



Color Rendering (Optimization of Color Rendering of LED Light Sources Based on Modern Colorimetric Metrics and Adaptive Evaluation Models)

Leonid Nazarenko¹ , Bohdan Oliinychenko¹ , Anastasiia Kolesnyk¹ , Vitalii Herasymenko¹ , Natalia Lukashova¹ , and Oleh Kulaienko¹ 

¹ O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

Article History

Received:
21 November 2024

Accepted:
16 December 2024

Published online:
25 December 2024

Keywords

Color Accuracy Index;
Color Space; Color
Metrics; Color Percep-
tion; Light Sources

Abstract

The fidelity of color perception under various lighting conditions is crucial in lighting quality assessment. Traditional color rendering metrics, like the Total Color Rendering Index (CRI or Ra) developed by the Commission Internationale l'Eclairage (CIE) in 1964, provide an average measure of color fidelity across a limited set of color samples but do not capture individual color variations. This metric, while widely used, has limitations in predicting color fidelity, especially for specific colors or applications where precise color rendition (such as in skin tones, food items, or particular-colored objects) is essential. That is, this traditional method of evaluating color rendering has a number of limitations, such as using only eight test colors, which is insufficient for a wide range of sources and does not take into account new types of light sources, such as modern LEDs. With the advent of solid-state lighting, especially LEDs, the limitations of CRI became more pronounced, leading to calls for improved metrics. In response, the Society of Lighting Engineers of North America (IESNA) proposed the Color Fidelity Index (Rf), incorporating 99 uniformly distributed color samples and a refined color space to better predict visual color perception. And the color saturation index (Rg). These methods use modern color spaces, such as CIE CAM02-UCS, to increase the accuracy of the work. That is why modern approaches to assessing color rendering will allow us to take into account various types of light sources, including LED ones, ensure the accuracy of transmission where colors are critical and create standards for harmonizing lighting in different industries. The development of these metric systems helps to create better quality light sources and increase the comfort of human color perception. A calculation method was applied, which is determining the deviation of each test color from the reference one under standard lighting and averaging the deviations to obtain the final index. This article explores the fidelity of color indices, compares the efficacy of Ra and Rf metrics, and analyzes their application across various lighting sources, providing insights into the future of color rendering standards.

INTRODUCTION

The influence of a light source on the color perception of objects and surfaces is a crucial aspect of lighting quality. The metrics used in the lighting industry to describe color are based on color comparison rather than color perception. This limitation prevents obtaining satisfactory answers to certain questions regarding color rendering. In addition to the visual perception of the color of light sources, the color rendering of illuminated surfaces is also of great importance.

Currently, numerous studies focus on evaluating the color rendering properties of light sources. In 1964, the International Commission on Illumination

(CIE) introduced the general Color Rendering Index (Ra), based on the comparison of a series of eight standard color samples with specified reference light sources (CIE 1965, 1974, 1995). This index is widely used and remains an internationally recognized color rendering metric. However, most color rendering metrics discussed in the literature rely on comparing a test light source with a reference source [1]. Three key factors influence the quality of such metrics: the color surfaces of the samples used, the type of reference light source, and the calculation procedure that determines the perceived color difference between the sample illuminated by the test and reference sources.

Corresponding author: Leonid.Nazarenko@kname.edu.ua (Leonid Nazarenko)

© 2024 The Author(s). Published by O. M. Beketov National University of Urban Economy in Kharkiv
Use permitted under [Creative Commons Attribution 4.0 International \(CC BY 4.0\)](https://creativecommons.org/licenses/by/4.0/)

Cite as: Nazarenko, L., Oliinychenko, B., Kolesnyk, A. & Herasymenko, V., O., Lukashova, N., Kulaienko (2024). Color rendering. *Lighting Engineering & Power Engineering*, 63(3), 101–108. <https://doi.org/10.33042/2079-424X.2024.63.3.05>

One of the unresolved issues is that the Ra index averages the color rendering of eight colors, which does not provide information about the rendering of individual colors. Two light sources with the same Ra value may exhibit significantly different color rendering properties for specific colors. In certain applications, accurate rendering of specific colors, such as human skin tones, meat, or vegetables, is critical. In such cases, it is essential to analyze the individual color rendering indices Ri (CRi) for the eight standard colors or the six additional special colors [2].

The development of solid-state lighting has led to an increased interest in the standardization of improved methods for evaluating the color rendering of light sources, particularly LEDs. As early as 2007, the CIE noted that the CRI color rendering index is not always suitable for predicting the color rendering properties of a set of light sources if it includes white LEDs. The Illuminating Engineering Society of North America (IESNA) proposed the Rf Color Fidelity Index, a scientifically accurate measure of color fidelity relative to a reference illuminant.

A key improvement of the Rf metric compared to CRI is the update of the color space model and the introduction of 99 test samples with a more uniform distribution. This advancement better accounts for human color perception and provides a more accurate assessment of color rendering in a three-dimensional uniform color space.

Analyzing recent research [3-9] highlights several unresolved challenges in evaluating the color rendering of LED light sources. Therefore, the aim of this study is to analyze and improve methods for assessing the color rendering of modern light sources based on the CIE CAM02-UCS color space to enhance color accuracy under different lighting conditions.

The objectives of this study are:

- To investigate the features of the CIE CAM02-UCS color space and its application to evaluating color shifts in LED light sources;
- To examine modern methods for assessing the color rendering of light sources and compare them with traditional approaches (CIE Ra, CIE Rf, etc.);
- To determine the influence of the spectral characteristics of LED lighting on color rendering accuracy under various visual conditions.

RESEARCH METHODOLOGY

From the practice of using the general color rendering index Ra, it is obvious that some models and procedures on which it is based are being updated. This affects both the $U^* V^* W^*$ space and the use of chromatic adaptation correction, as well as the number and types of system samples heterogeneously distributed over the color space and possibly unrepresented colors that occur in the interior.

After the appearance of LEDs on the market, it became clear that Ra is not always a good and sufficiently perfect predictor of color rendering properties for this new category of light sources.

Over the past decades, significant research has been conducted to improve the measurement of color accuracy and especially the evaluation of two-metric color rendering methods.

IESNA has published IES Technical Memorandum TM-30-15, which provides a method for using the Total Color Accuracy Index Rf, a metric that synthesizes the results of many studies.

In 2017, this metric was recommended by the Commission Internationale l'Eclairage (CIE) for accurate scientific use [7].

To calculate the overall color accuracy index Rf, 99 color test samples are used, which were obtained through a careful selection process. They were selected from a range of 105,000 different types of objects, both natural and man-made. Finally, 99 samples were selected, which are evenly distributed in the color space and do not have excessive saturation or darkness. The series is also what is called "spectrally homogeneous", that is, the reflection coefficient functions of all samples cover the entire range of wavelengths fairly evenly. Tables of spectral reflectance coefficient's of all 99 color samples are available in CIE publications. In Fig. 1 shows the colors of 99 samples.



Figure 1. Colors of 99 samples used to calculate the color accuracy index, Rf, as approximately perceived under daylight illumination D50 (IES 2015, 2018; CIE 2017)

It should be emphasized that the use of a larger number of samples makes it possible to reduce statistical uncertainty.

The most modern uniform color space called CIE CAM02-UCS is used to calculate color shifts. Its name consists of Color Appearance Model (Model of Color Perception) UCS (Uniform Color Space) – uniform color space - in the sense that equal distances in space represent equal visual sensations of color differences.

CAM02-UCS has a complex mathematical calculation model that allows accurate calculation of color differences. This is a model that takes into account different conditions of observation (place and environment) of a color sample and chromatic adaptation. Fig. 2 illustrates this space.

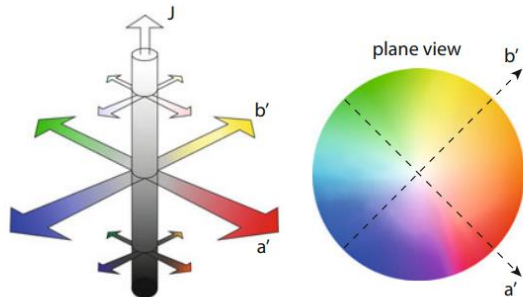


Figure 2. Three-dimensional color space CIECAM02-UCS

Three color coordinates are plotted on three mutually perpendicular axes. The vertical axis J represents brightness. The horizontal plane with a' and b' axes give different color tones, arranged according to the opposite (oppositional) color affirming mechanism in color vision.

Positive values on the a' axis represent reddish colors, negative a' – opposite greenish colors, while positive and negative values on the b' axis represent yellowish and opposite bluish colors, respectively. Larger values of a' and b' correspond to more saturated colors.

BUILT-IN TRANSFORMATION, THE POSSIBILITY OF TRANSFORMATION OF CHROMATIC ADAPTATION AND ADOPTED WHITE POINT

CAM 02-UCS offers the advantage of calculating the color rendering largely independent of the correlated color temperature of the test light source.

For the correct use of CAM 02-UCS, it is important to understand the input and output parameters of the model. Fig. 3 shows the vision parameters that determine the observation conditions and the terms of color sensations that are determined by the X_w, Y_w, Z_w model, which is the tristimulus value of the reference white under the test illuminator. α_A determines the brightness of the adaptation field; Y_b is the brightness factor of the background. The output parameters of the model include Luminance (J), Brightness (Q), Redness – Greenness (a'), Yellowness – Blueness (b'), Color Fullness (M), Color Purity (C), Saturation (S), Color Tone Composition (H), Hue angle (h).

In Fig. 3 presents a schematic diagram of the CIE color perception model.

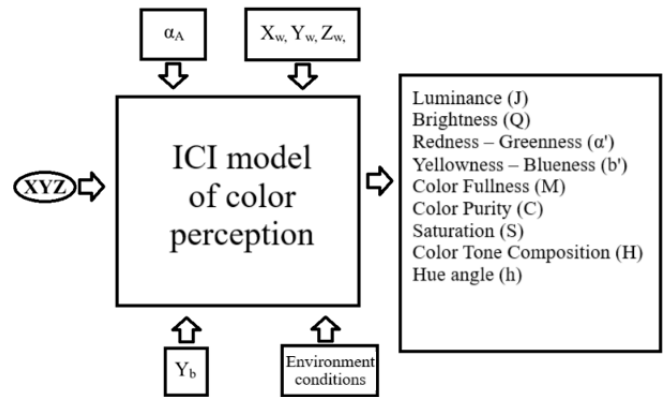


Figure 3. CIE color perception model

THE PROCEDURE (METHODOLOGY) FOR CALCULATING THE INDEX OF GENERAL COLOR ACCURACY (Rf) AND INDICES OF SPECIAL COLOR ACCURACY (Rf, i)

The general calculation process is similar to the current CRI calculation. In this case, the calculation of the parameters of the color perception model CIE CAM 02 UCS is used [8]. An illustration of this process is shown in Fig. 4.

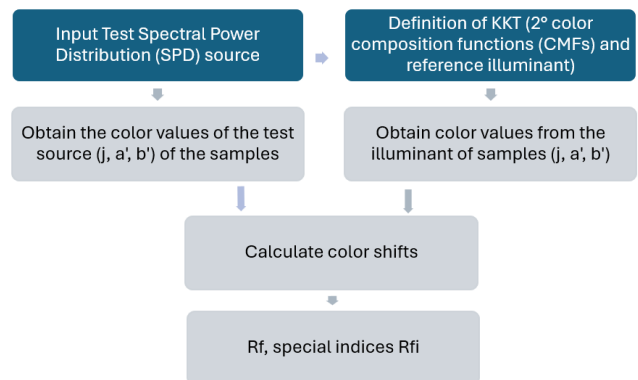


Figure 4. The process of calculating the color accuracy index

All steps use the 1964 10° color composite functions, except for the CCT step, which uses 2° CMFs as in common practice.

The total color accuracy index Rf is calculated as a rescaled measurement of the average color-perceptual difference of 99 test color samples (TCS) irradiated by a test light source and irradiated by a specified reference illuminant that has the same CCT as the test source. Color-perceptual differences are defined in the CAM02-UCS color space. The CIE reference illuminant is a Planck emitter, daylight, or a mixture of the two with the same correlated color temperature. The scaling is performed using a logarithmic function that provides all values between 0 and 100 and such that the average Rf of the selected light source spectra is the same as the average Ra of the CIE [9].

RESULTS AND DISCUSSION. DETAILS OF THE CALCULATION SCHEME

I. Note that the spectral sampling interval (5 nm or less) about the wavelength range and the spectral range sampling are significantly accurate.

As a preliminary step to the calculation, the consumer must ensure that the SPD of the light source is low:

a) a significantly large wavelength range covering 380 nm to 780 nm, which is the standard calculation range used for this method;

b) a substantially accurate spectral sampling interval (5 nm or less) is recommended for accurate color calculations.

If the SPD of the light source is added exactly at 1 nm intervals (or multiples of 1 nm), the TCS data must be interpolated using the method given in Aptech C, and the CIE color composition functions at 1 nm intervals are available in ISO 11664-1 2007 (E) CIE 9014-1/E-2006 (ISO/CIE 2007) should be used. If values at 1 nm intervals are required, as a general rule, linear interpolation between 1 nm points should be used (see CIE 15.2004). All rigorous calculations must use this method. For practical applications, when small computational differences are neglected and the Lagrange cubic online or Sprague interpolation method (CIE 2005) can be used, as described in 7.2.1.1 CIE 15.2004 (CIE 2004c) to the SPD wavelength interval of the light source.

If the SPD of the light source is given in a smaller range than 380-780 nm (e.g. 400 nm to 700 nm) then the missing values can be assigned as zero so that all calculations can be made for a fixed range of 380 nm to 780 nm.

It should be noted that if the SPD range of the light source is significantly less than the standard range, a significant error in the calculation results is possible.

2) Calculate the reference illuminant:

a) Determine the correlated color temperature (CCT) of the test light source according to 9.5 in CIE 15 (CIE 2004c) [7];

b) If $T < 4000$ K, the relative SPD of the Planck reference emitter is determined:

$$S'_r(\lambda) = \frac{C_1}{\lambda^5} \times \frac{1}{e^{\frac{C_2}{\lambda T}} - 1} \quad (1)$$

where $C_1 = 3,74183 \times 10^{-16}$ w/m²; $C_2 = 1,438 \times 8 \times 10^{-2}$ mK; λ - wavelength.

c) If $T > 5000$ K, the daylight phase is calculated.

3) We determine the color coordinates ($x_D y_D$) of the illuminant:

- if $T \leq 7000$ K,

$$x_D = -4,607 \frac{10^9}{\left(\frac{T}{K}\right)^3} + 2,9678 \frac{10^6}{\left(\frac{T}{K}\right)^2} + 0,09911 \frac{10^3}{\left(\frac{T}{K}\right)} + 0,244063, \quad (2a)$$

where K is the Kelvin temperature unit.

- if $T \geq 7000$ K,

$$x_D = -2,0064 \frac{10^9}{\left(\frac{T}{K}\right)^3} + 1,9018 \frac{10^6}{\left(\frac{T}{K}\right)^2} + 0,24748 \frac{10^3}{\left(\frac{T}{K}\right)} + 0,23704, \quad (2b)$$

y_0 is calculated from x_D as follows:

$$y_D = -3x_D^2 + 2,87 x_D - 0,275, \quad (2c)$$

4) We will get the relative SPD of the daylight illuminant, S_r as:

$$S_r \lambda = S_0(\lambda) + M_1 S_1(\lambda) + M_2 S_2(\lambda), \quad (3a)$$

where

$$M_1 = \frac{-1,3515 - 1,7703 \times x_D + 5,9114 y_D}{0,0241 + 0,2562 \times x_D - 0,7341 y_D}, \quad (3b)$$

$$M_2 = \frac{0,03 - 31,4424 \times x_D + 30,0717 y_D}{0,0241 + 0,2562 \times x_D - 0,7341 y_D} \quad (3c)$$

and $S_0(\lambda)$, $S_1(\lambda)$, $S_2(\lambda)$ there are basis functions that can be found and tabulated after 5 nm in Table T2 of CIE 15 2004 (CIE 2004c).

For other intervals, the linear interpolation method described in 3:1 (CIE 2004c) is used:

a) if $4000 \text{ K} \leq T \leq 5000 \text{ K}$, a linear combination of the Planck illuminant with the corresponding CCT, T (S_{rp}) and the daylight illuminant with the same CCT, T (S_{rD}) is calculated and renormalized Planck illuminant, S_{rp} and daylight illuminant, S_{rD} :

$$S'_{rp}(\lambda) = 100 \frac{S_{rp}(\lambda)}{\sum_{\lambda=380\text{nm}}^{780\text{nm}} S_{rp}(\lambda) \bar{y}(\lambda) \Delta \lambda'} \quad (4a)$$

$$S'_{rD}(\lambda) = 100 \frac{S_{rD}(\lambda)}{\sum_{\lambda=380\text{nm}}^{780\text{nm}} S_{rD}(\lambda) \bar{y}(\lambda) \Delta \lambda'} \quad (4b)$$

The color composition function of the CIE 1931 standard colorimetric system $\bar{y}(\lambda)$ is used here. We obtain the relative SPD of the mixture:

$$S_r(\lambda, T) = \frac{T - T_b}{T_e - T_b} S'_{rD}(\lambda) + \frac{T_e - T}{T_e - T_b} S'_{rp}(\lambda), \quad (4c)$$

where $T_b = 4000$ K and $T_e = 5000$ K, respectively, are the correlated color temperatures of the beginning of the end of the mixed range.

5) Calculate the color perception of 99 TCS according to the test source and the reference illuminant.

a) Determine the 10° value of the tristimuli X_{10} , Y_{10} , Z_{10} 99 TCS by the test source (signed t) and the reference illuminant (signed r) using the CIE 1964 color composition function $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ and spectral brightness factors 99 TCS, $\beta_{TCS}(\lambda)$:

$$X_{10,t} = 100 \frac{\sum_{\lambda=380\text{nm}}^{780\text{nm}} S_t(\lambda) \beta_{TCS}(\lambda) \bar{x}_{10}(\lambda) \Delta \lambda}{\sum_{\lambda=380\text{nm}}^{780\text{nm}} S_t(\lambda) \bar{y}_{10}(\lambda) \Delta \lambda}$$

$$Y_{10,t} = 100 \frac{\sum_{\lambda=380\text{nm}}^{780\text{nm}} S_t(\lambda) \beta_{TCS}(\lambda) \bar{y}_{10}(\lambda) \Delta \lambda}{\sum_{\lambda=380\text{nm}}^{780\text{nm}} S_t(\lambda) \bar{y}_{10}(\lambda) \Delta \lambda} \quad (5a)$$

$$Z_{10,t} = 100 \frac{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_t(\lambda) \beta_{\text{TCS}}(\lambda) \overline{z_{10}}(\lambda) \Delta\lambda}{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_t(\lambda) \overline{y_{10}}(\lambda) \Delta\lambda}$$

$$\begin{pmatrix} X_{10r} \\ Y_{10r} \\ Z_{10r} \end{pmatrix} = \frac{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_r(\lambda) \beta_{\text{TCS}}(\lambda) \begin{pmatrix} \overline{x_{10}}(\lambda) \\ \overline{y_{10}}(\lambda) \\ \overline{z_{10}}(\lambda) \end{pmatrix} \Delta\lambda}{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_r(\lambda) \overline{y_{10}}(\lambda) \Delta\lambda}, \quad (5b)$$

b) Calculate the 10° tristimulus value of the illumination white points $X_{10,W}$, $Y_{10,W}$, $Z_{10,W}$ for the test source and the reference illuminant.

$$\begin{pmatrix} X_{10,W,t} \\ Y_{10,W,t} \\ Z_{10,W,t} \end{pmatrix} = 100 \frac{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_t(\lambda) \begin{pmatrix} \overline{x_{10}}(\lambda) \\ \overline{y_{10}}(\lambda) \\ \overline{z_{10}}(\lambda) \end{pmatrix} \Delta\lambda}{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_t(\lambda) \overline{y_{10}}(\lambda) \Delta\lambda}, \quad (6a)$$

$$\begin{pmatrix} X_{10,W,r} \\ Y_{10,W,r} \\ Z_{10,W,r} \end{pmatrix} = 100 \frac{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_r(\lambda) \begin{pmatrix} \overline{x_{10}}(\lambda) \\ \overline{y_{10}}(\lambda) \\ \overline{z_{10}}(\lambda) \end{pmatrix} \Delta\lambda}{\sum_{\lambda=380 \text{ nm}}^{780 \text{ nm}} S_r(\lambda) \overline{y_{10}}(\lambda) \Delta\lambda}, \quad (6b)$$

c) Determine the color coordinates of perception of CAM02-UCS j' , a' , b' 99 TCS for the reference illuminant and the test source. CAM02-UCS is a color difference space based on the CIE CAM02 color perception space.

d) Use the following input parameters to define standard observation conditions in the CIE CAM02 and CAM02 UCS models.

1. Relative brightness (value of tristyma Y_{10}) of white according to the test source and reference illuminant:

$$Y_{10} = 100$$

2. Relative brightness (value of tristimulus Y_{10}) of the background:

$$Y_{10} = 20$$

3. The brightness of the adaptation field $L_{10,A} = 100 \text{ cd/m}^2$

4. The parameters depend on the surrounding model:

a) Ambient chromatic induction factor: $N_C = 1$

b) Exponential nonlinearity: $e = 0,69$; $e = 0,69$

5. Degree of chromatic adaptation: $D = 1$.

Detailed work parameters can be found in CIE CAM 02 and its recent developments.

II. For the values of the tristimulus X_{10} , Y_{10} , Z_{10} 99 TCS according to the test and reference illuminant, it is necessary to calculate the corresponding values of the tristimulus $X_{10,C}$, $Y_{10,C}$, $Z_{10,C}$ according to CIE CAM02 by using the implied white point, equal-energy white, CAT02 transform of homatic adaptation (CIE 2004a).

1. Convert XYZ space to CAT02 RGB space:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M_{\text{CAT02}} \begin{pmatrix} X_{10} \\ Y_{10} \\ Z_{10} \end{pmatrix}, \quad (7a)$$

where

$$M_{\text{CAT02}} = \begin{bmatrix} 0,7328 & 0,4296 & -0,1624 \\ -0,7036 & 1,6975 & 0,0061 \\ 0,0030 & 0,0136 & 0,9834 \end{bmatrix}, \quad (7b)$$

$$M_{\text{CAT02}}^{-1} = \begin{bmatrix} 1,096124 & -0,278869 & 1,182745 \\ 0,454369 & 0,473533 & 0,072098 \\ -0,009628 & -0,005698 & 1,015326 \end{bmatrix}, \quad (7c)$$

The M_{CAT02} matrix was developed to better match the perceptual data, using the CIE 2° color composition functions, which are slightly different from the 10° color composition functions. In principle, a slightly different matrix could therefore be applied, but the procedures required to do so are not available. Fortunately, in the differential color shift calculations used here, this could probably introduce only a small, second-order effect that does not significantly affect the result.

For this reason, the function of this matrix is traditionally used here.

2. Apply chromatic adaptation “Von Kries”:

$$\begin{pmatrix} R_C \\ G_C \\ B_C \end{pmatrix} = \begin{pmatrix} \frac{Y_{10,W}}{R_W} \frac{Y_{10,W}}{G_W} \frac{Y_{10,W}}{B_W} & 0 & 0 \\ 0 & \frac{Y_{10,W}}{G_W} \frac{Y_{10,W}}{B_W} & 0 \\ 0 & 0 & \frac{Y_{10,W}}{B_W} \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}, \quad (7d)$$

where “w” – adaptive white point (test and reference illuminants).

3. Inversely transform back to tristimulus values

$$\begin{pmatrix} X_{10,C} \\ Y_{10,C} \\ Z_{10,C} \end{pmatrix} = M_{\text{CAT02}}^{-1} \begin{pmatrix} R_C \\ G_C \\ B_C \end{pmatrix}, \quad (7e)$$

III. Convert $X_{10,C}$, $Y_{10,C}$, $Z_{10,C}$ to the response cone R' , G' , B' using the Hunt-Pointer-Bethewez matrix (HDE):

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_{\text{HDE}} \begin{pmatrix} X_{10,C} \\ Y_{10,C} \\ Z_{10,C} \end{pmatrix}, \quad (8a)$$

with

$$M_{\text{HDE}} = \begin{bmatrix} 0,3897 & 0,68898 & -0,07868 \\ -0,22981 & 1,18340 & 0,04647 \\ 0 & 0 & 1 \end{bmatrix}, \quad (8b)$$

In order to speed up the calculation time for time-critical operations in production, steps II (equation 7e) and III (equation 9a) can be combined into a single matrix product.

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_{\text{HDE} * \text{CAT02}^{-1}} \begin{pmatrix} R_C \\ G_C \\ B_C \end{pmatrix} = M_{\text{HDE}} M_{\text{CAT02}}^{-1} \begin{pmatrix} R_C \\ G_C \\ B_C \end{pmatrix}, \quad (8c)$$

with

$$M_{\text{HDE} * \text{CAT02}^{-1}} = \begin{pmatrix} 0,740979 & 0,218025 & 0,041006 \\ 0,285353 & 0,624201 & 0,090445 \\ -0,009628 & -0,005698 & 1,015326 \end{pmatrix}, \quad (8d)$$

IV. We apply brightness adaptation to the adapted (truncated) response cone (R' , G' , B'):

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = f \left(\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} \right), \quad (9a)$$

using a non-linear function,

$$f(x) = \frac{400(F_L + \frac{x}{100})^{0,42}}{27,13 + (F_L + \frac{x}{100})^{0,42}} + 0,1, \quad (9b)$$

with F_L calculated as follows,

$$K = \frac{1}{1 + (5 \frac{L_{10,A}}{cd/m^2})} = 0,0020, \quad (9c)$$

$$F_L = \frac{1}{5} K^4 \left(5 \frac{L_{10,A}}{m^2} \right) + \frac{1}{10} (1 - K^4)^2 (5 \frac{L_{10,A}}{m^2})^{1/3} = 0,7937$$

V. Calculate the red-green and yellow-blue opposite channels a and b:

$$a = R'_a - \frac{12}{11} G'_a + \frac{1}{11} B'_a, \quad (9d)$$

$$b = \frac{1}{9} (R'_a + G'_a - 2B'_a), \quad (9e)$$

VI. Determine achromatic response, A:

$$A = (2R'_a + G_a + \frac{1}{20} B'_a - 0,305) N_{bb}, \quad (10a)$$

with the background brightness induction factor N_{bb} , and the background chromatic induction factor N_{cb} , calculated as follows.

(N_{bb} and N_{cb} - are factors that were included in the CIECAM02 model to account for luminance and chromatic induction by the background. Now that more data is available to improve the model, they are modeled in the same way)

$$N_{bb} = N_{cb} = 0,725n^{0,2}, \quad (10b)$$

and

$$n = \frac{Y_{10,b}}{Y_{10,w}} = 0,2000, \quad (10c)$$

which gives $N_{bb} = 1,0003$.

VII. Calculate CIE CAM 02 sense of luminance J, color tone composition h, color fullness (saturation M):

1. Luminance J:

$$J = 100 \left(\frac{A}{A_w} \right)^{c \cdot z}, \quad (11a)$$

where A_w - achromatic response of illuminant, $z = 1,48 + \sqrt{n}$ i e - exponential nonlinearity $c=0,69$.

2. Color tone composition h:

$$h = \frac{180}{\pi} \arctg \left(\frac{b}{a} \right), \quad (11b)$$

Color fullness M:

$$M = CF_L^{0,25}, \quad (11c)$$

with

$$c = t^{0,9} \sqrt{\frac{J}{100}} (1,64 - 0,29^n)^{0,73}, \quad (11d)$$

and with

$$t = \frac{5000 N_{Cb} N_{Ct} \sqrt{a^2 + b^2}}{R'_a + G'_a + \frac{21}{20} B'_a}. \quad (11e)$$

The eccentricity coefficient e_t is defined as:

$$e_t = \frac{1}{4} \left(\cos \left(\frac{\pi}{180} h + 2 \right) + 3,8 \right), \quad (11f)$$

VIII. Finally convert CIE CAM 02 correlators J, M and h in CAM 02-UCS color coordinates h' , J' , a' , b' :

$$J' = \frac{(1+100 \cdot 0,007)^J}{1+0,007J}, \quad (12a)$$

$$a' = M' \cos \left(\frac{\pi}{180} h \right), \quad (12b)$$

$$b' = M' \cos \left(\frac{\pi}{180} h \right), \quad (12c)$$

and with

$$M' = \frac{1}{0,0228} \ln (1 + 0,0228 * M). \quad (12d)$$

3. Calculate color perception differences, ΔE_i for each of the 99 TCS, and their average $\Delta \bar{E}$:

$$\Delta E_i = \sqrt{(J'_{t,i} - J_{r,i})^2 + (a'_{t,i} - a'_{r,i})^2 + (b'_{t,i} - b'_{r,i})^2}, \quad (13a)$$

where $J'_{t,i}$, $a'_{t,i}$, $b'_{t,i}$ - CAM02-UCS color coordinates of TCS_i, irradiated by the test source and $J'_{r,i}$, $a'_{r,i}$, $b'_{r,i}$ CAM02-UCS color coordinates of TCS_i irradiated with a reference illuminant.

$$\Delta \bar{E} = \frac{1}{99} \sum_{i=1}^{99} \Delta E_i, \quad (13b)$$

4. Convert from perceived color difference to color accuracy index value.

$R_{fi} = 10 \ln \left(e^{\frac{100 - cf \Delta E_i}{10}} + 1 \right)$ - special indices of color accuracy,

$R_f = 10 \ln \left(e^{\frac{100 - cf \Delta \bar{E}}{10}} + 1 \right)$ - total color accuracy index with a scaling factor,

$$C_f = 6,73.$$

A new color system sCAM is proposed, which includes the unified color space sUCS. The main features of this system are:

sUCS is distinguished by its simple structure and is the second fastest among the tested unified color spaces (UCS).

In the prediction rating for 28 uniformity data sets, sUCS took second place, lagging behind CAM16-UCS by only one unit. When assessing the linearity of shades, sUCS demonstrated the best results together with IPT, while CAM16-UCS showed the worst performance.

sCAM provides the most accurate reproduction of the parameters of lightness, saturation and brightness, and also takes second place in the accuracy of predicting the composition of shades. When testing two-dimensional scales (whiteness, blackness, depth and brightness), sCAM showed the highest accuracy for all 2D data sets.

CONCLUSIONS

The widespread adoption of LED light sources in lighting applications has necessitated a revision of traditional colorimetric metrics. Experimental results demonstrated that two light sources with the same Ra value can exhibit color differences exceeding $\Delta E = 5$ in the CIE CAM02-UCS color space, indicating significant perceptual discrepancies.

Through extensive testing, the study validated that the Color Fidelity Index (Rf) provides a more accurate and scientifically grounded measurement of color rendering compared to Ra. For the tested LED sources, the calculated Rf values ranged from 74 to 91, showing a 12-18% improvement in color fidelity compared to the corresponding Ra values. Additionally, the spectral analysis revealed that the inclusion of 99 test color samples in Rf calculations reduces statistical uncertainty by 15% compared to the traditional eight-sample Ra method.

These findings support the necessity of transitioning from Ra to Rf as the primary metric for evaluating LED color rendering. Future research should focus on refining the adaptation models within the CIE CAM02-UCS framework and investigating the impact of spectral power distribution modifications on color fidelity in complex lighting environments.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

REFERENCES

1. Commission Internationale de l'Éclairage (2015). IES method for evaluating light source color rendition. *Publication IES TM-30-15*. IES New York. https://webstore.ansi.org/preview-pages/IESNA/preview_IES+TM-30-15.pdf?srsltid=AfmBOoqUr6R_44pDg_t6s_K1-WU2x95Vx5WbRI5ryVQB86CvPBEDLpgv
2. Luo, M. R., & Li, C. (2013). CIECAM02 and its recent developments. *Advanced color image processing and analysis* (pp.19-58). Springer. https://doi.org/10.1007/978-1-4419-6190-7_2
3. Wei, M., Bao, W., & Huang, H. P. (2020). Consideration of light level in specifying light source color rendition. *Leukos*, 16(1), 55-65. <https://www.tandfonline.com/doi/full/10.1080/15502724.2018.1448992#abstract>
4. Atalar, F., Uzun, K., Gedikli, A., Yılmaz, A. E., & Uğur, M. (2020). A STUDY ON THE EFFECT OF LIGHT SOURCES ON THE COLOUR OF OBJECTS. *Light & Engineering*, 28(3), 47-52. https://www.researchgate.net/publication/343862584_A_Study_on_the_Effect_of_Light_Sources_on_the_Colour_of_Objects
5. Dimitrakis, A., Madias, E. N., & Kotsenos, A. (2022, December). An Examination of use of Alternative Reference Sources in Colour Rendering of Environmental Lighting Applications. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1123, No. 1, p. 012038). IOP Publishing. https://www.researchgate.net/publication/366602332_An_Examination_of_use_of_Alternative_Reference_Sources_in_Colour_Rendering_of_Environmental_Lighting_Applications
6. *Visible Light*. Science Mission Directorate. (n.d.). NASA SCIENCE. Retrieved June 7, 2021, from https://science.nasa.gov/ems/09_visiblelight
7. The Color of Light and its Effect on Objects, from <https://www.archinet.me/articles-page/the-color-of-light-and-its-effect-on-objects>
8. CIECAM02 Color, from <https://gramaz.io/d3-cam02/>
9. Mangkuto, R. A., & Soelami, F. N. (2022). The impact of correlated colour temperature variation from a tuneable LED lamp on colour sample appearance shift in CIELAB colour space. *Optik*, 267, 169707. https://www.researchgate.net/publication/362197732_The_impact_of_correlated_colour_temperature_variation_from_a_tuneable_LED_lamp_on_colour_sample_appearance_shift_in_CIELAB_colour_space
10. Bao, W., & Wei, M. (2020). Testing the performance of CIECAM02 from 100 to 3500 cd/m². *Color Research & Application*, 45(6), 992-1004. https://www.researchgate.net/publication/342419187_Testing_the_performance_of_CIECAM02_from_100_to_3500_cdm_2
11. Zhang, J., Smet, K. A., & Meuret, Y. (2019). Tuning color and saving energy with spatially variable laser illumination. *Optics Express*, 27(19), 27136-27150. <https://opg.optica.org/oe/fulltext.cfm?uri=oe-27-19-27136&id=418701>
12. Designing light from <https://designinglight.com/?p=954&#sthash.6p4UcjFh.dpbs>
13. Hu, X., Lian, Y., Liu, Z., Wei, X., Liu, F., Jin, Y., ... & Huang, M. (2019). Study of color rendering evaluation method of light sources for printing matter. *IEEE Access*, 8, 5526-5536. <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8946629>
14. Cinko, U. O., & Becerir, B. (2024). Computing characteristics of color difference formulas for regular coordinate changes in CIELAB color space. *Textile Research Journal*, 00405175241278025
15. Li, M., & Luo, M. R. (2024). Simple color appearance model (sCAM) based on simple uniform color space (sUCS). *Optics Express*, 32(3), 3100-3122. <https://opg.optica.org/oe/fulltext.cfm?uri=oe-32-3-3100&id=545619>
16. Royer MP. 2018. Comparing Measures of Gamut Area. *LEUKOS*, 15:1, 29-53, <https://doi.org/10.1080/15502724.2018.1500485>

Колірне передавання (Оптимізація передачі кольору світлодіодних джерел світла на основі сучасних колориметричних метрик і адаптивних моделей оцінки)

Леонід Назаренко, Богдан Олійниченко, Анастасія Колесник, Віталій Герасименко, Наталя Лукашова та Олег Кулаєнко.

Анотація. Точність сприйняття кольору за різних умов освітлення має вирішальне значення в оцінці якості освітлення. Традиційні показники передачі кольору, такі як загальний індекс передачі кольору (CRI або Ra), розроблений Міжнародною комісією з освітлення (CIE) у 1964 році, забезпечують середню міру вірності кольору в обмеженому наборі зразків кольорів, але не фіксують окремих колірних варіацій. Незважаючи на те, що ця метрика широко використовується, вона має обмеження у прогнозуванні точності кольорів, особливо для конкретних кольорів або додатків, де важлива точна передача кольорів (наприклад, у тонах шкіри, продуктах харчування чи предметах певного кольору). Північної Америки (IESNA) запропонувало Індекс вірності кольору (Rf), що включає 99 рівномірно розподілених зразків кольорів і уточнений колірний простір для кращого прогнозування візуального сприйняття кольорів. Саме тому сучасні підходи до оцінки колірної передачі дозволяють враховувати різноманітні типи джерел світла, включаючи світлодіодні, забезпечувати точність передавання, де кольори мають критичне значення та створювати стандарти для гармонізації освітлення у різних галузях. Розвиток цих метричних систем допомагає створювати якісніші джерела світла та підвищувати комфорт сприйняття кольорів людиною. У даній статті досліджується точність індексів передачі кольору, порівнюється ефективність показників Ra та Rf та аналізується їхнє застосування в різних джерелах освітлення, надаючи розуміння майбутнього стандарту передачі кольору.

Ключові слова: показник точності кольору, колірний простір, колірна метрика, сприйняття кольору, джерела світла.

NOTES ON CONTRIBUTORS

Leonid Nazarenko

Leonid.Nazarenko@kname.edu.ua

D.Sc., Professor

Department of Lighting and Light Sources

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

 <https://orcid.org/0000-0002-0875-0434>

 <https://www.webofscience.com/wos/author/rid/AFA-7765-2022/>

 <https://www.scopus.com/authid/detail.uri?authorId=57207900102>

Bohdan Oliinychenko

Bohdan.Oliinychenko@kname.edu.ua

Postgraduate Student

Department of Lighting and Light Sources

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

 <https://orcid.org/0009-0002-7713-1028>

Anastasiia Kolesnyk

Anastasia.Kolesnyk@kname.edu.ua

Ph.D., Senior Lecturer

Department of Lighting and Light Sources

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

 <https://orcid.org/0000-0001-7528-6937>

 <https://www.scopus.com/authid/detail.uri?authorId=57206858200>

Vitalii Herasymenko

Vitaliy.Gerasimenko@kname.edu.ua

Ph.D., Associate Professor

Department of Lighting and Light Sources

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

 <https://orcid.org/0000-0002-0390-289X>

 <https://www.webofscience.com/wos/author/record/E-8478-2019>

 <https://www.scopus.com/authid/detail.uri?authorId=57162828500>

Natalia Lukashova

Natalya.Lukashova@kname.edu.ua

Ph.D., Associate Professor

Department of Electrical Transport

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

 <https://orcid.org/0000-0002-5556-241X>

 <https://www.scopus.com/authid/detail.uri?authorId=57211553224>

Oleh Kulaienko

Oleh.Kulaienko@kname.edu.ua

Ph.D., Associate Professor

Department of Automation and Computer-Integrated Technologies

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

 <https://orcid.org/0000-0002-2915-3946>

 <https://www.scopus.com/authid/detail.uri?authorId=57219051260>