

Physiologically-based colour matching functions

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All colour matches depend ultimately on the transduction properties of the light-sensitive photoreceptors in the eye, and in particular on their spectral sensitivities. In most observers with normal color vision, there are three types of cone photoreceptors, which are referred to as long-, middle- and short-wavelength-sensitive (L, M and S), according to the part of the visible spectrum in which they are most sensitive. A knowledge of their spectral sensitivities is central to the understanding and modeling of visual function, and to the specification of colour.

Photoreceptors are essentially sophisticated photon counters, the outputs of which vary univariantly according to the number of photons that they absorb. With its three cone types, photopic human vision is a *trichromatic* or trivariant system, a behavioral consequence of which is that colours can be defined by just three variables: the intensities of three independent primary lights required to match them, which are known as the $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$ color matching functions or CMFs. This specification does not require any knowledge of the underlying cone spectral sensitivities, and was the approach adopted by the CIE in 1931 and 1964 to define colour matches for small (2-deg) and large (10-deg) viewing conditions, respectively.

CMFs can be linearly transformed to any other set of real primary lights, and to *imaginary* primary lights, such as the all-positive **X**, **Y** and **Z** primaries favored by the CIE to define international lighting standards or the physiologically-relevant **L**, **M** and **S** cone *fundamental* primaries. In particular, the three *fundamental* primaries (or “Grundempfindungen” - fundamental sensations) are the three *imaginary* primary lights that would uniquely stimulate each of the three cones to yield $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ CMFs, or the L-, M- and S-cone spectral sensitivity functions.

Since the establishment of trichromatic colour theory, a central goal of colour science has been the accurate determination of the three cone spectral sensitivities, $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$. Most estimates depend on measurements made in normals and in dichromats: protanopes, deuteranopes and tritanopes, who lack the L-, M- and S-cones, respectively; and the assumption—known as the “loss”, “reduction” or “König” hypothesis—that their remaining cone classes are normal (1, 2). Although cone fundamentals can be estimated from dichromatic and trichromatic colour matches, the most straightforward method is to measure the cone spectral sensitivities directly in normals and dichromats using special procedures to isolate the appropriate cone response.

The cone fundamentals of Stockman and Sharpe (3), which are to be proposed by CIE Technical Committee 1-36 as new physiologically-relevant cone fundamentals, are based on a series of such measurements (3-6). The $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$ CMFs were derived from measurements made in red-green or X-linked dichromats of known genotype [including knowledge of their L-cone polymorphism, L(ser¹⁸⁰) or L(ala¹⁸⁰)]: M-cone sensitivities in 9 protanopes, and L-cone sensitivities in 20 deuteranopes. The $\bar{s}(\lambda)$ CMF was derived in two ways: (i) from spectral sensitivity measurements made in three blue-cone monochromats, who lack functioning M- and L-cones, and in normal trichromats under intense long-wavelength adaptation; and (ii) from a direct analysis of the 10-deg CMF data of Stiles & Burch (7).

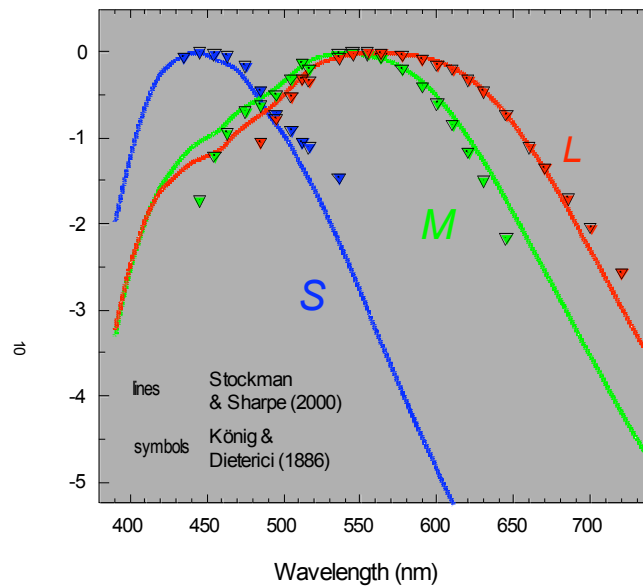


Figure 1. 120 years on: S-, M- and L-cone fundamentals of Stockman & Sharpe (3) (coloured lines) compared with the historical estimates of König & Dieterici (2) (inverted triangles).

Although the cone spectral sensitivities could be defined simply as the direct sensitivity measurements, it is customary to define them in terms of linear combinations of a set of CMFs, which are more precise. All that is required is to find the linear combinations of $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$ that best fits each cone spectral sensitivity, allowing for differences in prereceptor filtering and photopigment optical density. The Stockman & Sharpe (3) cone fundamentals are defined for 2- and 10-deg fields in terms of the “large-field” 10-deg CMFs of Stiles & Burch (7), which can be corrected for 2-deg viewing conditions. Measured in 49 subjects from approximately 390 to 730 nm (and in 9 subjects from 730 to 830 nm), these data are probably the most secure set of existing color matching data, and are available as individual as well as mean data. The cone fundamentals derived for 2-deg viewing conditions are shown in Fig. 1. More details about their derivation can be found in the original papers (3, 5).

We have, in addition, generated a consistent new estimate of $\bar{y}(\lambda)$, which is defined as a linear combination of $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$, based on new luminous efficiency measurements made in 40 observers of known genotype (8).

All CMFs, properly measured, are “physiologically-based”. The problem with the CIE 1931 CMFs (and with the CIE 1924 $V(\lambda)$ luminous efficiency function used to construct them) is that they are seriously flawed—particularly at short-wavelengths. Seventy-five years on, it is time not only to celebrate them, but also to replace them.

References

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