-1,5860E-01	1,0820E-01	8,2970E-01
465	-2,2350E-01	1,6170E-01	7,4170E-01
470	-2,8480E-01	2,2010E-01	6,1340E-01
475	-3,3460E-01	2,7960E-01	4,7200E-01
480	-3,7760E-01	3,4280E-01	3,4950E-01
485	-4,1360E-01	4,0860E-01	2,5640E-01
490	-4,3170E-01	4,7160E-01	1,8190E-01
495	-4,4520E-01	5,4910E-01	1,3070E-01
500	-4,3500E-01	6,2600E-01	9,1000E-02
505	-4,1400E-01	7,0970E-01	5,8000E-02
510	-3,6730E-01	7,9350E-01	3,5700E-02*
515	-2,8450E-01	8,7150E-01	2,0000E-02*
520	-1,8550E-01	9,4770E-01	9,5000E-03*
525	-4,3500E-02	9,9450E-01	7,0000E-04*
530	1,2700E-01	1,0203E+00	-4,3000E-03*

λ(nm)	$\bar{r}_{10}(\lambda)$	$\bar{g}_{10}(\lambda)$	$\bar{b}_{10}(\lambda)$
535	3,1290E-01	1,0375E+00	-6,4000E-03*
540	5,3620E-01	1,0517E+00	-8,2000E-03*
545	7,7220E-01	1,0390E+00	-9,4000E-03*
550	1,0059E+00	1,0029E+00	-9,7000E-03*
555	1,2710E+00	9,6980E-01	-9,7000E-03*
560	1,5574E+00	9,1620E-01	-9,3000E-03*
565	1,8465E+00	8,5710E-01	-8,7000E-03*
570	2,1511E+00	7,8230E-01	-8,0000E-03*
575	2,4250E+00	6,9530E-01	-7,3000E-03*
580	2,6574E+00	5,9660E-01	-6,3000E-03*
585	2,9151E+00	5,0630E-01	-5,3700E-03*
590	3,0779E+00	4,2030E-01	-4,4500E-03*
595	3,1613E+00	3,3600E-01	-3,5700E-03*
600	3,1673E+00	2,5910E-01	-2,7700E-03*
605	3,1048E+00	1,9170E-01	-2,0800E-03*
610	2,9462E+00	1,3670E-01	-1,5000E-03*
615	2,7194E+00	9,3800E-02	-1,0300E-03*
620	2,4526E+00	6,1100E-02	-6,8000E-04*
625	2,1700E+00	3,7100E-02	-4,4200E-04*
630	1,8358E+00	2,1500E-02	-2,7200E-04*
635	1,5179E+00	1,1200E-02	-1,4100E-04*
640	1,2428E+00	4,4000E-03	-5,4900E-05*
645	1,0070E+00	7,8000E-05	-2,2000E-06*
650	7,8270E-01	-1,3680E-03	2,3700E-05*
655	5,934E-01	-1,988E-03	2,8600E-05*
660	4,442E-01	-2,168E-03	2,6100E-05*
665	3,283E-01	-2,006E-03	2,2500E-05*
670	2,3940E-01	-1,6420E-03	1,8200E-05*
675	1,7220E-01	-1,2720E-03	1,3900E-05*
680	1,2210E-01	-9,4700E-04	1,0300E-05*
685	8,5300E-02	-6,8300E-04	7,3800E-06*
690	5,8600E-02	-4,7800E-04	5,2200E-06*
695	4,0800E-02	-3,3700E-04	3,6700E-06*
700	2,8400E-02	-2,3500E-04	2,5600E-06*
705	1,9700E-02	-1,6300E-04	1,7600E-06*
710	1,3500E-02	-1,1100E-04	1,2000E-06*
715	9,2400E-03	-7,4800E-05	8,1700E-07*

λ(nm)	$\bar{r}_{10}(\lambda)$	$\bar{g}_{10}(\lambda)$	$\bar{b}_{10}(\lambda)$
720	6,3800E-03	-5,0800E-05	5,5500E-07*
725	4,4100E-03	-3,4400E-05	3,7500E-07*
730	3,0700E-03	-2,3400E-05	2,5400E-07*
735	2,1400E-03	-1,5900E-05	1,7100E-07*
740	1,4900E-03	-1,0700E-05	1,1600E-07*
745	1,0500E-03	-7,2300E-06	7,8500E-08*
750	7,3900E-04	-4,8700E-06	5,3100E-08*
755	5,2300E-04	-3,2900E-06	3,6000E-08*
760	3,7200E-04	-2,2200E-06	2,4400E-08*
765	2,6500E-04	-1,5000E-06	1,6500E-08*
770	1,9000E-04	-1,0200E-06	1,1200E-08*
775	1,3600E-04	-6,8800E-07	7,5300E-09*
780	9,8400E-05	-4,6500E-07	5,0700E-09*
785	7,1300E-05	-3,1200E-07	3,4000E-09*
790	5,1800E-05	-2,0800E-07	2,2700E-09*
795	3,7700E-05	-1,3700E-07	1,5000E-09*
800	2,7600E-05	-8,8000E-08	9,8600E-10*
805	2,0300E-05	-5,5300E-08	6,3900E-10*
810	1,4900E-05	-3,3600E-08	4,0700E-10*
815	1,1000E-05	-1,9600E-08	2,5300E-10*
820	8,1800E-06	-1,0900E-08	1,5200E-10*
825	6,0900E-06	-5,7000E-09	8,6400E-11*
830	4,5500E-06	-2,7700E-09	4,4200E-11*

*) These values are not used for the determination of $\bar{s}_{10,q}(\lambda)$.

Table 6.2 10° cone fundamental sensitivity functions $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ in terms of energy.

To convert 10° cone fundamental sensitivity functions $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ in terms of energy into 10° cone fundamental sensitivity functions in terms of quanta, one should multiply values presented in Table 6.2 by $1/\lambda$ and re-normalise at the nearest 0,1 nm to the maximum values. Results are given in Table 6.3.

λ (nm)	$\bar{l}_{10}(\lambda)$	$\bar{m}_{10}(\lambda)$	$\bar{s}_{10}(\lambda)$	$\bar{s}_{10}(\lambda)$ *)
390	4,07615E-04	3,58227E-04	6,14265E-03	
395	1,06921E-03	9,64828E-04	1,59515E-02	
400	2,54073E-03	2,37208E-03	3,96308E-02	
405	5,31546E-03	5,12316E-03	8,97612E-02	
410	9,98835E-03	9,98841E-03	1,78530E-01	
415	1,60130E-02	1,72596E-02	3,05941E-01	
420	2,33957E-02	2,73163E-02	4,62692E-01	
425	3,09104E-02	3,96928E-02	6,09570E-01	
430	3,97810E-02	5,55384E-02	7,56885E-01	
435	4,94172E-02	7,50299E-02	8,69984E-01	
440	5,94619E-02	9,57612E-02	9,66960E-01	
445	6,86538E-02	1,16220E-01	9,93336E-01	
450	7,95647E-02	1,39493E-01	9,91329E-01	
455	9,07704E-02	1,62006E-01	9,06735E-01	
460	1,06663E-01	1,93202E-01	8,23726E-01	
465	1,28336E-01	2,32275E-01	7,37043E-01	
470	1,51651E-01	2,71441E-01	6,10456E-01	
475	1,77116E-01	3,10372E-01	4,70894E-01	
480	2,07940E-01	3,55066E-01	3,50108E-01	
485	2,44046E-01	4,05688E-01	2,58497E-01	
490	2,82752E-01	4,56137E-01	1,85297E-01	
495	3,34786E-01	5,22970E-01	1,35351E-01	
500	3,91705E-01	5,91003E-01	9,67990E-02	
505	4,56252E-01	6,66404E-01	6,49614E-02	
510	5,26538E-01	7,43612E-01		4,12337E-02
515	5,99867E-01	8,16808E-01		2,71300E-02
520	6,75313E-01	8,89214E-01		1,76298E-02
525	7,37108E-01	9,34977E-01		1,13252E-02
530	7,88900E-01	9,61962E-01		7,17089E-03
535	8,37403E-01	9,81481E-01		4,54287E-03

λ (nm)	$\bar{l}_{10}(\lambda)$	$\overline{m}_{10}(\lambda)$	$\bar{s}_{10}(\lambda)$	$\bar{s}_{10}(\lambda)$ *)
540	8,90871E-01	9,98931E-01		2,83352E-03
545	9,26660E-01	9,91383E-01		1,75573E-03
550	9,44527E-01	9,61876E-01		1,08230E-03
555	9,70703E-01	9,35829E-01		6,64512E-04
560	9,85636E-01	8,90949E-01		4,08931E-04
565	9,96979E-01	8,40969E-01		2,51918E-04
570	9,99543E-01	7,76526E-01		1,55688E-04
575	9,87057E-01	7,00013E-01		9,67045E-05
580	9,57841E-01	6,11728E-01		6,04705E-05
585	9,39781E-01	5,31825E-01		3,81202E-05
590	9,06693E-01	4,54142E-01		2,42549E-05
595	8,59605E-01	3,76527E-01		1,55924E-05
600	8,03173E-01	3,04378E-01		1,01356E-05
605	7,40680E-01	2,39837E-01		6,66657E-06
610	6,68991E-01	1,85104E-01		4,43906E-06
615	5,93248E-01	1,40431E-01		2,99354E-06
620	5,17449E-01	1,04573E-01		0 **)
625	4,45125E-01	7,65841E-02		0
630	3,69168E-01	5,54990E-02		0
635	3,00316E-01	3,97097E-02		0
640	2,42316E-01	2,80314E-02		0
645	1,93730E-01	1,94366E-02		0
650	1,49509E-01	1,37660E-02		0
655	1,12638E-01	9,54315E-03		0
660	8,38077E-02	6,50455E-03		0
665	6,16384E-02	4,42794E-03		0
670	4,48132E-02	3,06050E-03		0
675	3,21660E-02	2,11596E-03		0
680	2,27738E-02	1,45798E-03		0
685	1,58939E-02	9,98424E-04		0
690	1,09123E-02	6,77653E-04		0
695	7,59453E-03	4,67870E-04		0
700	5,28607E-03	3,25278E-04		0
705	3,66675E-03	2,25641E-04		0
710	2,51327E-03	1,55286E-04		0
715	1,72108E-03	1,07388E-04		0
720	1,18900E-03	7,49453E-05		0

λ (nm)	$\bar{l}_{10}(\lambda)$	$\overline{m}_{10}(\lambda)$	$\bar{s}_{10}(\lambda)$	$\bar{s}_{10}(\lambda)$ *)
725	8,22396E-04	5,24748E-05		0
730	5,72917E-04	3,70443E-05		0
735	3,99670E-04	2,62088E-05		0
740	2,78553E-04	1,85965E-05		0
745	1,96528E-04	1,33965E-05		0
750	1,38482E-04	9,63397E-06		0
755	9,81226E-05	6,96522E-06		0
760	6,98827E-05	5,06711E-06		0
765	4,98430E-05	3,68617E-06		0
770	3,57781E-05	2,69504E-06		0
775	2,56411E-05	1,96864E-06		0
780	1,85766E-05	1,45518E-06		0
785	1,34792E-05	1,07784E-06		0
790	9,80671E-06	8,00606E-07		0
795	7,14808E-06	5,96195E-07		0
800	5,24229E-06	4,48030E-07		0
805	3,86280E-06	3,38387E-07		0
810	2,84049E-06	2,54942E-07		0
815	2,10091E-06	1,93105E-07		0
820	1,56506E-06	1,47054E-07		0
825	1,16700E-06	1,11751E-07		0
830	8,73008E-07	8,48902E-08		0

The maximum-values 1,000 are respectively at 568,6 nm, 541,3 nm and 447,9 nm.

*) not derived from CMFs

**) The zero-values from 620 nm – 830 nm do not have a physiological meaning, but only signify that the values are so small, that these values can be neglected. Without introducing the zero-values here, the transformation from the $\bar{l}_{10}(\lambda)$, $\overline{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ into for instance $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}_{10}(\lambda)$ (see Chapter 7c of Part II, to be published), would lead to undetermined values for wavelengths beyond 620 nm.

Table 6.3 The 10° cone fundamental sensitivity functions log $\bar{l}_{10,q}(\lambda)$, log $\bar{m}_{10,q}(\lambda)$ and log $\bar{s}_{10,q}(\lambda)$ in terms of quanta.

To convert 10° cone fundamental sensitivity functions log $\bar{l}_{10,q}(\lambda)$, log $\bar{m}_{10,q}(\lambda)$ and log $\bar{s}_{10,q}(\lambda)$ in terms of quanta into 10° cone fundamental sensitivity functions $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ in terms of energy, one should add log(λ) and renormalize at the nearest 0,1 nm to the maximum values. Results are given in Table 6.2.

λ (nm)	log $\bar{l}_{10,q}(\lambda)$	log $\bar{m}_{10,q}(\lambda)$	log $\bar{s}_{10,q}(\lambda)$	log $\bar{s}_{10,q}(\lambda)$*)
390	-3,22745	-3,30405	-2,15199	
395	-2,81418	-2,87930	-1,74308	
400	-2,44375	-2,49408	-1,35331	
405	-2,12856	-2,16507	-1,00365	
410	-1,85993	-1,88044	-0,71035	
415	-1,66022	-1,64817	-0,48169	
420	-1,50076	-1,45398	-0,30724	
425	-1,38493	-1,29683	-0,19265	
430	-1,28044	-1,15602	-0,10372	
435	-1,19125	-1,03040	-0,04826	
440	-1,11586	-0,92941	-0,00732	
445	-1,05834	-0,85023	-0,00054	
450	-0,99914	-0,77581	-0,00627	
455	-0,94671	-0,71563	-0,04981	
460	-0,88139	-0,64390	-0,09626	
465	-0,80575	-0,56860	-0,14924	
470	-0,73790	-0,50557	-0,23572	
475	-0,67508	-0,45196	-0,35305	
480	-0,60995	-0,39808	-0,48632	
485	-0,54491	-0,34470	-0,62257	
490	-0,48543	-0,29825	-0,77161	
495	-0,41648	-0,24328	-0,91242	
500	-0,35265	-0,19453	-1,06238	
505	-0,29073	-0,14670	-1,23992	
510	-0,23278	-0,10337		-1,44160
515	-0,18040	-0,06684		-1,62764
520	-0,13314	-0,03415		-1,81903
525	-0,09927	-0,01651		-2,01539
530	-0,07390	-0,00827		-2,21798

λ (nm)	log $\bar{l}_{10,q}(\lambda)$	log $\bar{m}_{10,q}(\lambda)$	log $\bar{s}_{10,q}(\lambda)$	log $\bar{s}_{10,q}(\lambda)$*)
535	-0,05206	-0,00362		-2,42030
540	-0,02922	-0,00001		-2,62935
545	-0,01612	-0,00730		-2,84122
550	-0,01179	-0,02439		-3,05529
555	-0,00385	-0,04025		-3,27107
560	-0,00112	-0,06548		-3,48582
565	-0,00001	-0,09442		-3,70007
570	-0,00272	-0,13287		-3,91290
575	-0,01197	-0,18171		-4,12350
580	-0,02878	-0,24402		-4,33116
585	-0,04077	-0,30854		-4,53528
590	-0,06004	-0,38081		-4,73533
595	-0,08686	-0,46587		-4,93088
600	-0,11999	-0,56189		-5,12158
605	-0,15877	-0,66899		-5,30713
610	-0,20655	-0,78506		-5,48732
615	-0,26228	-0,90856		-5,66197
620	-0,32517	-1,04012		- ∞
625	-0,39404	-1,17889		- ∞
630	-0,47876	-1,32220		- ∞
635	-0,57184	-1,47103		- ∞
640	-0,66844	-1,62568		- ∞
645	-0,76901	-1,78809		- ∞
650	-0,88489	-1,94126		- ∞
655	-1,01120	-2,10370		- ∞
660	-1,14290	-2,27348		- ∞
665	-1,27961	-2,44377		- ∞
670	-1,42131	-2,60743		- ∞
675	-1,56855	-2,77095		- ∞
680	-1,72172	-2,93591		- ∞
685	-1,88110	-3,10352		- ∞
690	-2,04757	-3,27499		- ∞
695	-2,20813	-3,43901		- ∞
700	-2,36861	-3,59999		- ∞
705	-2,53055	-3,76192		- ∞
710	-2,69766	-3,92728		- ∞
715	-2,86515	-4,09050		- ∞

λ (nm)	log $\bar{l}_{10,q}(\lambda)$	log $\bar{m}_{10,q}(\lambda)$	log $\bar{s}_{10,q}(\lambda)$	log $\bar{s}_{10,q}(\lambda)$*)
720	-3,02880	-4,24974		- ∞
725	-3,19190	-4,40754		- ∞
730	-3,35187	-4,56175		- ∞
735	-3,51123	-4,71499		- ∞
740	-3,67097	-4,86695		- ∞
745	-3,82538	-5,01231		- ∞
750	-3,98031	-5,15841		- ∞
755	-4,13282	-5,30216		- ∞
760	-4,28309	-5,44320		- ∞
765	-4,43270	-5,58423		- ∞
770	-4,57952	-5,72308		- ∞
775	-4,72701	-5,86228		- ∞
780	-4,86977	-5,99633		- ∞
785	-5,01185	-6,12946		- ∞
790	-5,15275	-6,26136		- ∞
795	-5,29282	-6,39213		- ∞
800	-5,43021	-6,51893		- ∞
805	-5,56554	-6,64353		- ∞
810	-5,70174	-6,76919		- ∞
815	-5,83539	-6,89251		- ∞
820	-5,96593	-7,01349		- ∞
825	-6,09603	-7,13535		- ∞
830	-6,22470	-7,25737		- ∞

The maximum-values 0 are respectively at 564,7 nm, 539,8 nm and 446,85 nm.

*) not derived from CMFs

Table 6.4 Optical density $D_{\tau,\mathrm{macula}}(\lambda)$ of the macular pigment.

λ (nm)	2°	10°	relative
390	0,04533	0,012304	0,1295
395	0,06489	0,017613	0,1854
400	0,0868	0,02356	0,248
405	0,1120	0,0304	0,32
410	0,1365	0,03705	0,39
415	0,1631	0,04427	0,466
420	0,1981	0,05377	0,566
425	0,2345	0,06365	0,67
430	0,2618	0,07106	0,748
435	0,2772	0,07524	0,792
440	0,2884	0,07828	0,824
445	0,308	0,0836	0,88
450	0,3332	0,09044	0,952
455	0,3486	0,09462	0,996
460	0,3500	0,095	1
465	0,3269	0,08873	0,934
470	0,2996	0,08132	0,856
475	0,2842	0,07714	0,812
480	0,2786	0,07562	0,796
485	0,2772	0,07524	0,792
490	0,2688	0,07296	0,768
495	0,2485	0,06745	0,71
500	0,2093	0,05681	0,598
505	0,1652	0,04484	0,472
510	0,1211	0,03287	0,346
515	0,0812	0,02204	0,232
520	0,0525	0,01425	0,15
525	0,0329	0,00893	0,094
530	0,0175	0,00475	0,05
535	0,00929	0,00252	0,0265
540	0,00459	0,00125	0,0131
545	0,00166	0,00045	0,0047
550	0	0	0

Table 6.5 Optical density $D_{\tau,\mathrm{ocul}}(\lambda)$ of lens and other ocular media.

λ (nm)	D_{ocul}
390	2,51220
395	2,13060
400	1,76490
405	1,42570
410	1,13738
415	0,90630
420	0,72398
425	0,59572
430	0,48760
435	0,40810
440	0,34132
445	0,29998
450	0,26288
455	0,24380
460	0,22790
465	0,21306
470	0,20458
475	0,19292
480	0,18338
485	0,17490
490	0,16748
495	0,16006
500	0,15370
505	0,14628
510	0,13780
515	0,12932
520	0,12296
525	0,11660
530	0,11024
535	0,10494
540	0,09858
545	0,09222

λ (nm)	D_{ocul}
550	0,08586
555	0,07950
560	0,07420
565	0,06784
570	0,06148
575	0,05512
580	0,04876
585	0,04346
590	0,03812
595	0,03286
600	0,02968
605	0,02544
610	0,02226
615	0,01908
620	0,01696
625	0,01484
630	0,01166
635	0,00848
640	0,00530
645	0,00424
650	0,00318
655	0,00106
660	0,00000
665	0,00000
670	0,00000
675	0,00000
680	0,00000
685	0,00000
690	0,00000
695	0,00000
700	0,00000

Table 6.6 The photopigment relative quantal absorbance spectra in log units.

λ (nm)	L-pigment	M-pigment	S-pigment
390	-0,93379	-1,04790	-0,13385
395	-0,89477	-0,99737	-0,09075
400	-0,88346	-0,97071	-0,04990
405	-0,90163	-0,97422	-0,02576
410	-0,91541	-0,97112	-0,00926
415	-0,94085	-0,96230	-0,00238
420	-0,95489	-0,93984	-0,00003
425	-0,95756	-0,89896	-0,00547
430	-0,95359	-0,85645	-0,02225
435	-0,93902	-0,80274	-0,05000
440	-0,92675	-0,76267	-0,08115
445	-0,90407	-0,71587	-0,12009
450	-0,87342	-0,66754	-0,16670
455	-0,83350	-0,61743	-0,23983
460	-0,78013	-0,55431	-0,31463
465	-0,72114	-0,49235	-0,40119
470	-0,66428	-0,43737	-0,51694
475	-0,61223	-0,39247	-0,66272
480	-0,55146	-0,34047	-0,81657
485	-0,48714	-0,28496	-0,96832
490	-0,42894	-0,23781	-1,13208
495	-0,36178	-0,18206	-1,28916
500	-0,30399	-0,13844	-1,45859
505	-0,24990	-0,09801	-1,65743
510	-0,20069	-0,06439	-1,88089
515	-0,15585	-0,03834	-2,08698
520	-0,10935	-0,00948	-2,29299
525	-0,07711	0,00000	-2,50132
530	-0,05499	-0,00367	-2,71463
535	-0,03320	-0,00825	-2,92459
540	-0,00946	-0,01459	-3,14134
545	0,00000	-0,03704	-3,36041
550	-0,00396	-0,07306	-3,58132
555	-0,00144	-0,10546	-3,80348
560	-0,00553	-0,14855	-4,02353

λ (nm)	L-pigment	M-pigment	S-pigment
565	-0,01383	-0,19660	-4,24415
570	-0,02800	-0,25538	-4,46335
575	-0,05189	-0,32506	-4,68031
580	-0,08632	-0,40844	-4,89433
585	-0,11133	-0,49035	-5,10375
590	-0,14600	-0,57880	-5,30914
595	-0,18983	-0,67909	-5,50995
600	-0,23784	-0,78679	-5,70383
605	-0,29291	-0,90539	-5,89362
610	-0,35607	-1,03047	-6,07699
615	-0,42682	-1,16171	-6,25482
620	-0,50264	-1,29891	
625	-0,58334	-1,44247	
630	-0,68087	-1,59094	
635	-0,78537	-1,74439	
640	-0,89178	-1,90327	
645	-0,99863	-2,06748	
650	-1,12017	-2,22219	
655	-1,25234	-2,38712	
660	-1,38794	-2,55821	
665	-1,52676	-2,72867	
670	-1,67004	-2,89245	
675	-1,81845	-3,05604	
680	-1,97248	-3,22105	
685	-2,13249	-3,38870	
690	-2,29941	-3,56020	
695	-2,46026	-3,72423	
700	-2,62094	-3,88522	
705	-2,78302	-4,04716	
710	-2,95024	-4,21252	
715	-3,11779	-4,37575	
720	-3,28148	-4,53499	
725	-3,44462	-4,69279	
730	-3,60461	-4,84700	
735	-3,76398	-5,00024	
740	-3,92373	-5,15220	
745	-4,07815	-5,29757	

λ (nm)	L-pigment	M-pigment	S-pigment
750	-4,23309	-5,44366	
755	-4,38560	-5,58742	
760	-4,53587	-5,72846	
765	-4,68548	-5,86949	
770	-4,83230	-6,00833	
775	-4,97979	-6,14754	
780	-5,12256	-6,28158	
785	-5,26464	-6,41472	
790	-5,40553	-6,54661	
795	-5,54561	-6,67738	
800	-5,68300	-6,80419	
805	-5,81832	-6,92879	
810	-5,95452	-7,05445	
815	-6,08818	-7,17777	
820	-6,21871	-7,29874	
825	-6,34881	-7,42061	
830	-6,47749	-7,54263	

Maximum values are at 555,3 nm, 525,1 nm and 419,5 nm.

Table 6.7 2° cone fundamental sensitivity functions $\bar{l}(\lambda)$, $\overline{m}(\lambda)$ and $\bar{s}(\lambda)$ in terms of energy.

(To convert from terms of energy to terms of quanta, multiply by $1/\lambda$ and renormalize, see Table 6.8)

λ (nm)	$\bar{l}(\lambda)$	$\overline{m}(\lambda)$	$\bar{s}(\lambda)$
390	4,150019E-04	3,683495E-04	9,547289E-03
395	1,051914E-03	9,586496E-04	2,382484E-02
400	2,408353E-03	2,269917E-03	5,665002E-02
405	4,833371E-03	4,700132E-03	1,224503E-01
410	8,721273E-03	8,793667E-03	2,330076E-01
415	1,338382E-02	1,452780E-02	3,813643E-01
420	1,844803E-02	2,166506E-02	5,436132E-01
425	2,293190E-02	2,957127E-02	6,744815E-01
430	2,818772E-02	3,945663E-02	8,025461E-01
435	3,410515E-02	5,182030E-02	9,035662E-01
440	4,025595E-02	6,477837E-02	9,910145E-01
445	4,493761E-02	7,588048E-02	9,915166E-01
450	4,986433E-02	8,705225E-02	9,553885E-01
455	5,534138E-02	9,819288E-02	8,602408E-01
460	6,471575E-02	1,162733E-01	7,867016E-01
465	8,069006E-02	1,445407E-01	7,382611E-01
470	9,947639E-02	1,758936E-01	6,463534E-01
475	1,188010E-01	2,053998E-01	5,164164E-01
480	1,401458E-01	2,357545E-01	3,903373E-01
485	1,639532E-01	2,680649E-01	2,903220E-01
490	1,915579E-01	3,036267E-01	2,118654E-01
495	2,329271E-01	3,570590E-01	1,605240E-01
500	2,889615E-01	4,277598E-01	1,228400E-01
505	3,597162E-01	5,155847E-01	8,889554E-02
510	4,436801E-01	6,155169E-01	6,082050E-02
515	5,364880E-01	7,191508E-01	4,281244E-02
520	6,285647E-01	8,166012E-01	2,920317E-02
525	7,047255E-01	8,855437E-01	1,939099E-02
530	7,706373E-01	9,356857E-01	1,260114E-02
535	8,257146E-01	9,688577E-01	8,094500E-03
540	8,810083E-01	9,952221E-01	5,088971E-03

λ (nm)	$\bar{l}(\lambda)$	$\overline{m}(\lambda)$	$\bar{s}(\lambda)$
545	9,190730E-01	9,971948E-01	3,168911E-03
550	9,401995E-01	9,771922E-01	1,958935E-03
555	9,657395E-01	9,565771E-01	1,202763E-03
560	9,814541E-01	9,177407E-01	7,401673E-04
565	9,944890E-01	8,732126E-01	4,559845E-04
570	1	8,135046E-01	2,817993E-04
575	9,923160E-01	7,402868E-01	1,750370E-04
580	9,694379E-01	6,532810E-01	1,094536E-04
585	9,556085E-01	5,725982E-01	6,899855E-05
590	9,276625E-01	4,925950E-01	4,390257E-05
595	8,859720E-01	4,112444E-01	2,822280E-05
600	8,339884E-01	3,344260E-01	1,834593E-05
605	7,751040E-01	2,648744E-01	1,206675E-05
610	7,057161E-01	2,052721E-01	8,034895E-06
615	6,307685E-01	1,562428E-01	5,418387E-06
620	5,542300E-01	1,166407E-01	
625	4,799434E-01	8,558743E-02	
630	4,007098E-01	6,211264E-02	
635	3,278612E-01	4,448770E-02	
640	2,657847E-01	3,142824E-02	
645	2,132849E-01	2,180369E-02	
650	1,651391E-01	1,544792E-02	
655	1,247498E-01	1,071199E-02	
660	9,300794E-02	7,302475E-03	
665	6,850937E-02	4,971759E-03	
670	4,986664E-02	3,436687E-03	
675	3,582284E-02	2,376184E-03	
680	2,537932E-02	1,637344E-03	
685	1,772025E-02	1,121270E-03	
690	1,216998E-02	7,610442E-04	
695	8,471687E-03	5,254605E-04	
700	5,897527E-03	3,653171E-04	
705	4,091288E-03	2,534195E-04	
710	2,804465E-03	1,744014E-04	
715	1,920570E-03	1,206090E-04	
720	1,326875E-03	8,417245E-05	

λ (nm)	$\bar{l}(\lambda)$	$\overline{m}(\lambda)$	$\bar{s}(\lambda)$
725	9,177829E-04	5,893455E-05	
730	6,393665E-04	4,160449E-05	
735	4,460361E-04	2,943542E-05	
740	3,108708E-04	2,088575E-05	
745	2,193310E-04	1,504562E-05	
750	1,545503E-04	1,082007E-05	
755	1,095065E-04	7,822762E-06	
760	7,799195E-05	5,690886E-06	
765	5,562625E-05	4,139998E-06	
770	3,992916E-05	3,026843E-06	
775	2,861608E-05	2,211007E-06	
780	2,073194E-05	1,634330E-06	
785	1,504319E-05	1,210543E-06	
790	1,094460E-05	8,991658E-07	
795	7,977555E-06	6,695915E-07	
800	5,850594E-06	5,031874E-07	
805	4,311021E-06	3,800495E-07	
810	3,170079E-06	2,863255E-07	
815	2,344661E-06	2,168801E-07	
820	1,746666E-06	1,651581E-07	
825	1,302417E-06	1,255076E-07	
830	9,743162E-07	9,534106E-08	

Maximum values are at 570,2 nm, 542,8 nm and 442,1 nm.

Table 6.8 The 2° cone fundamental sensitivity functions log $\bar{l}_{10}(\lambda)$, $\overline{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ in terms of quanta.

(To convert terms of quanta into terms of energy, multiply linear values by λ and renormalize, see Table 6.7)

λ (nm)	log $\bar{l}_q(\lambda)$	log $\overline{m}_q(\lambda)$	log $\bar{s}_q(\lambda)$
390	-3,21863	-3,29076	-1,96598
395	-2,82023	-2,88089	-1,57436
400	-2,46595	-2,51201	-1,20366
405	-2,16882	-2,20131	-0,87429
410	-1,91782	-1,93457	-0,60021
415	-1,73708	-1,72181	-0,39150
420	-1,60291	-1,55345	-0,24275
425	-1,51356	-1,42347	-0,15422
430	-1,42902	-1,30331	-0,08379
435	-1,35128	-1,18995	-0,03732
440	-1,28423	-1,09798	-0,00216
445	-1,24136	-1,03418	-0,00685
450	-1,20104	-0,97939	-0,02782
455	-1,16057	-0,93189	-0,07819
460	-1,09736	-0,86324	-0,12174
465	-1,00625	-0,77342	-0,15403
470	-0,91999	-0,69281	-0,21642
475	-0,84748	-0,63006	-0,31849
480	-0,78028	-0,57474	-0,44460
485	-0,71664	-0,52346	-0,57766
490	-0,65351	-0,47381	-0,71893
495	-0,57300	-0,40782	-0,84385
500	-0,48375	-0,33372	-0,96443
505	-0,39294	-0,25695	-1,10920
510	-0,30611	-0,18429	-1,27831
515	-0,22786	-0,12094	-1,43503
520	-0,16327	-0,06995	-1,60537
525	-0,11776	-0,03890	-1,78735
530	-0,08304	-0,01910	-1,97866
535	-0,05714	-0,00805	-2,17496
540	-0,03303	-0,00043	-2,38056

λ (nm)	log $\bar{l}_q(\lambda)$	log $\overline{m}_q(\lambda)$	log $\bar{s}_q(\lambda)$
545	-0,01866	-0,00358	-2,59028
550	-0,01276	-0,01634	-2,80313
555	-0,00505	-0,02953	-3,01890
560	-0,00193	-0,05142	-3,23365
565	-0,00006	-0,07689	-3,44790
570	-0,00149	-0,11147	-3,66073
575	-0,00863	-0,15622	-3,87133
580	-0,02252	-0,21429	-4,07899
585	-0,03249	-0,27526	-4,28311
590	-0,04907	-0,34432	-4,48316
595	-0,07271	-0,42637	-4,67871
600	-0,10261	-0,51981	-4,86941
605	-0,13801	-0,62468	-5,05496
610	-0,18231	-0,73896	-5,23514
615	-0,23461	-0,86103	-5,40980
620	-0,29432	-0,99150	
625	-0,36030	-1,12943	
630	-0,44212	-1,27212	
635	-0,53269	-1,42049	
640	-0,62726	-1,57482	
645	-0,72621	-1,73699	
650	-0,84067	-1,89000	
655	-0,96582	-2,05233	
660	-1,09663	-2,22203	
665	-1,23268	-2,39227	
670	-1,37388	-2,55589	
675	-1,52075	-2,71938	
680	-1,67365	-2,88433	
685	-1,83284	-3,05194	
690	-1,99917	-3,22339	
695	-2,15963	-3,38741	
700	-2,32004	-3,54839	
705	-2,48194	-3,71031	
710	-2,64902	-3,87567	
715	-2,81649	-4,03889	
720	-2,98012	-4,19812	

λ (nm)	log $\bar{l}_q(\lambda)$	log $\bar{m}_q(\lambda)$	log $\bar{s}_q(\lambda)$
725	-3,14321	-4,35592	
730	-3,30318	-4,51014	
735	-3,46253	-4,66338	
740	-3,62227	-4,81534	
745	-3,77667	-4,96070	
750	-3,93161	-5,10679	
755	-4,08412	-5,25055	
760	-4,23438	-5,39159	
765	-4,38399	-5,53262	
770	-4,53081	-5,67146	
775	-4,67830	-5,81067	
780	-4,82106	-5,94471	
785	-4,96314	-6,07785	
790	-5,10404	-6,20974	
795	-5,24411	-6,34051	
800	-5,38150	-6,46732	
805	-5,51683	-6,59192	
810	-5,65303	-6,71758	
815	-5,78669	-6,84090	
820	-5,91722	-6,96187	
825	-6,04732	-7,08374	
830	-6,17600	-7,20576	

Maximum values are at 565,9 nm, 541,3 nm and 441,5 nm.

Table 6.9 Maximal optical density of the macular pigment as a function of field size.

field size (^{o})	$D_{macularpigm}$
1	0,412
2	0,350
3	0,297
4	0,253
5	0,215
6	0,182
7	0,155
8	0,132
9	0,112
10	0,095

Table 6.10 The optical density $D_{ocul}(\lambda)$ of lens and other ocular media as a function of age.

Function $D_{ocul}(\lambda)$ for an average 32-yr-old observer (pupil diameter < 3mm) (Stockman, Sharpe and Fach (1999).

D_{ocul} can be separated into two components: $D_{ocul}1$ represents portion affected by aging after age 20, and $D_{ocul}2$ represents portion stable after age 20. (After Pokorny, Smith and Lutze, 1987).

The optical density of the lens of an average observer between the ages of 20 and 60 yr is determined by

$$D_{ocul} = D_{ocul}1\ [1 + 0{,}02(A\text{-}32)] + D_{ocul}2$$

For an average observer over the age of 60

$$D_{ocul} = D_{ocul}1\ [1{,}56 + 0{,}0667(A\text{-}60)] + D_{ocul}2$$

where A is the observer's age.

$D_{ocul}2$ is the Stockman and Sharpe (2000) tabulation of lens density scaled to represent a 32-yr-old observer (the average age of the Stiles and Burch observers) with a small pupil (< 3 mm). To estimate the lens density function for a completely open pupil (> 7 mm), multiply the tabulated values by 0,86207.

λ (nm)	D_{ocul}	$D_{ocul}1$	$D_{ocul}2$
400	1,76490	0,661837	1,103063
405	1,42570	0,587956	0,837744
410	1,13738	0,530708	0,606672
415	0,90630	0,468040	0,438260
420	0,72398	0,427672	0,296308
425	0,59572	0,393583	0,202137
430	0,48760	0,372871	0,114729
435	0,40810	0,336814	0,071286
440	0,34132	0,310032	0,031288
445	0,29998	0,282708	0,017272
450	0,26288	0,258499	0,004381
455	0,24380	0,241650	0,002150
460	0,22790	0,227900	0,000000
465	0,21306	0,213060	0,000000
470	0,20458	0,204580	0,000000
475	0,19292	0,192920	0,000000
480	0,18338	0,183380	0,000000
485	0,17490	0,174900	0,000000
490	0,16748	0,167480	0,000000
495	0,16006	0,160060	0,000000
500	0,15370	0,153700	0,000000
505	0,14628	0,146280	0,000000
510	0,13780	0,137800	0,000000
515	0,12932	0,129320	0,000000

λ (nm)	D_{ocul}	$D_{ocul}1$	$D_{ocul}2$
520	0,12296	0,122960	0,000000
525	0,11660	0,116600	0,000000
530	0,11024	0,110240	0,000000
535	0,10494	0,104940	0,000000
540	0,09858	0,098580	0,000000
545	0,09222	0,092220	0,000000
550	0,08586	0,085860	0,000000
555	0,07950	0,079500	0,000000
560	0,07420	0,074200	0,000000
565	0,06784	0,067840	0,000000
570	0,06148	0,061480	0,000000
575	0,05512	0,055120	0,000000
580	0,04876	0,048760	0,000000
585	0,04346	0,043460	0,000000
590	0,03812	0,038120	0,000000
595	0,03286	0,032860	0,000000
600	0,02968	0,029680	0,000000
605	0,02544	0,025440	0,000000
610	0,02226	0,022260	0,000000
615	0,01908	0,019080	0,000000
620	0,01696	0,016960	0,000000
625	0,01484	0,014840	0,000000
630	0,01166	0,011660	0,000000
635	0,00848	0,008480	0,000000
640	0,00530	0,005300	0,000000
645	0,00424	0,004240	0,000000
650	0,00318	0,003180	0,000000
655	0,00106	0,001060	0,000000
660	0,00000	0,000000	0,000000
665	0,00000	0,000000	0,000000
670	0,00000	0,000000	0,000000
675	0,00000	0,000000	0,000000
680	0,00000	0,000000	0,000000
685	0,00000	0,000000	0,000000
690	0,00000	0,000000	0,000000
695	0,00000	0,000000	0,000000
700	0,00000	0,000000	0,000000

Table 6.11 The maximal values of the optical density of the visual pigments as a function of field size.

field size(°)	*D*(L- and M- pigment)	*D*(S- pigment)
1	0,635	0,513
2	0,500	0,400
3	0,437	0,347
4	0,407	0,322
5	0,393	0,311
6	0,386	0,305
7	0,383	0,302
8	0,381	0,301
9	0,381	0,301
10	0,380	0,300

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