Invited Paper

Fundamental chromaticity diagram with physiological axes

Walraven P[1] for CIE TC 1-36

1. Introduction

In 1931 CIE widened the scope of the photometric standard observer with the addition of colorimetric properties based on experimental studies by Wright and by Guild. 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 1924 V_λ function.

25 years 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 in 1955 did not consider the discrepancies between the CIE 1931 Standard Observer and these 2^o pilot data large enough to warrant a change in the standard data for practical colorimetry.

However, vision researchers felt a need for an improved colorimetric observer. To that purpose CIE established, in 1991, a Committee on the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1^o to 10^o.

This paper describes the underlying ideas, the methods, and the results, in terms of colour matching functions, receptor action spectra, absorption spectra for the eye media etc.

2. Procedure

The work of the committee proceeded as follows:

a. Agreement was sought on the best experimental database of colorimetric properties.

b. Agreement was sought on the most reliable linear transformation of the colour matching functions , $\overline{R}_\lambda$, $\overline{G}_\lambda$ and $\overline{B}_\lambda$ to cone system action spectra L_λ, M_λ and S_λ. König's interpretation of dichromacy (König and Dieterici, 1886), as due to the complete loss of one cone system, was taken as a starting point.

---

[1] Em TNO Human Factors Research Institute, Soesterberg, The Netherlands

c. Agreement was sought on the modifying effects of the intervening eye media on the spectra, so that a proposal could be made for the transformation from external (incident at the cornea) to internal (incident at the retina) action spectra.

d. Agreement was sought on a possible link with the V_M luminosity function. A reasonable fit could be obtained on the basis of the presumption that only the L- and M-systems contributed to luminance.

e. 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 accepted null luminosity from the S-system, a Luther-MacLeod-Boynton diagram was constructed in terms of S/(L+M) versus L/(L+M).

f. Finally, all data were tabulated, after interpolation and smoothing where appropriate, with 1 nm spacing, and where necessary, in terms of both energy and quanta.

3. Choices made

The fundamental spectral sensitivity $L(\lambda)$, $M(\lambda)$ and $S(\lambda)$ are derived by transformation of the colour matching functions at corneal level $R(\lambda)$, $G(\lambda)$ and $B(\lambda)$ by

$$L(\lambda) = a_{11}\,R(\lambda) + a_{12}\,G(\lambda) + a_{13}\,B(\lambda)$$
$$M(\lambda) = a_{21}\,R(\lambda) + a_{22}\,G(\lambda) + a_{23}\,B(\lambda)$$
$$S(\lambda) = a_{31}\,R(\lambda) + a_{32}\,G(\lambda) + a_{33}\,B(\lambda)$$

for 2^o from the Stiles 2^o data (Stiles, 1955), except for the definition of the $S(\lambda)$, and for 10^o from the Stiles-Burch 10^o data (Stiles and Burch, 1959).

The derivation of the coefficients for both field sizes is based on the principles laid down by Stockman et al (1993), and further refined by Stockman et al (1999a) and Stockman et al (1999b).

By appropriate definition of

* the absorption of the macular pigment as a function of visual field,
* the absorption by the lens and other ocular media,
* the density of the visual pigments as a function of visual field,

the absorptance curves of the visual pigments were derived.

These spectral absorptance curves are the same, whether they are derived from the 2^o data, or from the 10^o data. The $S(\lambda)$ of 2^o is derived in this way from the Stiles-Burch 10^o data in view of the higher accuracy of the colour matching, in particular at the long wavelength side of the fundamental.

This gives the possibility do derive, for any value of the visual field between 1^o and 10^o, the colour matching functions by taking the absorptance curves of the visual pigments, and apply the appropriate values of the absorption of the macular pigment, the absorption of the ocular media, and the density of the visual pigments at the desired field diameter.

4. Implications for the $V(\lambda)$ function

As it was presumed that only the L- and M-systems contribute to luminance, $V(\lambda)$ at an arbitrary field diameter is assumed to be equal to a weighted sum of $L(\lambda)$ and $M(\lambda)$:

$$V(\lambda) = b\,L(\lambda) + M(\lambda).$$

By choosing b = 1.7 reasonable approximations of $V_M(\lambda)$ and of $\bar{y}_{10}(\lambda)$ are obtained.

The use of the term reasonable approximation indicates that an exact coincidence of this weighted sum with the two standard CIE functions is not obtained.

Literature

Stiles, WS (1955). Interim report to the Commission Internationale d'Eclairage, Zurich 1955, On the National Physical Laboratory's Investigation of colour matching (1955), with an appendix by W.S. Stiles and J.M. Burch, *Optica Acta* **2**, 168-181.

Stiles, WS - Burch JM (1959). NPL colour matching investigation: final report (1958), *Optica Acta*, **6**, 1.

Stockman, A - MacLeod, DIA - Vivien, JA (1993). Isolation of the middle- and long-wavelength-sensitive cones in normal trichromats, *J Opt Soc Am* **A, 10**, 2471-2490.

Stockman A, Sharpe LT, Fach CC. The spectral sensitivity of the human short-wavelength cones, *Vision Research*, 1999a, *in press.*

Stockman A, Sharpe LT. New estimates of the spectral sensitivities of the middle- and long-wavelength sensitive cones, *Vision Research*, 1999b, *in press.*

König, A - Dieterici, C (1886). Die Grundempfindungen und ihre Intensitäts-Verteilung im Spectrum, *J Sitz Akad Wiss* (Berlin), 805-829.