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CONE FUNDAMENTALS: PAST, PRESENT AND FUTURE

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Abstract

Since the establishment of the 1931 standard colorimetric observer, considerable knowledge on colour vision mechanisms has been acquired. Establishing colorimetry directly on Physiology is a new approach to colour specification.

CIE technical committee 1-36 (TC 1-36) was established for proposing chromaticity diagrams based on the best set of colour-matching functions and cone fundamentals available to date. *Cone fundamental* is the name given to the relative spectral sensitivity of long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones. As explicated by Judd (1966), the cone fundamentals represent the spectral absorptances of the retinal photopigments included in cones multiplied by the spectral transmittances of the ocular media through which light passes to reach the retina. The CIE 2006 (Stockman and Sharpe, 2000; CIE, 2006) cone fundamentals are based on Stiles and Burch (1959) experimental colour matches and are validated by Physiology. A physiologically designed chromaticity diagram named the *MacLeod-Boynton chromaticity diagram* (MacLeod and Boynton, 1979) is proposed as well as a *cone-fundamental-based* (x_F, y_F) *chromaticity diagram*. All data are now fixed. Tables are available in the CIE publications (CIE, 2006; CIE in press).

1 Deriving the cone fundamentals

The primary goal was to propose cone fundamentals that are securely grounded on colour-matching experiments with real observers and that would comply with Physiology.

A comprehensive set of colour-matching data has been collected by Stiles and Burch (1959) from 49 colour normal observers. The colour matches were obtained at clearly photopic luminance levels, on 10° field, using spectral red, green and blue (RGB) primaries expressed in energy units. The Stiles-Burch colour matching data are recognised as the most secure experimental basis for founding cone fundamentals.

Independently, a physiological approach has allowed Stockman and Sharpe (2000) to derive estimates of the cone spectral sensitivities for 2° viewing angle. Given the fact that dichromats lack one family of cone pigment, and that S-cone responses can be cancelled by appropriate chromatic adaptation, these authors were able, using heterochromatic flicker photometry, to isolate and directly measure the L- and M-cone spectral sensitivities. In parallel, the gene sequence associated with every L-cone photopigment was analysed in order to associate each spectral sensitivity with a known genotype. Such piece of information has enabled taking account of the incidence of two variants of the L-cones in the normal population. The S-cone spectral sensitivities has been isolated in blue-cone monochromats and in chromatically adapted colour normal observers.

Thus, at this stage, an intermediate step of calculation was introduced by Stockman and Sharpe (2000). In 1955, a small (interim) set of colour matches had been collected by Stiles (1955) on 2° field which could be compared with the well-characterized cone spectral sensitivities for 2° viewing angle. Provided the individual dichromatic data was adjusted in macular pigment and lens density, an appropriate linear fit between the data could be found, thus validating the spectral sensitivity for every cone family.

To reinforce the colorimetric validity of the cone fundamentals, a linear transformation between the 10° cone spectral sensitivities and the 10° Stiles-Burch colour-matching functions had to be fixed.

So far, differences between colour assessments on 10° field and colour assessments on 2° field originate from differences in macular pigmentation and in photopigment optical density. Given some adjustment in lens optical density, in macular pigment optical density and in photopigment optical density, the best fit was found between the previously derived cone spectral sensitivities and the 10° Stiles and Burch observers' colour matching functions.

Ultimately, CIE TC 1-36 proposes cone fundamentals for 10° viewing angle and the corresponding set of colour-matching functions in the experimental RGB colour space (Figs. 1, 2).

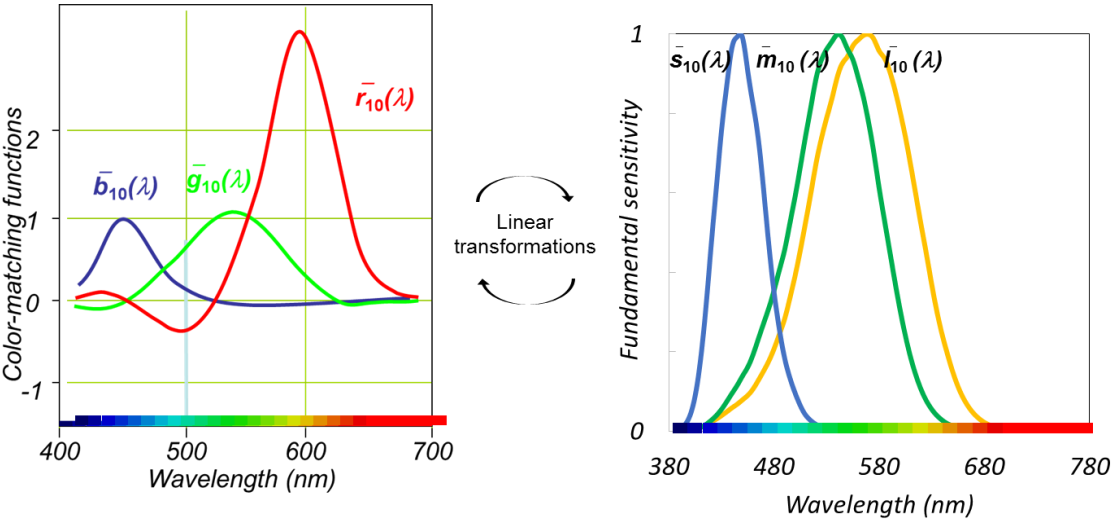


Figure 1 – 10° Stiles and Burch observers' colour matching functions and 10° cone fundamentals.

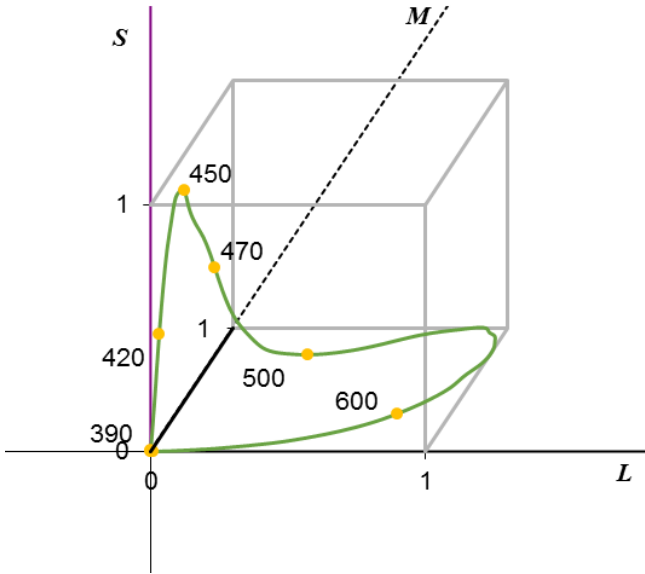


Figure 2 – Representation of the monochromatic stimuli in the cone fundamental space. The cone-fundamentals are normalised to unit-peak values. The selected wavelengths are given in nm.

2 The CIE 2006 cone fundamental framework

Not only the primary goal of establishing 10° cone fundamentals has been satisfactorily achieved, further their reconstruction has allowed CIE TC 1-36 to propose a cone fundamental model incorporating ocular media, macular pigment and photopigment density parameters.

Here the approach relies on the fact that the colour match is initiated by the absorption of photons in the cones while it is measured in the corneal plane. By correcting the 10° cone fundamentals for the absorption of the ocular media and the macular pigment, and taking into account the optical densities of the cone visual pigments, the spectral absorbance function of the dilute cone pigment can be modelled. Essentially, cone fundamentals for 2° viewing field are reconstructed, by incorporating into the fundamental model the 2° values of the parameters (Fig. 3).

Because colour vision varies with the diameter of the viewing field and with the age of the observer, the fundamental model allows the user to reconstruct cone fundamentals and adjust colour specification over a continuous range of field diameter from 1 to 10° and as a function of age.

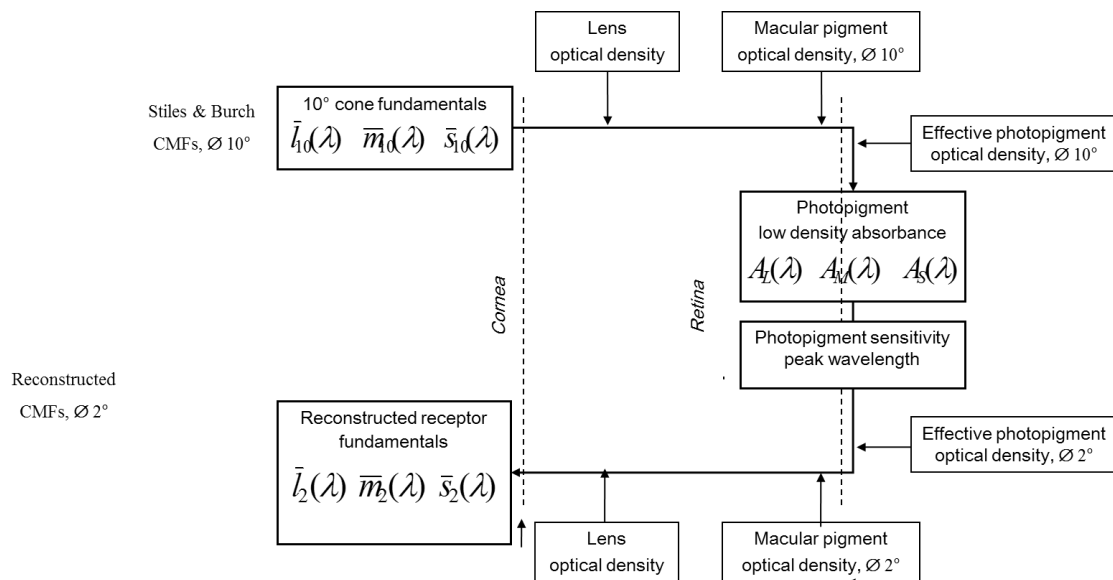


Figure 3 – The CIE 2006 cone fundamental framework for reconstructing cone fundamentals, for any viewing field.

3 From colorimetry to photometry

CIE TC 1-36 progress could have stopped with the definition of cone fundamentals. Indeed, it is the content of CIE publication 170-1:2006. However, further progresses have been accomplished.

On the one hand, relying on modern physiological interpretation of luminance that arises from the sum of L- and M- cone responses, a new *cone-fundamental-based spectral luminous efficiency function* $V_F(\lambda)$ has been defined in terms of the linear combination of the L- and M-cone fundamentals.

In fact, the spectral luminous efficiency function $V(\lambda)$ of the 1924 standard photometric observer has been known to be markedly low at short wavelengths which has urged the CIE to propose an improved spectral luminous efficiency function $V_M(\lambda)$ (CIE, 1990). Later, new heterochromatic flicker photometry measurements in colour normal observers, associated with the identification of the L-cone pigment genotype, have allowed Sharpe and colleagues (1999; 2005) to verify that a linear transformation of the L-cone and the M-cone fundamentals could be adjusted to $V_M(\lambda)$ provided suitable weights are applied (Fig. 4).

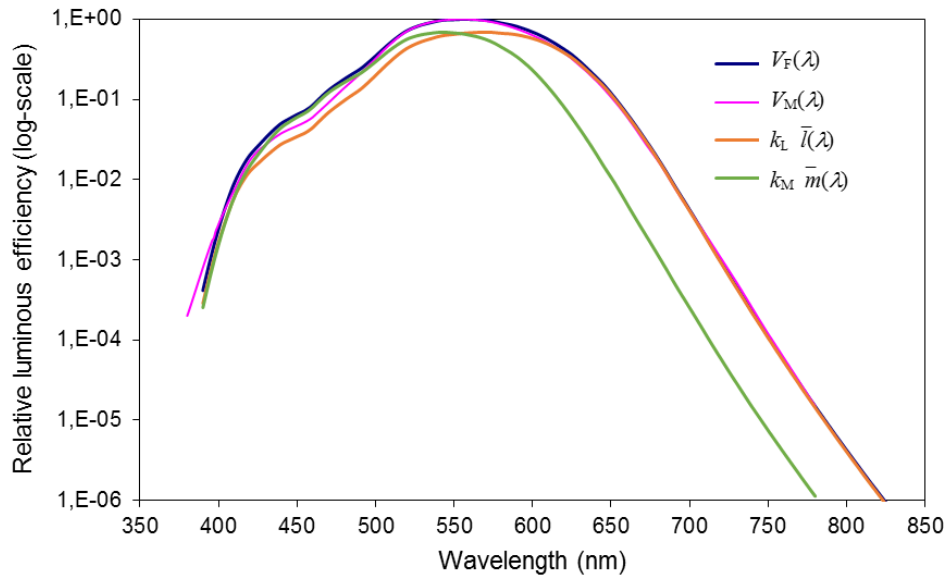


Figure 4 –The 2° cone-fundamental-based spectral luminous efficiency function $V_F(\lambda)$ defined as the linear combination of the cone fundamentals $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$, compared with the CIE 1988 modified spectral luminous efficiency function $V_M(\lambda)$ (log scale). The coefficients k_L and k_M (in the legend) are the coefficients of, respectively, the L- and the M-cone fundamentals in the linear combination defining the cone-fundamental-based relative spectral luminous efficiency function $V_F(\lambda)$.

4 The MacLeod-Boynton chromaticity diagram

Once photometry is properly associated with colorimetry, it is possible to propose a chromaticity diagram that lies in a *constant LM-luminance plane*. In the LMS cone fundamental space, the plane of the chromaticity diagram is parallel to the S-axis because the S-cone response does not contribute to luminance (MacLeod & Boynton, 1979). The plane is oriented so that the total contribution of the L-cone and the M-cone responses to luminance response remains constant within the surface.

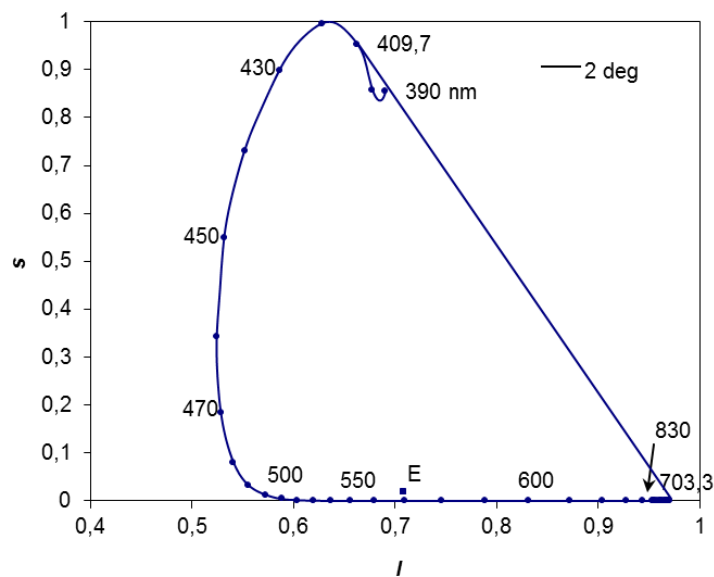


Figure 5 – The MacLeod-Boynton chromaticity diagram, for the 2° observer.

In the so-called *MacLeod-Boynton chromaticity diagram*, the abscissa l shows the fraction of luminance attributable to L-cones; the ordinate s shows the S-cone response relative to luminance, scaled for convenience to fit within the $[0,1]$ range (Figs. 5, 6).

Hence, the *MacLeod-Boynton tristimulus values* L , M and S can be calculated by integrating the product of the stimulus function and the cone fundamentals, applying appropriate weights to the cone fundamentals, with respect to LM-luminance and to s scaling in the MacLeod-Boynton chromaticity diagram.

In the LMS tristimulus space, the alychne plane that represents the locus of colour stimuli of zero LM-luminance includes the S-cone fundamental axis.

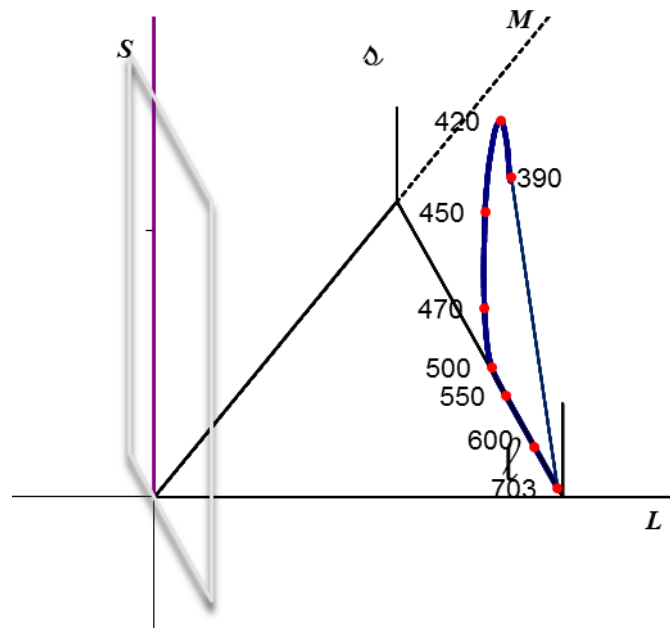


Figure 6 – Representation of the constant LM-luminance plane and of the MacLeod-Boynton chromaticity diagram in the cone fundamental space. The axes are appropriately re-scaled. The selected wavelengths are given in nm. A blurred contour is used to sketch the alychne plane.

5 Cone-fundamental-based chromaticity diagram and cone-fundamental-based tristimulus values

On the other hand, in order to comply with industrial practice and the current CIE practice, the final goal consists of offering colorimetric tools in the form of a traditional XYZ specification including a xy -like chromaticity diagram.

The *cone-fundamental-based spectral tristimulus values* $\bar{x}_F(\lambda)$, $\bar{y}_F(\lambda)$ and $\bar{z}_F(\lambda)$ are obtained from a linear transformation of the cone fundamentals. The principles having guided the establishment of the current CIE standard colorimetric system were followed (Wold & Valberg, 1999) to define the new (x_F, y_F) *cone-fundamental-based chromaticity diagram*

- All tristimulus values of real colours are non-negative
- The Y tristimulus value, alone, yields the luminance. Thus, X and Z primaries are located in the alychne plane.
- The tristimulus values of the equi-energy spectrum E are equal.

It was added that:

- The values of $\bar{z}_F(\lambda)$ are proportional to the values of the S-cone fundamental.
- The minimum value of x_F is the same as in the (x, y) chromaticity diagram.

- To be close to current practice in colorimetry, the overall difference between the *cone-fundamental-based spectral chromaticity coordinates* and the corresponding spectral chromaticity coordinates in the (x, y) chromaticity diagram of the CIE standard colorimetric system is minimized.

Finally, 2° and 10° fundamental colorimetric observers are available. The *cone-fundamental-based spectral tristimulus values* show some difference with the CIE 1964 standard colorimetric observer, and marked differences with the CIE 1931 standard colorimetric observer (Fig. 7).

All numerical data are available in the CIE publications and at CVRL website, with the number of significant digits that allows high precision colorimetric calculations.

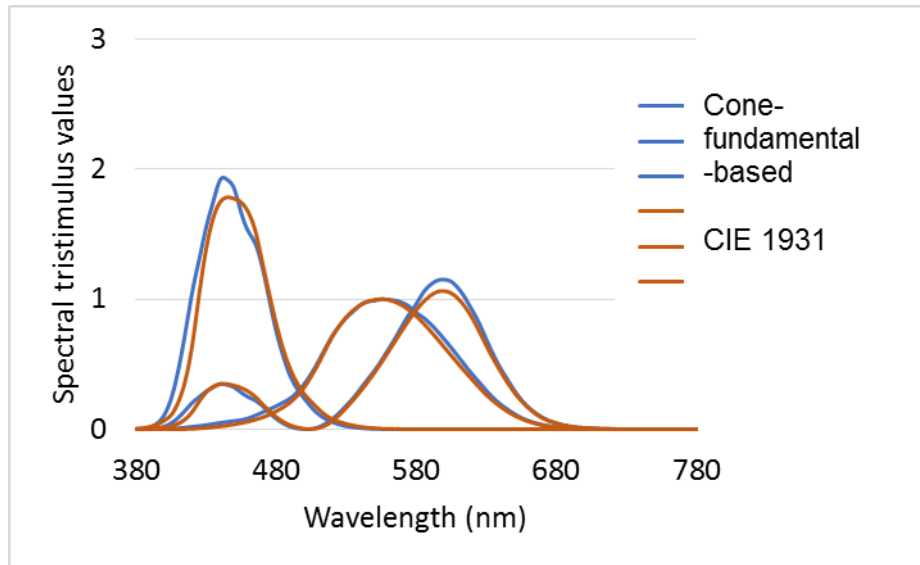


Figure 7 – Comparison of the cone-fundamental-based spectral tristimulus values $\bar{x}_F(\lambda)$, $\bar{y}_F(\lambda)$ and $\bar{z}_F(\lambda)$ with the CIE 1931 standard colorimetric observer.

6 The future

In the future, specifying colour in the LMS space will offer novel opportunities to applications through CIE divisions.

We propose examining questions and applications to be addressed by CIE divisions which could benefit from the cone fundamental framework: the variability of individual colour responses, building improved colour appearance models, the photometry of punctiform light sources, the colorimetry of solid-state light sources, interpreting colour differences at various viewing angles, the measurement of colour temperature, discussing colour rendering and colour rendition, measuring road and vehicle lighting, assessing the melanopsin contribution to visual responses and non-imaging visual functions, colour specification in enlarged gamut image display...

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