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TECHNICAL REPORT

Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

CIE 170-2:2015

UDC: 612.84
535.66

Descriptor: Physiological optics. vision
Colorimetry

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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 as well as by Division 1 of the Commission Internationale de l'Eclairage. 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.

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 et Division 1 de la Commission Internationale de l'Eclairage. 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.

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FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 2: SPECTRAL LUMINOUS EFFICIENCY FUNCTIONS AND CHROMATICITY DIAGRAMS

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 coordinates correspond to physiologically significant axes".

Part 1 of the report is presented in CIE 170-1 *Fundamental Chromaticity Diagram with Physiological Axes – Part 1: Definition of CIE 2006 Cone Fundamentals*. It is limited to the choice of a set of colour-matching functions (CMFs) and estimates of cone fundamentals for the normal observer, ranging in visual angle (field size) from 1° to 10°.

This report, entitled Part 2, aims at providing the user with practical colorimetric tools, in the form of chromaticity diagrams.

The report starts with the definition of cone-fundamental-based spectral luminous efficiency functions as a linear combination of the long-wave sensitive and the middle-wave sensitive cone fundamentals, following the proposal of Sharpe et al. (2011). Cone-fundamental-based spectral luminous efficiency functions are proposed for the 2° and for the 10° photometric observers.

The definition of the cone-fundamental-based spectral luminous efficiency functions offers the possibility of developing MacLeod–Boynton chromaticity diagrams based on cone fundamentals where the chromaticity is represented in an equi-luminant plane. MacLeod–Boynton tristimulus values L_{MB} , M_{MB} and S_{MB} are computed in the traditional form, while chromaticity coordinates l_{MB} and s_{MB} are computed so as to preserve the equi-luminant property of the diagram.

In addition, to allow for comparisons with the traditional CIE procedures, transformations of the cone fundamentals in the form of cone-fundamental-based X_F , Y_F , Z_F tristimulus values and x_F , y_F chromaticity coordinates are presented. Criteria that a colorimetric system should fulfil are maintained, and the properties of the spectral tristimulus values, summarized by Wold and Valberg (1999), are described in detail. The linear transformations that should be used to compute the X_F , Y_F , Z_F tristimulus values from the cone fundamentals are given with the number of decimal places necessary to produce spectral tristimulus values with 7 significant figures.

The report ends with tables and references.

All tables are downloadable in an Excel® file at http://files.cie.co.at/813_Tables_CIE_170-2.xls.

DIAGRAMME FONDAMENTAL DE CHROMATICITE AVEC DES AXES PHYSIOLOGIQUES – PARTIE 2: FONCTIONS D'EFFICACITÉ LUMINEUSE SPECTRALE ET DIAGRAMMES DE CHROMATICITÉ

Résumé

La CIE a créé, en 1991, le Comité technique TC 1-36 avec pour mandat : «Etablir un diagramme de chromaticité fondamental dont les coordonnées correspondent à des axes physiologiquement significatifs».

La première partie du rapport a été publiée dans le document CIE 170-1 *Fundamental Chromaticity Diagram with Physiological Axes – Part 1: Definition of CIE 2006 Cone Fundamentals*. Elle se limite au choix d'un ensemble de fonctions colorimétriques et à

l'estimation des fondamentales de cônes pour l'observateur à vision des couleurs normale, couvrant un champ visuel de 1° à 10°.

Ce rapport-ci, intitulé Partie 2, vise à fournir à l'utilisateur des outils colorimétriques pratiques, sous la forme de diagrammes de chromaticité.

Le rapport commence par la définition des fonctions d'efficacité lumineuse spectrale fondamentales comme résultant d'une combinaison linéaire de la fondamentale de cônes sensibles aux grandes longueurs d'onde et de la fondamentale de cônes sensibles aux moyennes longueurs d'onde, d'après la proposition de Sharpe et al. (2011). Des fonctions d'efficacité lumineuse spectrale fondamentales sont proposées pour les observateurs photométriques 2° et 10°.

La définition des fonctions fondamentales de l'efficacité lumineuse spectrale permet de développer des diagrammes de chromaticité selon MacLeod–Boynton basés sur les fondamentales de cônes où la chromaticité est représenté dans un plan équiluminant. Les composantes trichromatiques L_{MB} , M_{MB} et S_{MB} selon MacLeod–Boynton sont calculées sous la forme traditionnelle, tandis que les coordonnées trichromatiques l_{MB} et s_{MB} sont calculées de manière à préserver la propriété equi-luminante du diagramme.

En outre, pour permettre des comparaisons avec les procédures traditionnelles de la CIE, on présente des transformations de fondamentales de cônes en composantes trichromatiques X_F , Y_F et Z_F basées sur les fondamentales de cônes et des coordonnées trichromatiques x_F et y_F . Les critères que doit respecter un système colorimétrique sont maintenus ainsi que les propriétés des fonctions colorimétriques, tels que résumés par Wold et Valberg (1999), sont décrits en détail. Les transformations linéaires devant être utilisées pour calculer les composantes trichromatiques X_F , Y_F et Z_F à partir des fondamentales de cônes sont données avec le nombre de décimales nécessaires pour produire des valeurs de composantes trichromatiques spectrales à 7 chiffres significatifs.

Tous les tableaux sont disponibles dans un fichier Excel® téléchargeable à l'adresse http://files.cie.co.at/813_Tables_CIE_170-2.xls.

GRUNDLEGENDE FARBTAFEL MIT PHYSIOLOGISCHEN ACHSEN – TEIL 2: FUNKTIONEN DES SPEKTRALEN HELLEMPFINDLICHKEITSGRADS UND FARBTAFELN

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 1 des Berichts ist in CIE 170-1 *Fundamental Chromaticity Diagram with Physiological Axes – Part 1: Definition of CIE 2006 Cone Fundamentals* niedergelegt. Er ist begrenzt 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.

Dieser mit Teil 2 bezeichnete Bericht hat das Ziel, dem Nutzer praktische farbmétrische Werkzeuge in Form von Farbtafeln an die Hand zu geben.

Der Bericht beginnt mit der Definition von auf Sehzapfen-Grundfunktionen basierenden Spektralwertfunktionen als eine Linearkombination der langwelligen und mittelwelligen Sehzapfen-Grundfunktionen, einem Vorschlag von Sharpe et al. (2011) folgend. Auf Sehzapfen-Grundfunktionen basierende Spektralwertfunktionen werden für den 2° und den 10° photometrischen Normalbeobachter vorgeschlagen.

Die Definition der auf Sehzapfen-Grundfunktionen basierenden Spektralwertfunktionen bietet die Möglichkeit, MacLeod–Boynton-Farbtafeln zu entwickeln, die auf Sehzapfen-Grundfunktionen basieren, wobei die Farbart in einer Ebene gleicher Leuchtdichte repräsentiert wird. MacLeod–Boynton-Farbwerte L_{MB} , M_{MB} und S_{MB} werden in üblicher Weise berechnet, während die Farbkoordinaten l_{MB} und s_{MB} so berechnet werden, dass die Eigenschaft gleicher Leuchtdichte des Diagramms erhalten bleibt.

Des Weiteren werden, um Vergleiche mit üblichen CIE-Verfahren zu erlauben, Transformationen der Sehzapfen-Grundfunktionen in Form von auf Sehzapfen-Grundfunktionen basierenden Farbwerten X_F , Y_F , Z_F und Farbkoordinaten x_F , y_F präsentiert. Von einem farbmétrischen System zu erfüllende Kriterien werden erhalten, und die Eigenschaften der spektralen Farbwerte, zusammengefasst von Wold und Valberg (1999), werden im Detail beschrieben. Die linearen Transformationen, die zur Berechnung der Farbwerte X_F , Y_F , Z_F aus den Sehzapfen-Grundfunktionen benutzt werden sollten, werden mit der Anzahl von Dezimalstellen angegeben, welche zur Ermittlung spektraler Farbwerte mit 7 signifikanten Stellen erforderlich sind.

Der Bericht endet mit Tabellen und Referenzen.

Alle Tabellen sind in einer Excel®-Datei unter http://files.cie.co.at/813_Tables_CIE_170-2.xls verfügbar.

Introduction to Part 2

Since colorimetry was established in 1931, considerable improvements in the metrology of the colour stimulus and immense advances in the knowledge of colour vision have been made.

The colour sensation results from physiological processes, the first of which is the capture of photons by the cones of the retina. The fundamental sensitivities of the cones need to be precisely known to accurately specify a colour stimulus from a given spectral power distribution.

Part 1 of this report provides the scientific community with cone fundamentals, which are the relative spectral sensitivities of the long-wave sensitive (LWS), middle-wave sensitive (MWS) and short-wave sensitive (SWS) cones as measured at the entrance of the eye. The cone fundamentals have been derived from the best set of colour-matching functions experimentally collected on a 10° field. In particular, the 2° cone fundamentals, which have been reconstructed from the 10° data by guidance of psychophysical data for 2° field size, represent the best proposal available today.

Part 2 of the report aims at providing the user with practical colorimetric tools, in the form of chromaticity diagrams. The chromaticity diagram is a two-dimensional representation of colour, independent of the luminance of the colour stimulus. The hypothesis that luminous quantity as measured by flicker photometry (referred to as LM-luminance in this report) relies only on the sum of the activity of the LWS and MWS cones has been recognized, and a cone-fundamental-based spectral luminous efficiency function is implemented in Clause 7. As outlined in 8.1, this hypothesis offers the possibility of proposing an equi-luminant chromaticity diagram directly based on cone fundamentals, which is a considerable advantage for understanding colour. In addition, to allow for comparison with the traditional CIE procedures, a transformation of the cone fundamentals in the form of cone-fundamental-based XYZ tristimulus values and of an accompanying chromaticity diagram is presented in 8.2.

Part 2 ends by concluding that a link has been established between colorimetry and physiology. Such a reasoning, which has been developed by several scientists in the past, is a modern CIE approach that will improve the understanding of colour. It will be useful for education and will offer novel opportunities of solving problems of colour measurement and colour perception in everyday life and in industry.

NOTE The clause numbers in this document are continuous with respect to Part 1 of the report, i.e. start with Clause 7.

7 Photometric Aspects; the Choice of the Cone-Fundamental-Based Spectral Luminous Efficiency Functions

7.1 Task Definition

Once the essential step of proposing cone fundamentals is taken, it is possible to represent colours in a colorimetric colour space with physiologically significant axes.

The tristimulus values L , M and S of a colour stimulus given by the colour stimulus function $\varphi_\lambda(\lambda)$ are obtained by the equations

$$L = k_L \int \varphi_\lambda(\lambda) \cdot \bar{l}(\lambda) \cdot d\lambda \quad (7.1a)$$

$$M = k_M \int \varphi_\lambda(\lambda) \cdot \bar{m}(\lambda) \cdot d\lambda \quad (7.1b)$$

$$S = k_S \int \varphi_\lambda(\lambda) \cdot \bar{s}(\lambda) \cdot d\lambda, \quad (7.1c)$$

in which $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ are the cone fundamentals normalized to unity peak, originally from Stockman and Sharpe (2000), and k_L , k_M and k_S are constants that scale the tristimulus values for normalizing purpose.

In this document a purely colorimetric observer is dealt with. An attractive, but artificial, aspect of the CIE 1931 system is that $\bar{y}(\lambda)$ is identical to the spectral luminous efficiency function $V(\lambda)$, so that the CIE 1931 standard observer is both a colorimetric and photometric observer.

However, as mentioned in the general introduction in Clause 1 (see Part 1 of this document), the spectral luminous efficiency function $V(\lambda)$ in the CIE 1931 standard colorimetric system was introduced in a dubious way, since it was used to construct the colour-matching functions. The 1924 photometric observer thus became an essential ingredient in the 1931 colorimetric observer. In this clause the opposite route is taken: On the basis of the purely colorimetric functions $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$, an optimal spectral luminous efficiency function $V_F(\lambda)$ as a linear combination of $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ is sought, where optimal is intended to mean being close to experimental data as well as being close to a currently used photopic spectral luminous efficiency function. Thus, the task is to determine appropriate values of the coefficients α , β and γ in the equation

$$V_F(\lambda) = \alpha \bar{l}(\lambda) + \beta \bar{m}(\lambda) + \gamma \bar{s}(\lambda). \quad (7.2)$$

7.2 The Cone-Fundamental-Based Spectral Luminous Efficiency Functions $V_{F,q}(\lambda)$ and $V_F(\lambda)$ for 2° Field Size

It is generally recognized that the CIE 1924 photopic spectral luminous efficiency function for the 2° observer, $V(\lambda)$, was defined as a poor compromise between very divergent experimental data, particularly at short wavelengths. Judd (1951) and Vos (1978) made suggestions for an improved $V(\lambda)$, which resulted in the $V_M(\lambda)$ function as described in CIE 86-1990 (CIE, 1990). Therefore, in line with our basic assumption that the S-cone system does not notably contribute to luminance, the question of determining a linear combination of the kind given in Eq. 7.2 reduces to the problem of finding coefficients α_2 and β_2 that make $\alpha_2 \bar{l}(\lambda) + \beta_2 \bar{m}(\lambda)$ an optimal fit to $V_M(\lambda)$.

Computations show that an exact fit cannot be achieved, as might be expected since $V_M(\lambda)$ is somewhat removed from experimental data.

But based on experimental data Sharpe et al. (2011), by revising their 2005-paper (Sharpe et al., 2005), proposed a reasonable practical solution described by the equation

$$V_{F,q}(\lambda) = [1,89 \bar{l}_q(\lambda) + \bar{m}_q(\lambda)] / 2,803\,605\,72 \quad (7.3a)$$

or

$$V_{F,q}(\lambda) = 0,674\,13188 \bar{l}_q(\lambda) + 0,356\,683\,54 \bar{m}_q(\lambda), \quad (7.3b)$$

in which $V_{F,q}(\lambda)$ is the proposed cone-fundamental-based spectral luminous efficiency function for 2° field size in terms of quanta (subscript F denoting “cone-fundamental-based”), and $\bar{l}_q(\lambda)$ and $\bar{m}_q(\lambda)$ are the quantal 2° cone fundamentals.

The denominator value 2,803 605 72 in Eq. 7.3a is needed for normalization to unity peak (which means normalization at the nearest 0,1 nm to the maximum value at 546,1 nm). Note that this function has a broad flat peak with local undulations. 546,1 nm is a local maximum—the central wavelength of the broad peak is about 550 nm. These undulations reflect the properties of the underlying Stiles and Burch (1959) data. $V_{F,q}(\lambda)$ is representative of an average spectral luminous efficiency function, which, as shown by Hofer et al. (2005), is an average of considerable variations between observers, or one could say, within this scheme, of considerable variations of weighting factors between observers (Stockman et al., 2008).

It should be mentioned that the choice as made in Eq. 7.3 is the one for a background adaptation of Standard Illuminant D65 (Stockman et al., 2008). This choice is made because D65 is one of the illuminants recommended by the CIE for all specifications of surface colour (see for instance ISO/CIE (2007)).

$V_{F,q}(\lambda)$ is very close to the photopic sensitivity curve as determined by Sharpe et al. (2011).

When the photopic luminous efficiency and the cone fundamentals are defined on an energy basis, Eqs. 7.3 a–b become

$$V_F(\lambda) = [1,980\,647\,04 \bar{l}(\lambda) + \bar{m}(\lambda)] / 2,870\,907\,67 \quad (7.4a)$$

or

$$V_F(\lambda) = 0,689\,902\,72 \bar{l}(\lambda) + 0,348\,32189 \bar{m}(\lambda), \quad (7.4b)$$

where $V_F(\lambda)$ is the proposed cone-fundamental-based spectral luminous efficiency function for 2° field size in terms of energy, and $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$ are the energy-based 2° cone fundamentals.

$V_F(\lambda)$ is normalized to unity peak at 556,1 nm.

For the field size of 2°, it is recommended to use Eq. 7.3 in terms of quanta (see Table 10.1) and Eq. 7.4 in terms of energy (see Table 10.2).

The ratio of the weighting of $\bar{l}(\lambda)$ to the weighting of $\bar{m}(\lambda)$ is, although individual differences in the ratio of L-cones to M-cones are known, close to the value 2 (see Eq. 7.4a), the mean value in the determination by Nerger and Cicerone (1992), a value first proposed by Vos and Walraven (1971), and used since in many colour models (Guth et al., 1980; Lennie et al., 1993).

The new function $V_F(\lambda)$ in Eq. 7.4 is introduced as a supplement to $V_M(\lambda)$ within the context of this report.

As Figure 7.1 shows, the discrepancies between $V_F(\lambda)$ and $V_M(\lambda)$ are rather small, and actually insignificant in comparison with individual variability, so that switching from $V_M(\lambda)$ to $V_F(\lambda)$ does not mean a repudiation of $V_M(\lambda)$, but should rather be seen as one step further in defining an integrated photometric and colorimetric observer.

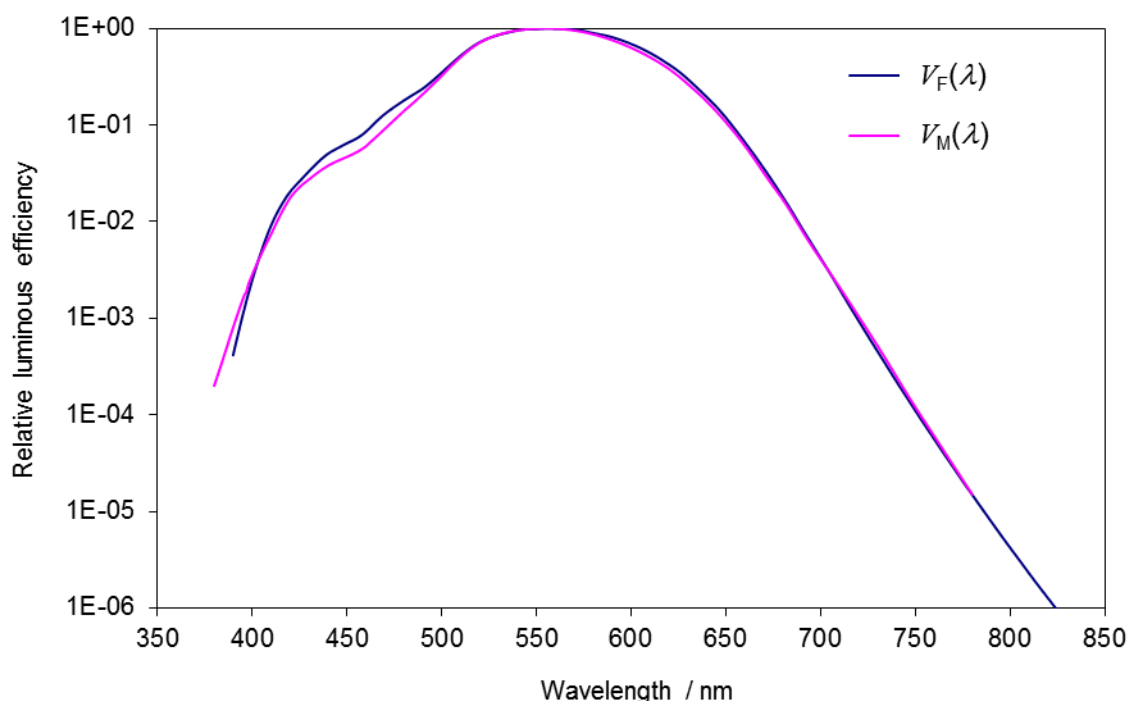


Figure 7.1 – Relative spectral luminous efficiency (log-scale) in terms of energy, for the 2° field size: the proposed cone-fundamental-based spectral luminous efficiency function $V_F(\lambda)$ compared with the CIE 1988 $V_M(\lambda)$

7.3 The Cone-Fundamental-Based Spectral Luminous Efficiency Functions $V_{F,q,10}(\lambda)$ and $V_{F,10}(\lambda)$ for 10° Field Size

CIE (2005) has recommended the use of $\bar{y}_{10}(\lambda)$ of the CIE 1964 standard colorimetric observer as the appropriate photopic spectral luminous efficiency function for the field size of 10°. As $\bar{y}_{10}(\lambda)$ does not suffer the same weakness as the CIE $V(\lambda)$ function for the 2° field size, it seems therefore obvious to find the coefficients α_{10} and β_{10} that make $\alpha_{10} \cdot \bar{l}_{10}(\lambda) + \beta_{10} \cdot \bar{m}_{10}(\lambda)$ an optimal fit to $\bar{y}_{10}(\lambda)$.

Computations show, however, that a truly close fit cannot be achieved, which is not too surprising, since $\bar{y}_{10}(\lambda)$ is a linear combination of the CIE 1964 10° CMFs rather than the Stiles and Burch (1959) CMFs used here. The CIE 1964 CMFs incorporate the Speranskaya (1959) data as well as the Stiles and Burch data, and the CMFs were subjected to several other adjustments by the CIE.

Given the finding that for a broad range of values of α_{10} / β_{10} the difference between $\alpha_{10} \cdot \bar{l}_{10}(\lambda) + \beta_{10} \cdot \bar{m}_{10}(\lambda)$ on the one hand and $\bar{y}_{10}(\lambda)$ on the other hand is almost the same, and no clear optimal value of α_{10} / β_{10} can be established, other ways should be found to determine α_{10} / β_{10} .

According to Cicerone and Nerger (1989), Nerger and Cicerone (1992), and Knau et al. (2001), the L/M-ratio does not significantly change as a function of retinal eccentricity.

Bearing in mind that α_2 / β_2 is given as 1,89 in Eq. 7.3a, it seems, on the basis of this evidence, reasonable to choose the same value 1,89 for α_{10} / β_{10} in the 10° case.

It should be stressed that this argument is given as a practical solution to the problem of establishing the ratio α_{10} / β_{10} . A straightforward comparison with an experimentally measured $V_{10}(\lambda)$ function would be preferred. It should be further stressed that this provisional solution is offered mainly as a means of defining a $(x_{F,10}, y_{F,10})$ cone-fundamental-based chromaticity diagram similar to the CIE 1964 (x_{10}, y_{10}) diagram. It is noted that further study is required and that this is by no means a proposal to replace the $\bar{y}_{10}(\lambda)$.

Adopting 1,89 as the ratio of α_{10} to β_{10} , the cone-fundamental-based spectral luminous efficiency function for 10° field size in terms of quanta, $V_{F,q,10}(\lambda)$, is given by the equation

$$V_{F,q,10}(\lambda) = [1,89 \bar{l}_{q,10}(\lambda) + \bar{m}_{q,10}(\lambda)] / 2,804\,550\,17 \quad (7.5a)$$

or

$$V_{F,q,10}(\lambda) = 0,673\,904\,86 \bar{l}_{q,10}(\lambda) + 0,356\,563\,42 \bar{m}_{q,10}(\lambda), \quad (7.5b)$$

in which $\bar{l}_{q,10}(\lambda)$ and $\bar{m}_{q,10}(\lambda)$ are the quantal 10° cone fundamentals.

The denominator value 2,804 550 17 in Eq. 7.5a is needed for normalization to unity peak, which is at 544,8 nm.

When the photopic luminous efficiency and the cone fundamentals are defined on an energy basis, Eqs. 7.5 a–b become

$$V_{F,10}(\lambda) = [1,981\,376\,97 \bar{l}_{10}(\lambda) + \bar{m}_{10}(\lambda)] / 2,859\,792\,94 \quad (7.6a)$$

or

$$V_{F,10}(\lambda) = 0,692\,839\,32 \bar{l}_{10}(\lambda) + 0,349\,675\,67 \bar{m}_{10}(\lambda), \quad (7.6b)$$

where $V_{F,10}(\lambda)$ is the cone-fundamental-based spectral luminous efficiency function for 10° field size in terms of energy, and $\bar{l}_{10}(\lambda)$ and $\bar{m}_{10}(\lambda)$ are the energy-based 10° cone fundamentals.

$V_{F,10}(\lambda)$ is normalized to unity peak at 555,7 nm.

For the field size of 10°, it is recommended to use Eq. 7.5 in terms of quanta (see Table 10.3) and Eq. 7.6 in terms of energy (see Table 10.4).

Figure 7.2 shows that the discrepancies between $V_{F,10}(\lambda)$ and $\bar{y}_{10}(\lambda)$ are very small.

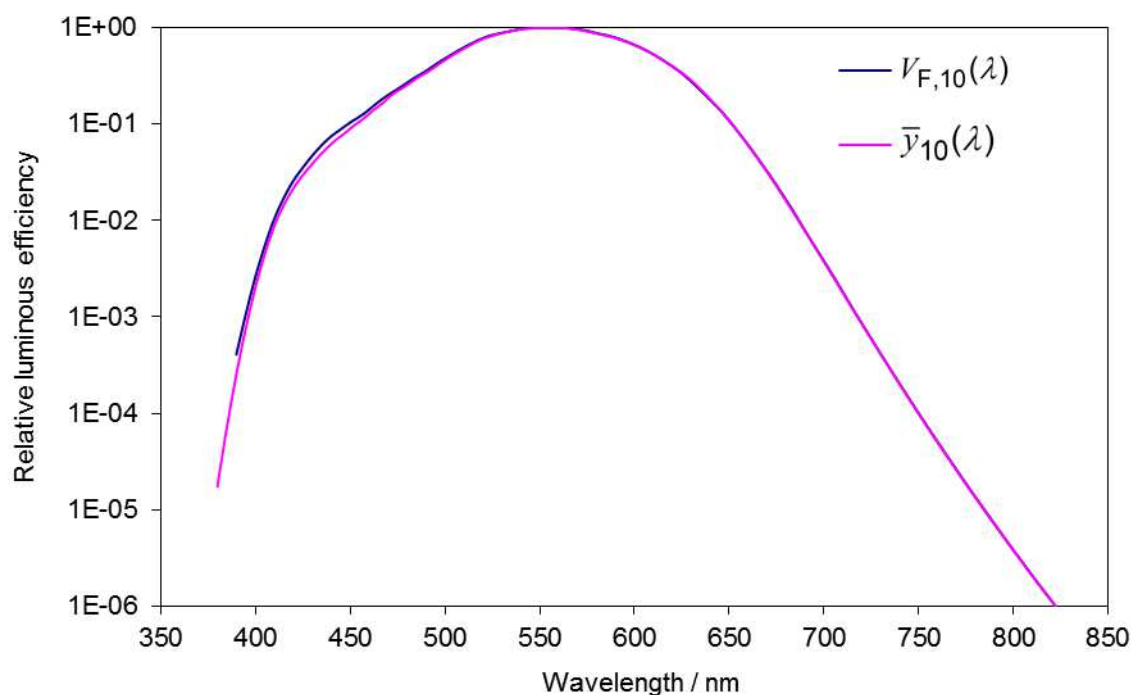


Figure 7.2 – Relative spectral luminous efficiency (log-scale), in terms of energy, for the 10° field size: the proposed cone-fundamental-based spectral luminous efficiency function $V_{F,10}(\lambda)$ compared with the $\bar{y}_{10}(\lambda)$ of the CIE 1964 10° observer

8 Chromaticity Diagrams

This clause deals with chromaticity, i.e. with the specification of the chromatic properties of the colour stimulus in a two-dimensional plane.

Several choices are possible (Valberg, 2005). In line with what is known from physiology, emphasis is given to an equi-luminant chromaticity diagram that allows the separation of the luminous and the chromatic components of the stimulus.

Finally, to bridge the gap between the cone-fundamental framework and the current CIE practice, an (x, y) -like cone-fundamental-based chromaticity diagram is developed.

8.1 The MacLeod–Boynton Chromaticity Diagram

An advantage of defining the cone-fundamental-based spectral luminous efficiency function ($V_F(\lambda)$ function) as a particular sum of the LWS cone (L-cone) and MWS cone (M-cone) responses is that it offers an elegant and useful way of representing cone chromaticities in an equi-luminant plane or diagram. A chromaticity diagram of this kind, based in part on earlier proposals by Schrödinger (1925), Luther (1927) and Le Grand (1949), was developed by MacLeod and Boynton (1979).

This diagram is now commonly referred to as the *MacLeod–Boynton chromaticity diagram*.

8.1.1 MacLeod–Boynton Tristimulus Values

For the derivation of the MacLeod–Boynton chromaticity diagram, the LMS tristimulus space needs to be defined. An LMS tristimulus space is a three-dimensional vector space where the coordinate axes represent the excitations of the three cone types involved in colour vision. In particular, a Cartesian LMS tristimulus space reflecting the weighted contribution of L- and M-cones to the LM-luminance is referred to below as a *MacLeod–Boynton tristimulus space*. The coordinates of such a space are named *MacLeod–Boynton tristimulus values*.

In the derivation of the tristimulus values, care is taken of the weighted contribution of L- and M-cones to the LM-luminance. Thus, when weighting factors for luminance are applied, the MacLeod–Boynton tristimulus values L_{MB} , M_{MB} and S_{MB} of a colour stimulus given by the colour stimulus function $\varphi_{\lambda}(\lambda)$ are obtained by the equations

$$L_{MB} = \alpha_L \int_{\lambda} \varphi_{\lambda}(\lambda) \bar{l}(\lambda) d\lambda \quad (8.1a)$$

$$M_{MB} = \alpha_M \int_{\lambda} \varphi_{\lambda}(\lambda) \bar{m}(\lambda) d\lambda \quad (8.1b)$$

$$S_{MB} = \alpha_S \int_{\lambda} \varphi_{\lambda}(\lambda) \bar{s}(\lambda) d\lambda, \quad (8.1c)$$

in which $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ are the cone fundamentals normalized to unity peak, and α_L , α_M and α_S are weighting factors that, in addition to providing an appropriate overall normalization, ensure equi-luminance within the corresponding chromaticity diagram.

The MacLeod–Boynton tristimulus values may be defined on either a quantum basis or an energy basis. In both cases, the above-mentioned characteristics of a MacLeod–Boynton tristimulus space are obtained by normalizing the MacLeod–Boynton tristimulus values L_{MB} and M_{MB} (referring to the L- and M-cone fundamentals) so that the unweighted sum $L_{MB} + M_{MB}$ is proportional to the LM-luminance. There is no specific criterion for the scaling of the S -axis. For convenience, however, the MacLeod–Boynton tristimulus value S_{MB} (referring to the S-cone fundamental) is normalized so that, for real colour stimuli, the ratio $S_{MB} / (L_{MB} + M_{MB})$ has a maximum value of one.

It is recommended to use the following MacLeod–Boynton tristimulus values:

8.1.1.1 The Quantum-Based MacLeod–Boynton Tristimulus Values for 2° Field Size

$$L_{MB,q} = 0,674\,131\,88 \sum_{i=1}^{441} \varphi_{\lambda,q}(\lambda_i) \bar{l}_q(\lambda_i) \Delta\lambda \quad (8.2a)$$

$$M_{MB,q} = 0,356\,683\,54 \sum_{i=1}^{441} \varphi_{\lambda,q}(\lambda_i) \bar{m}_q(\lambda_i) \Delta\lambda \quad (8.2b)$$

$$S_{MB,q} = 0,046\,688\,58 \sum_{i=1}^{441} \varphi_{\lambda,q}(\lambda_i) \bar{s}_q(\lambda_i) \Delta\lambda, \quad (8.2c)$$

where $(\lambda_1, \lambda_2, \dots, \lambda_{441}) = (390\text{ nm}, 391\text{ nm}, \dots, 830\text{ nm})$, $\Delta\lambda = 1\text{ nm}$, $\varphi_{\lambda,q}(\lambda)$ is the quantum-based colour stimulus function and $\bar{l}_q(\lambda)$, $\bar{m}_q(\lambda)$ and $\bar{s}_q(\lambda)$ are the 2° cone fundamentals as defined in terms of quantum units in Clauses 2 and 4 of Part 1.

NOTE The scaling factors 0,674 131 88 and 0,356 683 54 equal the coefficients of the linear combination $V_{F,q}(\lambda) = 0,674\,131\,88 \bar{l}_q(\lambda) + 0,356\,683\,54 \bar{m}_q(\lambda)$ (see Eq. 7.3b). The factor 0,046 688 58 is needed for normalizing $\bar{s}_q(\lambda)/V_{F,q}(\lambda)$ to a maximum value of one.

8.1.1.2 The Energy-Based MacLeod–Boynton Tristimulus Values for 2° Field Size

$$L_{\text{MB}} = 0,689\,902\,72 \sum_{i=1}^{441} \varphi_{\lambda}(\lambda_i) \bar{l}(\lambda_i) \Delta\lambda \quad (8.3a)$$

$$M_{\text{MB}} = 0,348\,321\,89 \sum_{i=1}^{441} \varphi_{\lambda}(\lambda_i) \bar{m}(\lambda_i) \Delta\lambda \quad (8.3b)$$

$$S_{\text{MB}} = 0,037\,159\,71 \sum_{i=1}^{441} \varphi_{\lambda}(\lambda_i) \bar{s}(\lambda_i) \Delta\lambda, \quad (8.3c)$$

where $(\lambda_1, \lambda_2, \dots, \lambda_{441}) = (390\text{ nm}, 391\text{ nm}, \dots, 830\text{ nm})$, $\Delta\lambda = 1\text{ nm}$, $\varphi_{\lambda}(\lambda)$ is the colour stimulus function and $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ are the 2° cone fundamentals as defined in terms of energy units in Clauses 2 and 4 of Part 1.

NOTE The scaling factors 0,689 902 72 and 0,348 321 89 equal the coefficients of the linear combination $V_F(\lambda) = 0,689\,902\,72 \bar{l}(\lambda) + 0,348\,321\,89 \bar{m}(\lambda)$ (see Eq. 7.4b). The factor 0,037 159 71 is needed for normalizing $\bar{s}(\lambda)/V_F(\lambda)$ to a maximum value of one.

8.1.1.3 The Quantum-Based MacLeod–Boynton Tristimulus Values for 10° Field Size

$$L_{\text{MB},q,10} = 0,673\,904\,86 \sum_{i=1}^{441} \varphi_{\lambda,q}(\lambda_i) \bar{l}_{q,10}(\lambda_i) \Delta\lambda \quad (8.4a)$$

$$M_{\text{MB},q,10} = 0,356\,563\,42 \sum_{i=1}^{441} \varphi_{\lambda,q}(\lambda_i) \bar{m}_{q,10}(\lambda_i) \Delta\lambda \quad (8.4b)$$

$$S_{\text{MB},q,10} = 0,068\,348\,28 \sum_{i=1}^{441} \varphi_{\lambda,q}(\lambda_i) \bar{s}_{q,10}(\lambda_i) \Delta\lambda, \quad (8.4c)$$

where $(\lambda_1, \lambda_2, \dots, \lambda_{441}) = (390\text{ nm}, 391\text{ nm}, \dots, 830\text{ nm})$, $\Delta\lambda = 1\text{ nm}$, $\varphi_{\lambda,q}(\lambda)$ is the quantum-based colour stimulus function and $\bar{l}_{q,10}(\lambda)$, $\bar{m}_{q,10}(\lambda)$ and $\bar{s}_{q,10}(\lambda)$ are the 10° cone fundamentals as defined in terms of quantum units in Clauses 2 and 4 of Part 1.

NOTE The scaling factors 0,673 904 86 and 0,356 563 42 are the coefficients of the linear combination $V_{F,q,10}(\lambda) = 0,673\,904\,86 \bar{l}_{q,10}(\lambda) + 0,356\,563\,42 \bar{m}_{q,10}(\lambda)$ (see Eq. 7.5b). The factor 0,068 348 28 is needed for normalizing $\bar{s}_{q,10}(\lambda)/V_{F,q,10}(\lambda)$ to a maximum value of one.

8.1.1.4 The Energy-Based MacLeod–Boynton Tristimulus Values for 10° Field Size

$$L_{\text{MB},10} = 0,692\,839\,32 \sum_{i=1}^{441} \varphi_{\lambda}(\lambda_i) \bar{l}_{10}(\lambda_i) \Delta\lambda \quad (8.5a)$$

$$M_{\text{MB},10} = 0,349\,675\,67 \sum_{i=1}^{441} \varphi_{\lambda}(\lambda_i) \bar{m}_{10}(\lambda_i) \Delta\lambda \quad (8.5b)$$

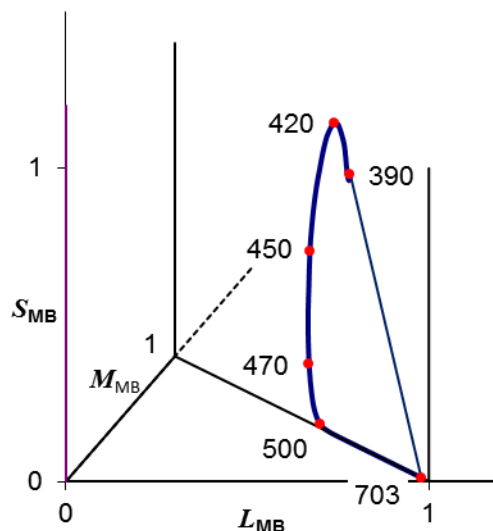
$$S_{\text{MB},10} = 0,055\,478\,58 \sum_{i=1}^{441} \varphi_{\lambda}(\lambda_i) \bar{s}_{10}(\lambda_i) \Delta\lambda, \quad (8.5c)$$

where $(\lambda_1, \lambda_2, \dots, \lambda_{441}) = (390 \text{ nm}, 391 \text{ nm}, \dots, 830 \text{ nm})$, $\Delta\lambda = 1 \text{ nm}$, $\phi_\lambda(\lambda)$ is the colour stimulus function and $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ are the 10° cone fundamentals as defined in terms of energy units in Clauses 2 and 4 of Part 1.

NOTE The scaling factors 0,692 839 32 and 0,349 675 67 equal the coefficients of the linear combination $V_{F,10}(\lambda) = 0,692\,839\,32 \bar{l}_{10}(\lambda) + 0,349\,675\,67 \bar{m}_{10}(\lambda)$ (see Eq. 7.6b). The factor 0,055 478 58 is needed for normalizing $\bar{s}_{10}(\lambda)/V_{F,10}(\lambda)$ to a maximum value of one.

8.1.2 The MacLeod–Boynton Constant LM-Luminance Plane

From the hypothesis that only L- and M-cone responses contribute to luminous quantity as measured by flicker photometry (LM-luminance), points in the MacLeod–Boynton LMS tristimulus space representing colour stimuli of equal LM-luminances will lie in a plane parallel to the S_{MB} -axis. Such a plane is a constant LM-luminance plane. Any constant LM-luminance plane intersects the L_{MB} - and M_{MB} -axes at numerically equal values (Figure 8.1).



NOTE 1 The values along the spectrum locus are in nanometre.

NOTE 2 The subscript of the axes labels, MB, indicates that the axes are scaled such that the coordinates possess the properties particular of MacLeod–Boynton tristimulus values (see 8.1.1).

Figure 8.1 – Three axes of the MacLeod–Boynton tristimulus space and the spectrum locus as given in a constant LM-luminance plane

8.1.3 The MacLeod–Boynton Chromaticity Diagram

A MacLeod–Boynton chromaticity diagram is a two-dimensional colorimetric representation that can be regarded as the projective counterpart of a constant LM-luminance plane in a MacLeod–Boynton tristimulus space.

The abscissa of the diagram represents the L- and the M-cone excitations in such a way that the one trades off for the other, thereby taking care of the weighted contribution of L- and M-cones to the LM-luminance. The S-cone excitation is represented along the ordinate axis, orthogonal to the L–M dimension. The scaling of the ordinate relative to the abscissa is arbitrary, but, for convenience, the ordinate is scaled such that, for real colour stimuli, the maximum ordinate value is equal to unity.

No matter where a point lies in this chart, a given horizontal distance implies the same amount of trade-off between L- and M-cone excitations, and a given vertical distance implies a fixed change in that of the S-cones. As a main feature, the representation thus provides a diagram in which the 'gravity rule' applies with weights proportional to LM-luminance (see

MacLeod & Boynton, 1979, p. 1183). Moreover, lines of equal S-cone excitation and lines representing fixed ratios of L- and M-cone excitation intersect at right angles.

The coordinates of the diagram are referred to below as *MacLeod–Boynton chromaticity coordinates*.

The general form of the MacLeod–Boynton chromaticity coordinates is:

$$l_{MB} = \frac{L_{MB}}{L_{MB} + M_{MB}} \quad (8.6a)$$

$$m_{MB} = \frac{M_{MB}}{L_{MB} + M_{MB}} \quad (8.6b)$$

$$s_{MB} = \frac{S_{MB}}{L_{MB} + M_{MB}}. \quad (8.6c)$$

A disadvantage of the diagram is that the white point does not fall into the centre of the diagram.

8.1.4 The MacLeod–Boynton Chromaticity Diagram for 2° Field Size

It is recommended to use as the MacLeod–Boynton chromaticity diagram for 2° field size the constant LM-luminance diagram determined by the MacLeod–Boynton chromaticity coordinates l_{MB} , m_{MB} and s_{MB} defined by the equations

$$l_{MB} = \frac{L_{MB,q}}{L_{MB,q} + M_{MB,q}} = \frac{L_{MB}}{L_{MB} + M_{MB}} \quad (8.7a)$$

$$m_{MB} = \frac{M_{MB,q}}{L_{MB,q} + M_{MB,q}} = \frac{M_{MB}}{L_{MB} + M_{MB}} \quad (8.7b)$$

$$s_{MB} = \frac{S_{MB,q}}{L_{MB,q} + M_{MB,q}} = \frac{S_{MB}}{L_{MB} + M_{MB}}, \quad (8.7c)$$

in which $L_{MB,q}$, $M_{MB,q}$ and $S_{MB,q}$ are the quantum-based MacLeod–Boynton tristimulus values as defined in Eqs. 8.2 a–c, and L_{MB} , M_{MB} and S_{MB} are the energy-based MacLeod–Boynton tristimulus values as defined in Eqs. 8.3 a–c.

Given the cone-fundamental-based spectral luminous efficiency function for 2° field size in terms of energy,

$$V_F(\lambda) = 0,689\,902\,72 \bar{l}(\lambda) + 0,348\,321\,89 \bar{m}(\lambda) \quad (\text{see Eq.7.4b}),$$

the spectral MacLeod–Boynton chromaticity coordinates $l_{MB}(\lambda)$, $m_{MB}(\lambda)$ and $s_{MB}(\lambda)$ are thus given in terms of the energy-based 2° cone fundamentals by the equations

$$l_{MB}(\lambda) = 0,689\,902\,72 \bar{l}(\lambda) / (0,689\,902\,72 \bar{l}(\lambda) + 0,348\,321\,89 \bar{m}(\lambda)) \quad (8.8a)$$

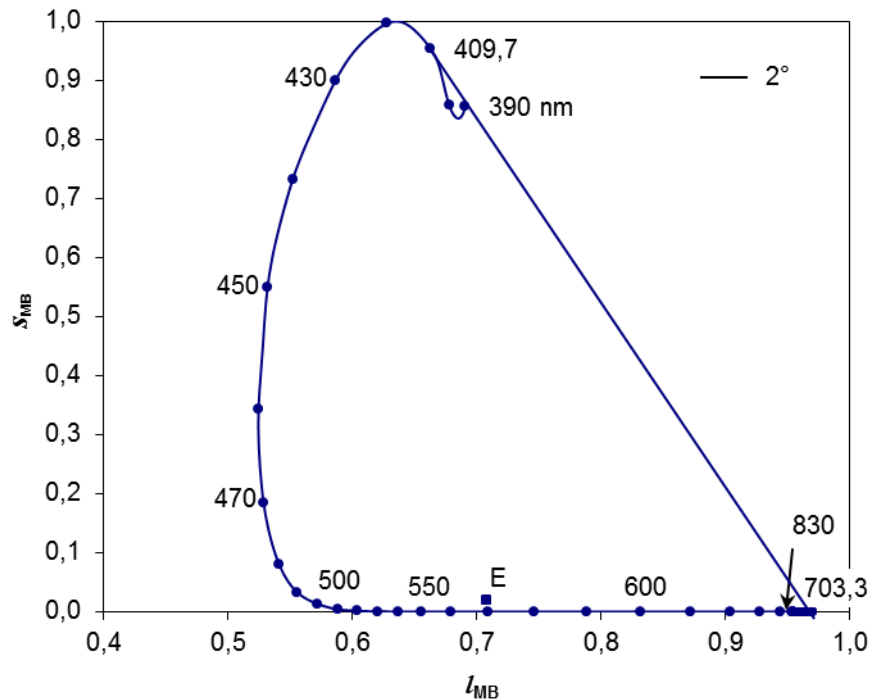
$$m_{MB}(\lambda) = 0,348\,321\,89 \bar{m}(\lambda) / (0,689\,902\,72 \bar{l}(\lambda) + 0,348\,321\,89 \bar{m}(\lambda)) \quad (8.8b)$$

$$s_{MB}(\lambda) = 0,037\,159\,71 \bar{s}(\lambda) / (0,689\,902\,72 \bar{l}(\lambda) + 0,348\,321\,89 \bar{m}(\lambda)). \quad (8.8c)$$

The spectral MacLeod–Boynton chromaticity coordinates for 2° field size resulting from Eqs. 8.8 a–c are given in wavelength steps of 5 nm in Table 10.5.

The MacLeod–Boynton chromaticity diagram for 2° field size is shown in Figure 8.2. In particular, Illuminant E (the equi-energetic spectrum) is represented at (0,707 823; 0,019 205).

The purple line is defined as the straight line tangent to the spectrum locus at short wavelengths and ending at the extremity of the spectrum locus at long wavelengths, in such a way that all real colour stimuli are represented inside the domain enclosed by the spectrum locus and the purple line. For the 2° field size, the wavelength parameter of the purple line's terminus at the long-wavelength extremity of the spectrum locus is 703,3 nm. At the other terminus, i.e. the point where the purple line is tangent to the spectrum locus in the short wavelength region, the wavelength parameter is 409,7 nm. The colour reversal at long wavelengths up to 830 nm, as shown in Figure 8.2, has been described by Brindley (1955), and the concavity below 410 nm results from the experimental colour matches.



NOTE The values along the spectrum locus are in nanometre.

Figure 8.2 – MacLeod–Boynton chromaticity diagram for 2° field size

8.1.5 The MacLeod–Boynton Chromaticity Diagram for 10° Field Size

It is recommended to use as the MacLeod–Boynton chromaticity diagram for 10° field size the constant LM-luminance diagram determined by the MacLeod–Boynton chromaticity coordinates $l_{MB,10}$, $m_{MB,10}$ and $s_{MB,10}$ defined by the equations

$$l_{MB,10} = \frac{L_{MB,q,10}}{L_{MB,q,10} + M_{MB,q,10}} = \frac{L_{MB,10}}{L_{MB,10} + M_{MB,10}} \quad (8.9a)$$

$$m_{MB,10} = \frac{M_{MB,q,10}}{L_{MB,q,10} + M_{MB,q,10}} = \frac{M_{MB,10}}{L_{MB,10} + M_{MB,10}} \quad (8.9b)$$

$$s_{MB,10} = \frac{S_{MB,q,10}}{L_{MB,q,10} + M_{MB,q,10}} = \frac{S_{MB,10}}{L_{MB,10} + M_{MB,10}}, \quad (8.9c)$$

in which $L_{MB,q,10}$, $M_{MB,q,10}$ and $S_{MB,q,10}$ are the quantum-based MacLeod–Boynton tristimulus values as defined in Eqs. 8.4 a–c, and $L_{MB,10}$, $M_{MB,10}$ and $S_{MB,10}$ are the energy-based MacLeod–Boynton tristimulus values as defined in Eqs. 8.5 a–c.

Given the cone-fundamental-based spectral luminous efficiency function for 10° field size in terms of energy,

$$V_{F,10}(\lambda) = 0,692\,839\,32 \bar{l}_{10}(\lambda) + 0,349\,675\,67 \bar{m}_{10}(\lambda) \quad (\text{see Eq. 7.6b}),$$

the spectral MacLeod–Boynton chromaticity coordinates $l_{MB,10}(\lambda)$, $m_{MB,10}(\lambda)$ and $s_{MB,10}(\lambda)$ are thus given in terms of the energy-based 10° cone fundamentals by the equations

$$l_{MB,10}(\lambda) = 0,692\,839\,32 \bar{l}_{10}(\lambda) / (0,692\,839\,32 \bar{l}_{10}(\lambda) + 0,349\,675\,67 \bar{m}_{10}(\lambda)) \quad (8.10a)$$

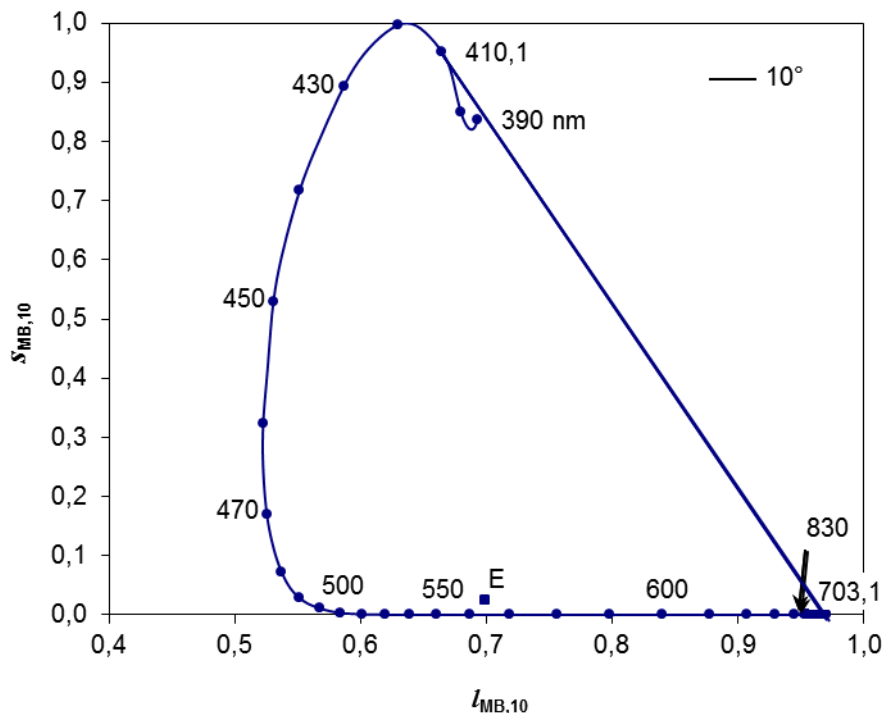
$$m_{MB,10}(\lambda) = 0,349\,675\,67 \bar{m}_{10}(\lambda) / (0,692\,839\,32 \bar{l}_{10}(\lambda) + 0,349\,675\,67 \bar{m}_{10}(\lambda)) \quad (8.10b)$$

$$s_{MB,10}(\lambda) = 0,055\,478\,58 \bar{s}_{10}(\lambda) / (0,692\,839\,32 \bar{l}_{10}(\lambda) + 0,349\,675\,67 \bar{m}_{10}(\lambda)). \quad (8.10c)$$

The spectral MacLeod–Boynton chromaticity coordinates for 10° field size resulting from Eqs. 8.10 a–c are given in wavelength steps of 5 nm in Table 10.6.

The MacLeod–Boynton chromaticity diagram for 10° field size is shown in Figure 8.3. In particular, Illuminant E (the equi-energetic spectrum) is represented at (0,699 237; 0,025 841).

For the 10° field size, the wavelength parameter of the purple line's terminus at the long-wavelength extremity of the spectrum locus is 703,1 nm. At the other terminus, i.e. the point where the purple line is tangent to the spectrum locus in the short wavelength region, the wavelength parameter is 410,1 nm. The colour reversal at long wavelengths up to 830 nm, as shown in Figure 8.3, has been described by Brindley (1955) and the concavity below 410 nm results from the experimental colour matches.



NOTE The values along the spectrum locus are in nanometre.

Figure 8.3 – MacLeod–Boynton chromaticity diagram for 10° field size