# Color Matching Functions Optimized for Display Color Consistency

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**Abstract**

The development of novel display technologies with varieties of emission spectra has increased the potential for an observer to perceive mismatched appearance of a single scene on multiple calibrated displays. Recent observations on displays have shown substantial gaps between perceived colors and measurements with the same CIE 1931 tristimulus values after calibration, suggesting that the CIE 1931 Color Matching Functions (CMFs) need to be revisited. This is even more evident on modern wide-color-gamut displays, where narrow-band spectral emissions exacerbate metameric failure. The development of a physiological model for human color vision in the latter part of the 20th century provides the means to optimize CMFs to achieve display color consistency, based on user color-matching data and the CIE 2006 physiological model. This paves the way for a standardization effort at CIE to propose a framework that leads to CMFs that improve display color consistency across display technologies for an average observer.

Problem Statement and Impact on Modern Display Technology: The CIE 1931-based colorimetric system has been widely used in color reproduction on displays. A persistent color appearance mismatch occurs when displays of different technologies are viewed under the same conditions and all calibrated with identical CIE 1931 tristimulus values.[1] Observers perceive distinct color differences between displays, such as Organic Light-Emitting Diode (OLED) displays typically appearing more yellowish-green than Liquid Crystal Displays (LCD) even after accurate display calibration. Color-matching studies on displays of different panel technologies have shown that Color differences between the two matched fields can be substantial when both are calibrated using the CIE 1931 CMFs.[2] This mismatch is severely exacerbated by modern wide color gamut displays featuring increasingly narrow primary spectra that create more metameric failures.[3] This suggests that a revision of CMFs is required to achieve a more consistent display color appearance after calibration.

## The Evolution of Color Matching Functions and Physiological Model

The CIE 1931 Color Matching Functions (CMFs) rely heavily on the outdated 1924 luminosity function, which is notoriously insensitive at short wavelengths, producing systematic color shifts in perception. The CIE 1931 Color Matching Functions (CMFs) were derived from color-matching experiments involving only 17 observers, before modern knowledge of human color-vision modeling was available. Since then, we have made significant progress in understanding the physiological parameters that determine human color vision and in data collection practices.

Stiles and Burch directly measured 2° CMFs on 10 observers in 1955 and 10° CMFs on 49 observers in 1959, as instrumentation allowed CMFs to be measured together with absolute radiometry.[4] This later became the basis of the Stockman and Sharpe cone fundamentals[5] and the standard 10° CMFs recommended by CIE in 1964 for field size larger than 4°.[6] Based almost entirely on Stockman and Sharpe's work and on data from 10° Stiles-Burch observers, in 2006, CIE published a new physiological observer model and a framework for calculating average cone fundamentals for field sizes between 1° and 10° and observer ages between 20 and 80 years.[7] The CIE 2006 model enables the prediction of L-, M-, and S-cone fundamentals given physiological factors including macular and lens optical densities, photopigment optical densities, or shifts in cone photopigment peak spectral sensitivities. These factors in human color perception modeling enable the modeling of individual differences in color perception.

In more recent work, Stockman and Rider developed formulae to calculate corneal LMS spectral sensitivities based on LMS cone absorptions and lens and macula pigment optical-density spectra defined as continuous functions of wavelength from 360 to 850nm. These functions enable cone fundamentals with various peak wavelengths of cone spectral sensitivities and different macular, lens, and photopigment optical densities to be easily generated.[8] There is ongoing effort to test and refine the standard cone spectral sensitivities, CMFs, and individual differences by CIE TC 1-104: "Verification of the physiologically relevant CIE 2006 LMS cone fundamental CMFs and their linear transformation to the 2015 XYZ CMFs."

## Physiologically-Driven CMFs and Display Applications

The display industry has undertaken efforts to correct for the mismatch in display color appearances due to the limitations of the CIE 1931 standard. For example, in 2012, Sony introduced a global calibration offset based on Judd-Vos modified CMFs in the TRIMASTER EL professional RGB OLED monitors.[9] This calibration approach was designed to mitigate the greenish appearance that occurs in narrow-spectrum OLED panels when calibrated to the CIE 1931 standard, to match industry-standard CRT reference monitors.

In 2020, Apple implemented a slight variation of the D65 CIE 1931 standard chromaticities in the Pro Display XDR monitor to achieve optimal visual matching with the perceptually perceived D65 white point.[10] More recently, Apple announced Apple CMF 2026, taking into account the physiological characteristics of human vision by optimizing the physiological parameters to best fit large-scale color matching data on different display technologies and across observers with various demographics. Apple intends this redefinition of CMF to establish a new foundation for measuring and calibrating Apple displays, significantly improving visual consistency across devices.[11]

## Standardization at CIE

Divisions 8 (Image Technologies) and 1 (Vision and Color) of The International Commission on Illumination (CIE) established a new joint technical committee (JTC), the **CIE JTC22,** in March 2026, gathering experts in human color vision from academia and industry from around the globe. This JTC provides a description of fundamental work on systematic derivation of physiologically driven color matching functions optimized to improve perceived color consistency across observers and electronic display technologies:

- To standardize a set of new color matching functions for self-emissive display devices that minimize color inconsistency caused by imperfections in the CIE 1931 standard observer.
- To propose an optimization framework of physiologically driven color matching functions to achieve color consistency amongst electronic displays of different technologies.
- To provide a set of optimized parameters associated with physiological templates and components of the human eye.

The goal of CIE JTC 22 is to define a foundational framework that paves the way for updated standards, providing alternatives for outdated models with more accurate, physiologically grounded CMFs tailored for modern wide-gamut displays. The optimized CMFs are intended to reduce average color differences, effectively achieving consistent color appearance across diverse display technologies.


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