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 CIE 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. 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 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.

1) 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 had been collected by Stiles and Burch (1959) from 49 colour normal observers. They result from colour matches obtained at clearly photopic luminance levels, on 10 degree field, using spectral red, green and blue (RGB) primaries expressed in energy units. They are recognised as the most secure experimental basis for founding cone fundamentals.

Independently, a physiological approach using heterochromatic flicker photometry and appropriate chromatic adaptation of dichromatic and normal observers has allowed Stockman and Sharpe (2000) to tailor cone spectral sensitivities for 2 degree viewing angle.

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 degree field which could be compared with the well-characterized cone spectral sensitivities. Provided the individual dichromatic data is adjusted in macular pigment and lens density, an appropriate linear fit between the data could be found, for every cone family.

2) To reinforce the colorimetric validity of the cone fundamentals, a linear transformation between the 10 degree cone spectral sensitivities and the 10 degree Stiles-Burch colour-matching functions has been fixed.

Nonetheless, differences between colour assessments on 10 degree field and colour assessments on 2 degree 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 10 degree Stiles and Burch observers' colour matching functions and the previously derived cone spectral sensitivities.

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

3) Not only the primary goal of establishing 10 degree cone fundamentals has been satisfactorily achieved, further the TC proposes a cone fundamental model incorporating the ocular media, macular pigment and photopigment density as 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 degree 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 absorbance function of the dilute cone pigment can be modelled.

4) 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 from the absorbance function of the dilute cone pigment and adjust colour specification over a continuous range of field diameter from 1 to 10 degree and as a function of age.

Essentially, cone fundamentals for 2 degree viewing angle are reconstructed, by incorporating into the fundamental model the 2 degree values of the parameters.

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

On the one hand, relying on modern physiological interpretation of luminance which arises from the sum of L- and M- cone responses, a new luminous efficiency function has been defined in terms of the linear combination of the L- and M-cone fundamentals.

Once photometry is properly associated with colorimetry, it is possible to propose a chromaticity diagram that lies in a constant luminance plane. In the LMS space, the plane of the chromaticity diagram is parallel to the S-axis because the S-cone responses do 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.

Hence, LMS tristimulus values 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 luminance.

6) On the other hand, to bridge the gap between the fundamental framework and the current CIE practice, a (x, y)-like chromaticity diagram and a *XYZ* representation of the cone fundamentals were developed.

The *XYZ* representation of the cone fundamentals is 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)-like chromaticity diagram

7) The final XYZ representations of the cone fundamentals shows some difference with the CIE 1964 standard colorimetric observer, and marked differences with the CIE 1931 standard colorimetric observer.

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

We propose (urge) examining questions and applications that could 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, 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, the enlarged gamut image display…