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Light quality — White light parameters

Application Note

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Abstract

White light is not the same as white light. When different light sources are used, color differences may become visible. To understand why this can happen, it is necessary to understand how people perceive color and light. Nevertheless, it is possible to reduce the color shifts by choosing suitable white LEDs combined with an appropriate system setup. This application note provides basic information on optical quantities, color spaces and CIE chromaticity diagrams. Furthermore, it describes how color consistency for white light applications can be achieved.

Further information:
Please also refer to the application note Light quality Part II: “Light quality — Color metrics.”

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A. Optical quantities

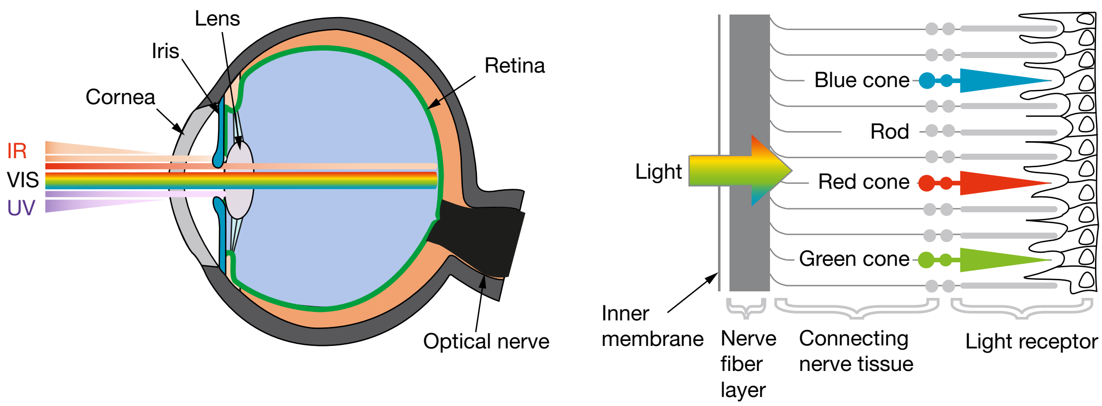
Visible light is part of the electromagnetic spectrum, comprising all electromagnetic radiation within the wavelength range of 380 — 780 nm. The wavelength of this radiation defines the color perceived by the human eye. Certain colors, such as pink or purple, are absent from this part of the electromagnetic spectrum and can only be conceived via a mix of multiple wavelengths. As such, monochromatic colors with a single wavelength are known as spectral colors.

A general knowledge of how the eye works is required to understand the idea of colorimetry. Light is focused onto the retina by the lens (see Figure 1). There are two types of photoreceptor cells on the retina which contribute to vision:

- The rods: Rods sense very low light levels and also contribute to peripheral vision.
- The cones: Cones are concentrated in the center of the retina; they function as color detectors and come in three types (short, medium and long). Each

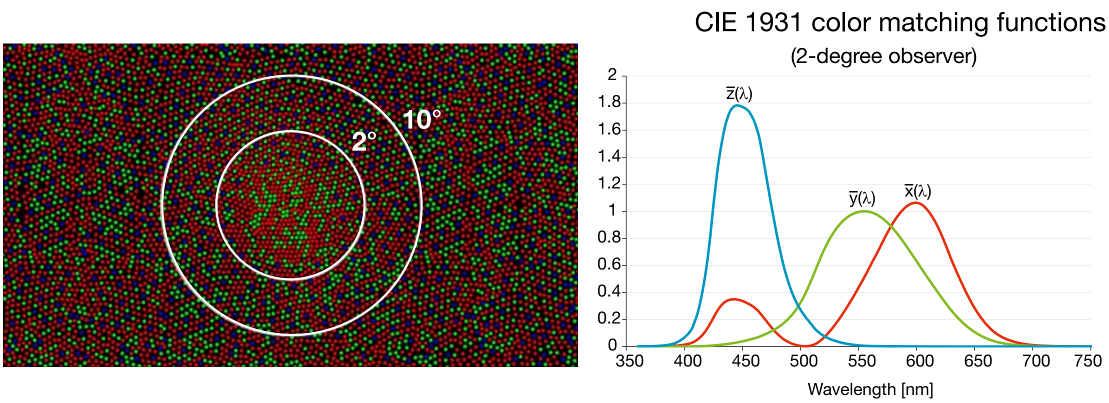
type senses a different wavelength range, and can roughly be thought of as red, green and blue detectors. The resulting perceived color is the combination of the stimuli that the brain receives from these three cone cells. A cone's level of reaction to a color stimulus is found by integrating the cone spectral response with the emission spectrum of the incoming light.

Figure 1: Schematic of a human eye and the photoreceptor cells



Colorimetry is the science that describes the color perception of the human eye in terms of numbers. Starting with the spectral power distribution of the light, scaled to the response of the human eye, color space coordinates are calculated. Human response to color has been characterized as Color Matching Functions based on experiments by the CIE in 1931 with a 2° field of view. This represents the average human eye's chromatic response within a 2° arc inside the fovea (see Figure 2).

Figure 2: Cone distribution on the retina and color matching functions of the CIE 1931 2° standard observer



The following section provides a brief introduction to the basic terms and definitions in photometry and colorimetry. It is important to distinguish between radiometric and photometric quantities which describe the physical radiation properties and its effects on the human eye.

Radiometric quantities

Radiometry is the measurement of the power of optical radiation for a specific direction of propagation. This measurement covers the entire radiometric spectrum, which extends far beyond the visible light spectrum (including UV and infrared). Therefore, radiometric quantities are independent of human eye sensitivity to brightness and color.

Definitions from the International Electrotechnical Commission can be found at: http://www.electropedia.org [1]

Radiant power or radiant flux. Radiant power, Φ_e is the sum of power (dQ_e) emitted by a light source per unit of time, measured in Watt (W).

$$\Phi_e = \frac{dQ_e}{dt}$$

Radiant intensity. Radiant intensity I_e is the power $d\Phi_e$ emitted per unit solid angle $d\Omega$, expressed in Watts per steradian (W/sr).

$$I_e = \frac{d\Phi_e}{d\Omega}$$

Radiant intensity $d\Phi_e$ is measured with a detector with an active area A positioned at a distance r from a light source. Assuming a point light source the inverse square law holds true. The distance r and the detector area dA define the solid angle $d\Omega$.

$$d\Omega = \frac{dA}{r^2}$$

Irradiance. Irradiance, E_e is the ratio of radiant power $d\Phi_e$ and detector active area, dA, expressed in Watts per square meter (W/m^2).

$$E_e = \frac{d\Phi_e}{dA}$$

Irradiance and radiant intensity can be mathematically related to a point light source.

$$E_e = \frac{d\Phi_e}{dA} = I_e \cdot \frac{d\Omega}{dA} = \frac{I_e}{r^2}$$

Radiance. Radiance, L_e is valid for extended light sources and can be defined as the radiant power, $d\Phi_e$ emitted from an area dA_e per unit solid angle $d\Omega$, expressed in Watts per steradian per square meter, W/sr*m^2.

$$L_e = \frac{d^2\Phi_e}{dA \cdot d\Omega}$$

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[1]G. Leschhorn, R. Young, Handbook of LED and SSL Metrology, Chapter 2.1;

Photometric quantities

Photometric quantities consider the visual perception of the human eye with reference to radiometric quantities, scaled by the V(λ) curve which describes the human eye response in the spectral wavelength range from 380 – 780 nm. An important parameter is the perceived brightness or luminous flux which is obtained by integrating radiant power $\Phi_e(\lambda)$:

$$\Phi_V = K_m \int V(\lambda)\left(\frac{d\Phi_e(\lambda)}{d\lambda}\right)(d\lambda),$$

where K_m = 683 lm/W.

K_m establishes the relationship between the physical radiometric unit Watt and the physiological photometric unit lumen.

Table 1 lists some brief explanations of relevant photometric quantities for LEDs.[2] Where applicable, the reference to the official definition in the International Lighting Vocabulary (ILV) from 2011 is given in parentheses (ILV CIE S 017/E:2011).[3] For more detailed information refer to DIN 5032 and DIN 5033.

Table 1: Photometric quantities

Quantity	Symbol	Definition	Reference
Luminous intensity	Cd or lm/sr	Luminous flux emitted per unit solid angle in a given direction.	ILV CIE S 017/E:2011 17-739. For a definition of the solid angle refer to ILV CIE S 017/E:2011 17-1201.
Luminous flux	lm	Total emitted optical power weighted by the standardized spectral response function of the human eye V(λ).	ILV CIE S 017/E:2011 17-738. For the definition of V(λ) refer to ILV CIE S 017/E:2011 17-1222.
Chromaticity coordinates	x,y	Determined from the XYZ tristimulus values according to the formulas x = X/(X+Y+Z); y = Y/(X+Y+Z)	ILV CIE S 017/E:2011 17-144. Additional explanations can be found in CIE 15 “Colorimetry”.

[2]Technical Guide: The Radiometry of LEDs, Chapter 3.1.
[3]ILV CIE S 017/E:2011.

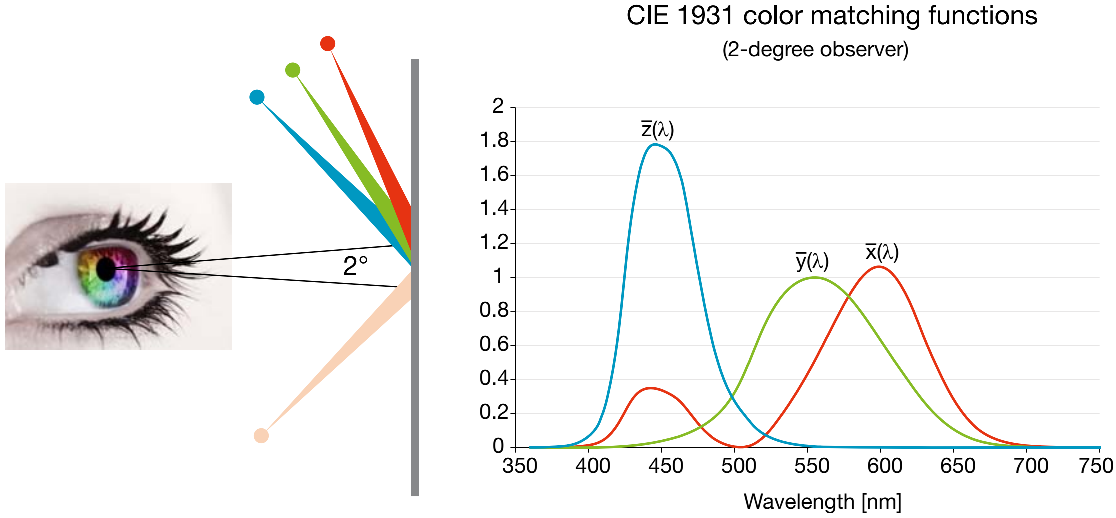
Table 1: Photometric quantities

Quantity	Symbol	Definition	Reference
Dominant wavelength	nm	Wavelength of the monochromatic stimulus which, when mixed additively in suitable proportions is considered in the CIE 1931 x, y chromaticity diagram. It can be determined from the chromaticity coordinates by drawing a straight line from the equal energy white point to the sample point and to the boundary of the color diagram. This intersection represents the dominant wavelength. The equal energy white point is x = 1/3 and y = 1/3.	ILV CIE S 017/E:2011 17-345
Peak wavelength	nm	Maximum position of the spectrum.	
Centroid wavelength	nm	Wavelength that divides the integral of a spectrum into two equal parts.	
(Excitation) purity	%	Ratio of the distance of the straight line from the equal energy white point E to the chromaticity point and the distance from the equal energy white point E to the boundary of the chromaticity chart.	ILV CIE S 017/E:2011 17-408.
Correlated color temperature (CCT)	K	Color temperature of a black body radiator which is closest to the color coordinates of the light source in the uv color space.	ILV CIE S 017/E:2011 17-258). For the definition of uv (= u';2 / 3v') color space refer to ILV CIE S 017/E:2011 17-162.
Color rendering index (CRI)	N/A	Quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison to a reference light source of the matching CCT.	ILV CIE S 017/E:2011 17-222. Further and more detailed explanations can be found in CIE 13 "Method of Measuring and Specifying Color Rendering of Light Sources" as well as in DIN 6169.

B. Color spaces

For the quantitative and qualitative description of color, a tristimulus system and a standard observer were defined and established by the International Commission on Illumination (CIE) in 1931. The tristimulus system is based on the assumption that by combination of the colors red, green and blue every other color can be represented. CIE recommended the model of a standard observer with a 2° viewing angle (see Figure 3). It is based on the work of Wright and Guild. These two independent research groups presented almost the same results for color matching functions (CMF) to describe human color perception. The maximum saturation method was used to determine the CMF. Thereby a monochromatic attraction was presented on a reference surface and a test person replicated the reference color with a modified RGB primary source on a test surface. The test and reference surface were observed together under a 2° field of view.

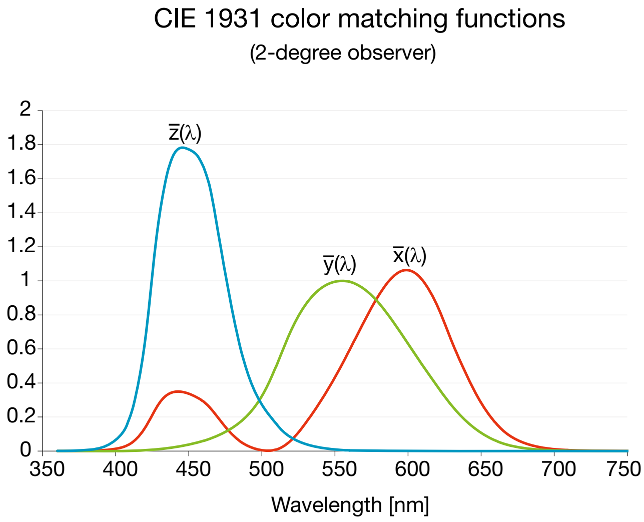
Figure 3: Color matching functions based on the CIE 1931 2° standard observer



CIE 1931 color space — xy color space

To describe the color of a light source by the XYZ system, the color matching functions x(λ), y(λ), z(λ) are multiplied with the spectral power distribution of the light source and integrated over the wavelength range of the spectral response function of the human eye (380 nm to 780 nm). For a simplified representation of the three-dimensional color space, the two-dimensional chromaticity diagram was developed by the CIE. The 1931 CIE diagram and the color matching functions for a 2-degree observer (Figure 4) are widely used in the LED industry.

Figure 4: Color matching functions

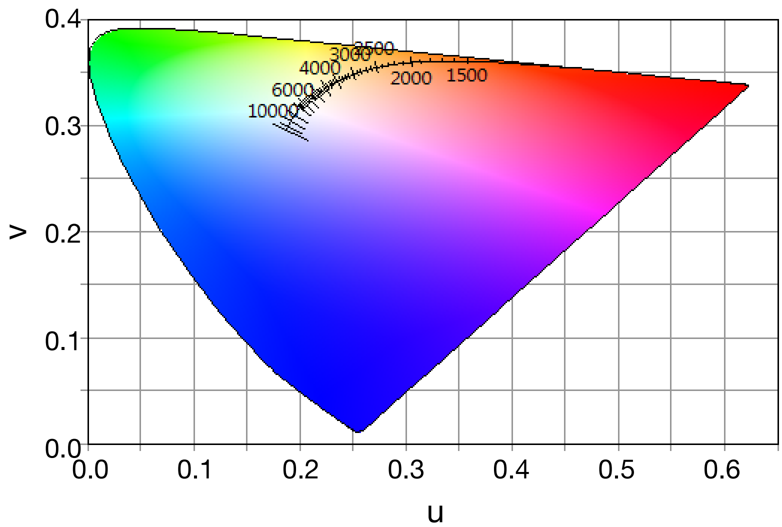


CIE 1960

After first experiences using the CIE 1931 xy chromaticity diagram, the scientific world realized that the color space is not uniform. This means that differences in color coordinates do not match the visual perception of these differences. This was also supported by experiments and studies by MacAdam (see chapter "MacAdam ellipses"). Based on the resulting MacAdam ellipses a more uniform color space was created. The CIE 1960 uv chromaticity diagram is a first attempt towards a more uniform color space, where the MacAdam ellipses should form circles and therefore better represent visually perceived color differences.

The CIE 1960 uv color space (see Figure 5) is also the basis for the definition of the correlated color temperature (CCT) as well as the distance to the black body radiator Duv. The values and definitions mentioned above are still used today.

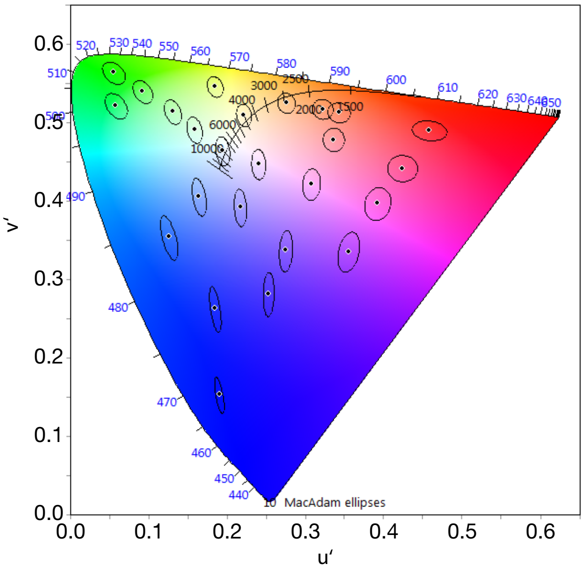
Figure 5: CIE 1960



CIE 1976 uniform color space CIE Luv — u´v´color space

While the CIE 1931 color space is an easily implementable color scheme, the variation in color sensitivity between green and blue regions portrays an inaccurate picture of the human eye's sensitivity to color. To overcome this drawback, the CIE 1976 color diagram, a geometric transformation of the CIE 1931 chromaticity diagram, has become the most recent adaptation of colorimetry standards. The CIE 1976 color scheme gives the user a more accurate picture of color sensitivity by improving perceptual uniformity in color sensitivity. This is observed in the more balanced MacAdam ellipse dimensions (u´v´circles) especially in the area of white light.

Figure 6: CIE 1976 color space



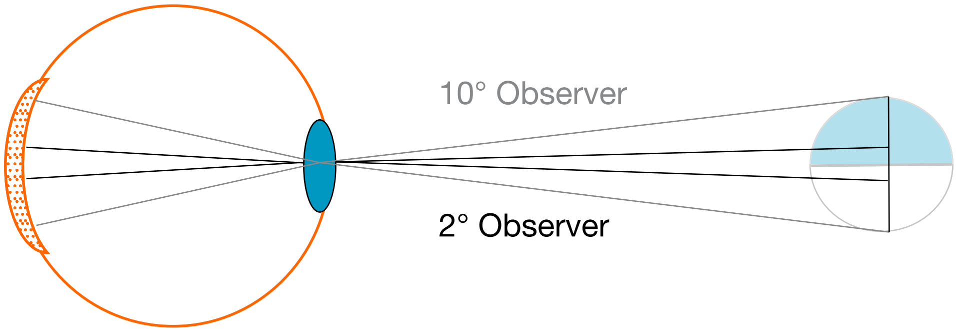
C. CIE 2015 fundamental chromaticity diagram with physiological axes

In 2006, new physiologically-based color matching functions of Stockman and Sharpe were recommended by the CIE Technical Committee 1-36. Stockman and Sharpe tried to find real sensitivities of the human color receptors – the cones. There are three different types of cones:

- L-cones with a sensitivity in the long wavelength range (red)
- M-cones in the middle wavelength range (green)
- S-cones in the short wavelength range (blue)

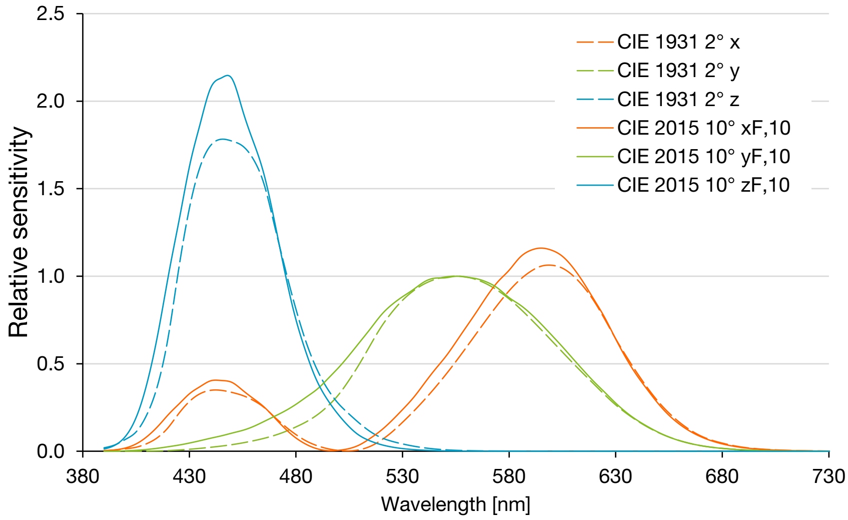
The final fundamental cone estimates resulted from a linear transformation of the 10°-CMFs guided mainly by the cone spectral sensitivity data. Based on their research, Stockman and Sharpe proposed color matching functions for 2°- and 10°-viewing conditions (see Figure 7).

Figure 7: 2° and 10° observer



The latest publication "CIE 170-2:2015: Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams" also provides a complete color space based on the new fundamental color matching functions from 2006. Figure 8 shows the difference between the CIE 1930 2° and the CIE 2015 10° color matching functions.

Figure 8: Color matching functions for CIE 1930 2° and 2015 10°

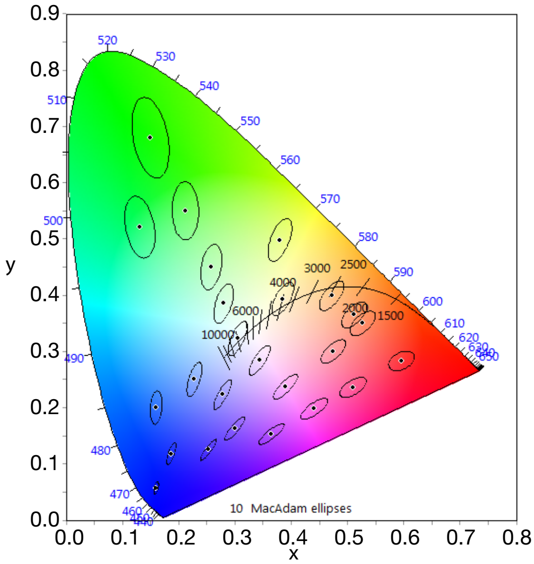


D. Color consistency of white light

MacAdam ellipses

In 1942, MacAdam published a paper illustrating the human eye's ability to distinguish color differences at various positions in the CIE 1932 color diagram. The eye is least sensitive to color variations in the green wavelength, followed by white, red and blue. The eye's ability to detect color differences is quantified in terms of MacAdam ellipse steps, with each step representing a standard deviation of the population which can notice color difference. A MacAdam ellipse (Figure 9) describes the limit of variation where the color difference would be just noticeable.

Figure 9: CIE 1931 color space with MacAdam ellipses

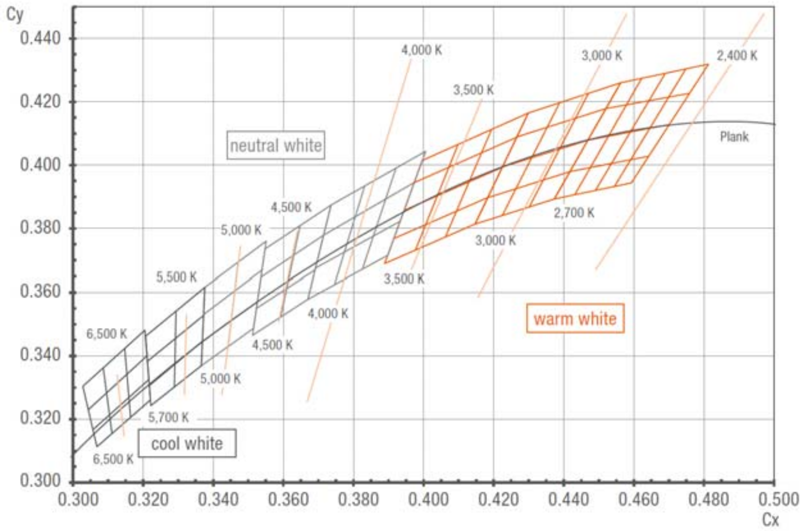


When comparing and evaluating different white light sources, color differences may become visible. During the production process of the white LEDs a certain distribution of color coordinates cannot be avoided. Therefore a reasonable selection has to be made taking into account the application requirements in which the final product will be used. This selection of LEDs belonging to one group of similar white LEDs is called binning.

CCT and Duv (below black body)

The color coordinate of the LED bin is often referenced to as the correlated color temperature (CCT). The color coordinate of a certain CCT is defined by the emission spectrum of a black body or Planckian radiator at the same absolute temperature. It is already known from conventional light sources that color coordinates slightly below the Planckian locus have a more whitish appearance. This point can be determined by the shortest distance of the color coordinate to the Planckian locus in the uv color space. It is also known as “below black body” and provides a clean white look of the light. Figure 10 shows the correlated color temperatures and the black body curve.

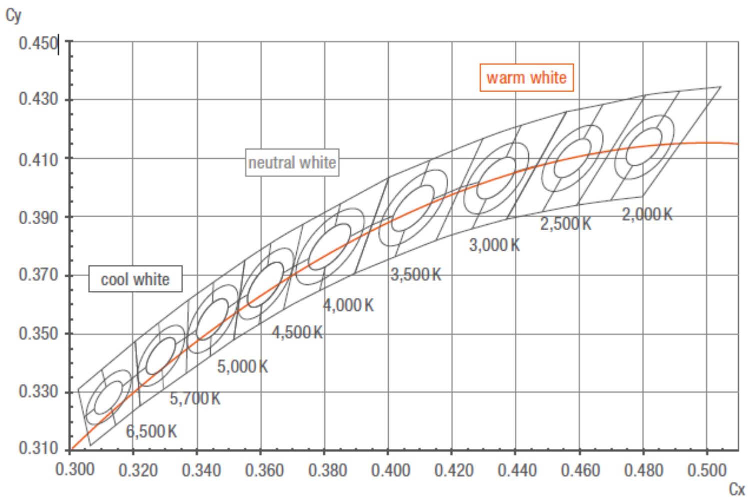
Figure 10: Correlated color temperatures and black body curve



LED binning

Binning of LEDs can be done in various bin shapes. In the past, LEDs were usually binned in quadrangles. For general lighting applications the studies from MacAdam inspired the so-called hybrid binning. Here the bin definition for the LEDs follows a 3 step and a 5 step ellipse with subgroups to ensure a similar white color impression of the LEDs (see Figure 11).

Figure 11: Hybrid binning



Today the LED industry bins in the CIE 1931 2° color space. However, in certain applications where the scene is not observed under a narrow 2° field of view but more towards a 10° observation angle, color differences are visible. This occurs even if binning in the CIE 1931 2° is done in very narrow 1-step bins. This effect is caused by the irregular distribution of cones in the eye.

In order to avoid such an effect, binning in a different color space as proposed by CIE 170-2:2015 would be beneficial. This color space is currently still not used in the LED industry but discussions are ongoing.

More details can be found at: https://www.osram.com/os/applications/ten-binning/index.jsp

An additional aspect when discussing color consistency between light sources is the CIE TN 001:2014 Chromaticity Difference Specification for Light Sources. The definition of the MacAdam ellipses is quite difficult and not explicit since ellipse parameters must be read and interpolated from an array of curves in the original publication. Therefore CIE proposes to define circles in the u'v' chromaticity diagram for a clear definition. This definition is still not generally used in the industry.

Color over angle (CoA)

Color consistency may not only be considered from light source to light source but also within the radiation characteristic of a single LED. Light quality and color consistency is becoming more and more important and color artefacts such as yellow or blue rings should be avoided to ensure the uniform and pleasant appearance of illuminated areas.

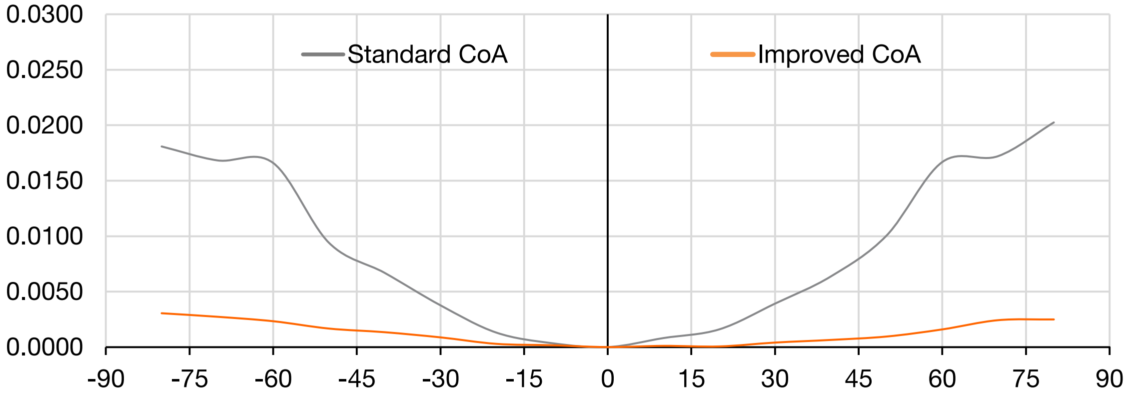
LEDs with lenses are known for their high efficacy at high luminance which makes them the preferred choice for use in beam shaping in combination with secondary optics. However these domed high power LEDs may feature a certain variation of color coordinates over the radiation angle (CoA). This may result in a color variation from the center at 0° to the large angles at 90°. Figure 12 shows various color consistence quality within the radiation characteristic. It starts from large blue yellow color separation on the left side and improves to no visible color variation on the right side.

Figure 12: CoA

Any optics would have to cope with these variations in order to prevent unpleasant color artefacts in the illumination system. The perceived and visible differences within the radiation characteristic could be quantified in a goniometer measurement.

With special attention to this issue, color over angle variation can be significantly improved. This enables faster and easier optics design, provides much better color uniformity and higher efficacy of the complete systems. Figure 13 shows the result of an improved CoA.

Figure 13: Color over angle variation in Δu´v´



Color uniformity

The specification and evaluation of color uniformities is quite challenging. Usual methods of minimum and maximum values are not suitable since variations have to be considered relative to the field of view in order to obtain a reasonable assessment of the severity of the situation.

The VDI/VDE 5595 “Photometric and colorimetric quality criteria – Method to assess uniformity” proposes a method to address this challenge. Since the method is quite new, industry will have to evaluate the boundaries and criteria for its proper implementation in various application conditions.

Don't forget: LED Light for you is your place to be whenever you are looking for information or worldwide partners for your LED Lighting project.

www.ledlightforyou.com

ABOUT OSRAM OPTO SEMICONDUCTORS

OSRAM, Munich, Germany is one of the two leading light manufacturers in the world. Its subsidiary, OSRAM Opto Semiconductors GmbH in Regensburg (Germany), offers its customers solutions based on semiconductor technology for lighting, sensor and visualization applications. OSRAM Opto Semiconductors has production sites in Regensburg (Germany), Penang (Malaysia) and Wuxi (China). Its headquarters for North America is in Sunnyvale (USA), and for Asia in Hong Kong. OSRAM Opto Semiconductors also has sales offices throughout the world. For more information go to www.osram-os.com.

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