AALTO UNIVERSITY
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Department of Electronics
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Study of various metrics evaluating color quality of light sources

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Supervisor Professor Liisa Halonen

Instructor D. Sc. Pramod Bhusal

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Abstract text:

CIE (Commission Internationale del´Eclairage) color rendering index (CRI) is the only internationally recognized and widely used metric to assess color rendering abilities of light sources. Despite its simplicity, CIE CRI has many shortcomings. These include outdated color space and outdated chromatic adaptation formula.

CIE established technical committees several times to tackle the problems with CIE CRI. However, every committee was closed in five to ten years as they could not find a solution that every member would agree upon. One such committee formed by CIE in 2006 is CIE TC 1-69 (Color Rendition by White Light Sources). The aim of CIE TC 1-69 is to recommend new assessment procedures for assessing the color rendition properties of white-light source used for illumination. A wide variety of approaches have been proposed. Till now nine metrics have been submitted to CIE TC 1-69. Some of the proposed metrics address specific aspect of color rendition while other metrics try to intregate more than one aspects of color rendition. CIE is in the process of developing and recommending a new final metric.

This work provides walk-through of various metrics to evaluate color quality of light sources. Altogether fourteen different metrics are discussed. This work also discusses how the new metrics will solve the limitations of CIE CRI.

Keywords: Color quality, Color rendition, Color rendering index

Preface

This study was conducted at the Lighting Unit of Aalto University School of Electrical Engineering. It would not have been possible to write this thesis without the help and support of my colleagues, my family, and my friends.

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Espoo 23.02.2012 Rupak Raj Baniya

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List of Symbols and Abbreviations

Symbols

$\bar{x}(\lambda)$,$\bar{y}(\lambda)$, $\bar{z}(\lambda)$	Color matching functions of the CIE 1931 standard observer
$\phi_{\lambda}(\lambda)$	Color stimulus function of light
ΔE	Colour difference
ΔE_{UVW}	CIEUVW color difference
$\Delta E^{*}{}_{Lab}$	CIELAB color difference
$\Delta E^{*}{}_{Luv}$	CIELLUV color difference
$\Delta U^{*}, \Delta V^{*}, \Delta W^{*}$	Difference of CIEUVW coordinates between two points
$\Delta L^{*},\ \Delta a^{*}, \Delta b^{*}$	Difference of CIELAB coordinates between two points
$\Delta L^{*}, \Delta u^{*}, \Delta v^{*}$	Difference of CIELUV coordinates between two points
A	Achromatic response
A_w	Achromatic response for white
C	chroma
C^{*}_{ab}	CIELAB chroma
C^{*}_{uv}	CIELUV chroma
h	hue angle
h_{ab}	CIELAB hue angle
h_{uv}	CIELUV hue angle
H	Hue composition
J	Lightness
l	Length of the slope of cone
L_A	Luminance of the adapting field
L*, a*, b*	Coordinates of CIELAB color space
L*, u*, v*	Coordinates of CIELUV color space
M	Colorfulness
M_{CCT}	CCT factor
Q	Brightness
Q_a	General color quality scale
$Q_{a,rms}$	Rms average color quality scale
Q_p	Color preference scale
Q_f	Color fidelity scale
Q_g	Gamut area scale

r	Radius of base of the cone
R_a	General color rendering index
R_i	Special color rendering indices
R_f	Judd's flattery index
R_{hr}	Color Harmony Rendering Index
s	Saturation
S_a	Memory color rendering index
S_i	Region of four reference color sample under reference source
S_t	Region of four reference color sample under the test light source
s_{ab}	CIELAB saturation
s_{uv}	CIELUV saturation
u,v	Chromaticity coordinates of CIE 1960 chromaticity diagram
u', v'	Chromaticity coordinates of CIE 1976 chromaticity diagram
u_0 , v_0	u v coordinates of the reference white point
$u_n{}'$, $v_n{}'$	u' v' coordinates of reference white point
U*V*W*	Coordinates of CIEUVW color space
w'	perpendicular height of the cone
W*	lightness index
X_c	Distribution centre which represents the most likely location of memory color
x, y	Chromaticity coordinates of CIE x, y chromaticity diagram
XYZ	Tristimulus values of CIE XYZ trichromatic system
X_n, Y_n, Z_n	Tristimulus value of the specified white object color stimulus
X_w, Y_w, Z_w	Tristimulus value of the reference white under the test source
Y_b	Luminance factor of the background field

Abbreviations

CAT	Chromatic Adaptation Transform
CAT02	Chromatic Adaptation Transform 2002
CCRI	Categorical Color Rendering Index
CCT	Correlated Color Temperature
CDI	Color Discrimination Index
CH	Color Harmony
CHF	Color Harmony Formula

CHI	Color Harmony Index
CIE	Commission Internationale de L'eclairage (International Commision on Illumination)
CIECAM97s	CIE Color Appearance Model 1997 (simplified version)
CIECAM02	CIE Color Appearance Model 2002
CIE CRI	CIE Color Rendering Index
CIELAB	CIE 1976 (L*a*b*) color space
CIELUV	CIE 1976 (L*u*v*) color space
CIEUVW	CIE 1964 (U*V*W*) color space
CMF	Color Matching Function
CMCCAT97	Color Management Committee Chromatic Adaptation Transform 1997
CMCCAT2000	Color Management Committee Chromatic Adaption Transform 2000
CPI	Color Preference Index
CQS	Color Quality Scale
CRI	Color Rendering Index
CSA	Cone Surface Area
FCI	Feeling of Contrast Index
FI	Flattery index
GA	Gamut Area
GAI	Gamut Area index
HRI	Harmony Rendering Index
IPT	Image Processing Transform
LED	Light Emitting Diode
MCRI	Memory Color Rendering Index
NIST	National Institute of Standards and Technology
RCRI	Rank-order based Color Rendering Index
SPD	Spectral Power Distribution
TC	Technical Committee

1 Introduction

Light is electromagnetic radiation which can be detected by human eye and is responsible for the sense of sight. The visible portion of electromagnetic spectrum covers the wavelength range from approximately 380 nm to 780 nm which are associated with different colors. Light source is uniquely characterized by radiant power emitted by the source at each wavelength in the visible spectrum called spectral power distribution (SPD). The SPD contains all the basic physical data about the light and serves as the starting point for quantitative analysis of color.

Color of an object is not a physical property but rather a human perception enabled by light. Color of any objects depends on the type of light that illuminate the objects. When a red apple is illuminated by daylight it will absorb all other wavelengths and reflect red. The reflected red light is detected by photoreceptors cells in the retina of the eye. The color data (red light) from the retina is transmitted to the visual cortex in the brain through the optic nerve and hence apple is perceived as red. The components for perceiving color are the wavelengths emitted by the light source, the wavelengths reflected by the object, the surroundings in which we see the object, and the characteristics of the visual system [1].

Light source color quality includes different aspects of the observer's general evaluation about the color perception and judgment of the colored objects in a visual environment illuminated by light source. In current practice, chromaticity of light itself and color rendering performance of light source describe the color quality of light source. Various dimensions of perceived color rendition of light source such as color fidelity, visual clarity, color discrimination, color preference, color harmony, and color acceptability are recognized [2]. It is important to assess the color quality of light sources for varieties of reasons. The obvious reason of course is that consumers expect reasonable color quality for many applications. Indeed, history has shown poor color quality and undesirable light source chromaticity will cause consumers to reject new lighting technologies [3].

During the period when artificial illumination was not much developed, spectral power distribution and color temperature was used to describe how light source will affect the color of objects [4].

Color temperature is a method for describing the color characteristics of light source by comparing it to the color of a blackbody radiator. For example, if the color appearance of an incandescent lamp is similar to a blackbody radiator heated to about 3000K then it is said that the incandescent lamp has a color temperature of 3000K. To assign a color temperature to a light source, the chromaticity of light source must match with the chromaticity of blackbody radiator. If the chromaticity of the test source does not perfectly match with chromaticity of blackbody radiator then correlated color temperature (CCT) is used [5].

When the lighting industry was able to develop light sources with different spectral power distributions but equal correlated color temperature the problem of light source color rendering became important [6]. Lighting industry and users need color rendering metric to know how well the light source can render the color and to assess the equality as well as superiority among test light sources in term of color quality. The First CIE (Commission Internationale de L´eclairage) method for the evaluation of color rendering of light sources was based on the spectral band method developed in 1948 [7]. Spectral band method (SBM) is based on the idea of creating a spectrum identical to or very similar to a known good color rendering reference source such as incandescent lamp or daylight [6]. This method usually divides the spectrum of test source into bands and compares the spectral content of each band to the reference illuminant. Spectral band method motivates the lamp designer to create spectra similar to incandescent lamp or daylight resulting light sources with good color rendering but yield poor energy efficiency [7]. Similarly, to produce good color rendering, light source spectra do not need to be smooth and broad in the entire visual region [8].

Experts soon realized that color rendering method based on color difference between the test source and a reference source called test color sample method is better than spectral band method. Test color sample method is based on the principle of assessing the magnitude of the change in chromaticity produced when a colored sample is viewed first using a test lamp and then a reference lamp. After long investigation CIE recommended the procedure of measuring and specifying color rendering properties of light sources based on test color sample method called CIE Color Rendering Index (CRI) in 1965 [9]. CIE updated test color sample method in 1974 taking the chromatic adaptation shift into account and republished it in 1995 with minor editorial changes [6].

The CIE CRI is based on colorimetric techniques and was developed nearly 50 years ago. Both colorimetry and light source technology have advanced significantly after the introduction of CIE CRI. Currently there are better colorimetric methods than those used in CIE CRI. Also, there has been increasing evidence from psychophysical experiments that the CIE CRI correlates poorly with the visual appreciation of the light source particularly LED sources and tri-phosphor fluorescent lamps [1, 6, 7, 10, 11].

CIE realized the problems with CIE CRI and established technical committee several times to tackle the problems. However, every committee was closed in five to ten years as they could not find a solution that every member would agree upon [6]. CIE TC 1-33 was one such committee established in 1991 with the term of reference: "*Study indices for evaluation of color rendering properties of light sources based on a color appearance model. Prepare a technical report on a proposed method that will replace CIE publication 13.2, this model shall be consistent with all the official recommendations on colorimetry*" [12]. CIE TC 1-33 was unable to recommend a new color rendering index and closed down in 1999 with status report and closing remarks.

CIE formed another technical committee CIE TC 1-69 (Color Rendition by White light Sources) in 2006 with the aim: "*To investigate new methods for assessing the color rendition properties of white-light sources used for illumination, including solid-state light sources, with the goal of recommending new assessment procedures*" [13]. CIE TC 1-69 has been meeting since 2007 and has analysed the problems of the CIE CRI and conducted different visual experiments and researches. Research topics cover color memory for real objects, chromatic discrimination, attractiveness and naturalness of fruits and vegetables, estimations of color differences, rendering of human skin, color harmony. Seven new metrics were proposed during the Princeton meeting held in 2010 [14]. Proposed metrics were: Color quality scale (CQS), CRI-CAM02UCS, Rank-order based color rendering index (RCRI), Feeling of contrast index (FCI), Harmony rendering index (HRI), Memory CRI (MCRI), and Categorical color rendering index (CCRI). In addition to these seven metrics, two additional metrics CIE CRI + GAI (Gamut Area Index) and a Monte Carlo method of assessment were submitted to the CIE TC 1-69 after the Princeton meeting [15]. Till date nine metrics have been submitted to TC 1-69 but work is still underway to recommend a final metric that every member would agree upon [16].

1.1 Objectives of the Work

The overall aim of the work was to study various metrics evaluating color quality of light sources. The objective was also to find out the limitations of CIE CRI and compare the performance of each metric with CIE CRI and find out how the new metrics solve the limitations of CIE CRI.

2 Theoretical Background

This chapter describes the basic concepts and terminology in colorimetry. The descriptors of the color stimulus: tristimulus values, chromaticity co-ordinates, and chromaticity diagrams are described in section 2.1, 2.2, and 2.3 respectively. Sections 2.4, 2.5, and 2.6 describe various color spaces, chromatic adaptation and CIE color appearance models respectively.

2.1 Tristimulus Values

Tristimulus values of a color stimulus are the amounts of the three reference color stimuli, in a given trichromatic system, required to match the color of the stimulus considered [17]. They are the descriptors of the color stimulus. Tristimulus values in CIE-XYZ trichromatic system are defined by:

$$X = k\int_{380nm}^{780nm} \phi_\lambda(\lambda)\overline{x}(\lambda)d\lambda \quad \textbf{(1)}$$

$$Y = k\int_{380nm}^{780nm} \phi_\lambda(\lambda)\overline{y}(\lambda)d\lambda \quad \textbf{(2)}$$

$$Z = k\int_{380nm}^{780nm} \phi_\lambda(\lambda)\overline{z}(\lambda)d\lambda \quad \textbf{(3)}$$

Where,

X, Y, Z	are the tristimulus values in CIE-XYZ trichromatic system
$\phi_\lambda(\lambda)$	is the color stimulus function of the light seen by the observer or spectral distribution of light stimulus
$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$	are the color matching function (CMF) of the CIE 1931 standard observer
k	is a normalizing constant

2.2 CIE Chromaticity Coordinates

The chromaticity coordinates are the ratio of each of a set of three tristimulus values to their sum [17]. The chromaticity coordinates are mathematically defined using the foolowing equations:

$$x = \frac{X}{X+Y+Z} \quad \textbf{(4)}$$

$$y = \frac{Y}{X+Y+Z} \qquad \textbf{(5)}$$

$$z = \frac{Z}{X+Y+Z} \qquad \textbf{(6)}$$

Where,

x, y, z	are the chromaticity coordinates such that x + y+ z=1
X, Y, Z	are the tristimulus value

2.3 CIE Chromaticity Diagrams

The plot of x, y chromaticity coordinates in a rectangle coordinate system gives the CIE x, y chromaticity diagram [6]. This diagram is also referred as the CIE 1931 chromaticity diagram.

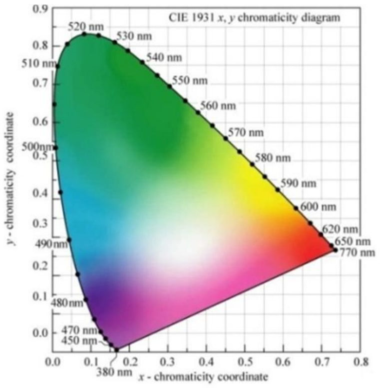


Figure 1. CIE 1931 chromaticity diagram **[18]**.

In 1942, David MacAdam showed color difference in elliptical form in different area of the CIE 1931 chromaticity diagram as shown in Figure 2. These ellipses are known as MacAdam ellipses. It can be seen from Figure 2 that the chromaticity difference that corresponds to a just noticeable color difference will be different in different area of CIE 1931 chromaticity diagram [19].

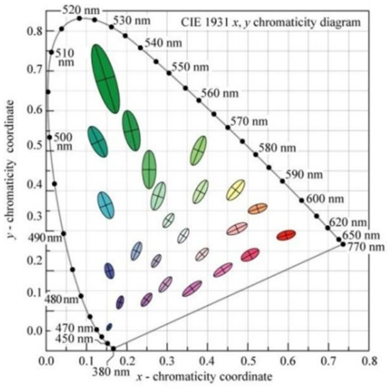


Figure 2. MacAdam Ellipses in CIE 1931 chromaticity diagram **[18]**.

MacAdam ellipses show that the CIE 1931 chromaticity diagram is not uniform. To make chromaticity diagram more uniform CIE defined an improved diagram in 1960 known as CIE 1960 (u, v) chromaticity diagram. The coordinates u and v in this diagram are defined as:

$$u = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3} \qquad \textbf{(7)}$$

$$v = \frac{6Y}{X+15Y+3Z} = \frac{6y}{-2x+12y+3} \qquad \textbf{(8)}$$

Where,

X, Y, Z	are the tristimulus value
x, y	are chromaticity coordinates of CIE 1931 chromaticity diagram

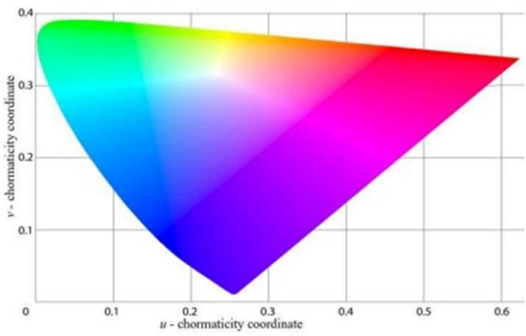


Figure 3. CIE 1960 (u, v) chromaticity diagram **[18]**.

In 1976, CIE recommended further improved diagram known as CIE 1976 (u´, v´) uniform chromaticity diagram as shown in Figure 4. In this diagram, the distance between points is approximately proportional to the perceived color difference [20].

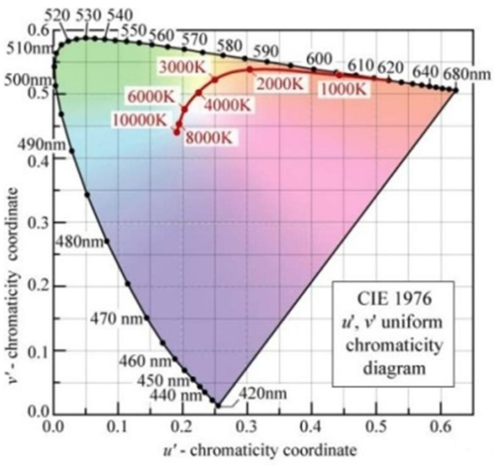


Figure 4. CIE 1976 (u', v’) chromaticity diagram **[18]**.

The chromaticity coordinates u´ and v´ of CIE 1976 chromaticity diagram are given as:

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3} \quad \textbf{(9)}$$

$$v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3} \quad \textbf{(10)}$$

Where,

X, Y, Z	are the tristimulus values
x, y	are chromaticity coordinates of CIE 1931 chromaticity diagram

The MacAdam's ellipses in CIE 1976 chromaticity diagram (Figure 5) illustrate that the color difference has decreased in CIE 1976 chromaticity diagram than in CIE 1931 chromaticity diagaram. Although, MacAdam's ellipses are not completely converted to circle, CIE 1976 chromaticity diagram is more uniform than the CIE 1931 chromaticity diagram.

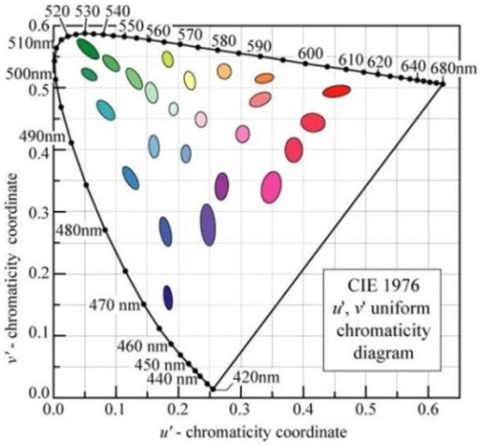


Figure 5. MacAdam's ellipses transformed to CIE 1976 chromaticity diagram **[18]**.

2.4 Color Spaces

A color space is a mathematical representation of visual perception. It is a notation, by which color can be specified, created, and visualized. Color space extends tristimulus colorimetry to three-dimensional spaces with dimensions that approximately correlate with perceived color attributes (hue, chroma, and lightness) of stimulus [21]. The main aim of the development of color space was to provide uniform practices for the measurement of color differences.

2.4.1 CIE color spaces

2.4.1.1 CIEUVW color space

The CIEUVW color space is based on CIE 1960 uniform chromaticity diagram with the co-ordinates U*, V*, W* [22]. The co-ordinates of CIEUVW color space are defined by:

$$U^* = 13W^*(u - u_0) \quad \textbf{(11)}$$

$$V^* = 13W^*(v - v_0) \quad \textbf{(12)}$$

$$W^* = 25Y^{\frac{1}{3}} - 17 \quad \textbf{(13)}$$

Where,

U^*, V^*, W^*	are the co-ordinates of CIEUVW color space
u_0, v_0	are the u, v coordinates of the white point and are placed in the origin of the U*V*W* system

The lightness index W* is defined as a function of the luminance factor Y of the given color [22]. The color difference in CIEUVW color space is calculated by:

$$\Delta E_{UVW} = \sqrt{(\Delta U^*)^2 + (\Delta V^*)^2 + (\Delta W^*)^2} \quad \textbf{(14)}$$

Where,

ΔE_{UVW}	is the color difference in CIEUVW color space
$\Delta U^*, \Delta V^*, \Delta W^*$	are the differences of CIEUVW coordinates between two points

Although this color space is now outdated, CIE CRI calculation are still performed in this color space [6].

2.4.1.2 CIELAB color space

The CIELAB color space which is based directly on the tristimulus values in CIE-XYZ trichromatic system is defined by the equations 15 to 19 for tristimulus values normalizes to the white that are greater than 0.008856 [21].

$$L^* = 116(\frac{Y}{Y_n})^{\frac{1}{3}} - 16 \quad \textbf{(15)}$$

$$a^* = 500[(\frac{X}{X_n})^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}] \quad \textbf{(16)}$$

$$b^* = 200[(\frac{Y}{Y_n})^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}] \quad \textbf{(17)}$$

$$C^*_{ab} = \sqrt{(a^{*2} + b^{*2})} \quad \textbf{(18)}$$

$$h_{ab} = \arctan(b^*/a^*) \quad \textbf{(19)}$$

Where,

L^*, a^*, b^*	are the coordinates of CIELAB color space
X, Y, Z	are the tristimulus values of the stimulus
X_n, Y_n, Z_n	are the tristimulus value of the reference white
C^*_{ab}	Chroma
h_{ab}	hue angle

L* is the luminance of the stimulus which represents the lightness. The maximum value of L* is 100 representing white and minimum value is zero representing black. The axis a* represents red to green with positive a* indicate redness and negative a* indicate greenness. Similarly, b* axis represents yellow to blue with positive b* indicate yellowness and negative b* indicate blueness. Axes a* and b* have no specific numerical limits. The color difference in CIELAB color space is calculated by:

$$\Delta E^*_{Lab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{\frac{1}{2}} \quad \textbf{(20)}$$

Where,

ΔE^*_{Lab}	is the color difference in CIELAB color space
$\Delta L^*, \Delta a^*, \Delta b^*$	are the differences of CIELAB coordinates between two points

Figure 6 shows the structure of CIELAB color space. It is organized in cube form.

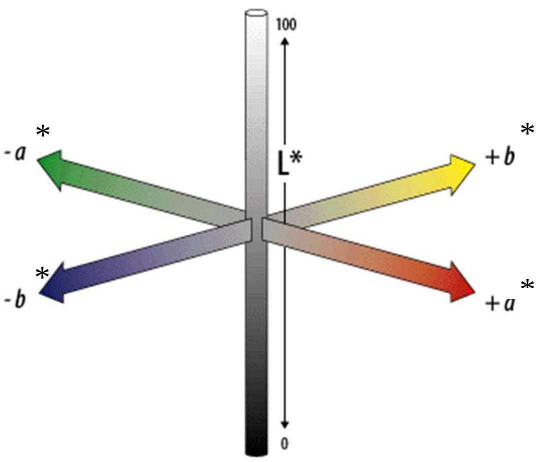


Figure 6. CIELAB Color Space **[23]**.

2.4.1.3 CIELUV color space

The CIELUV color space is defined by equations 21 to 26 for tristimulus values normalized to the white that are greater than 0.008856 [21]. The L* function of the CIELUV color space is same as L*of the CIELAB color space.

$$L^* = 116(\frac{Y}{Y_n})^{\frac{1}{3}} - 16 \quad \textbf{(21)}$$

$$u^* = 13L^*(u' - u_n') \quad \textbf{(22)}$$

$$v^* = 13L^*(v' - v_n') \quad \textbf{(23)}$$

$$s_{uv} = 13[(u' - u'_n)^2 + (v' - v'_n)^2]^{\frac{1}{2}} \quad \textbf{(24)}$$

$$C^*_{uv} = (u^{*^2} + v^{*^2})^{\frac{1}{2}} = L^*.s_{uv} \quad \textbf{(25)}$$

$$h_{uv} = \arctan({}^{v^*}/_{u^*}) \quad \textbf{(26)}$$

Where,

L^*, u^*, v^*	are the coordinates of CIELUV color space
u', v'	Chromaticity coordinates of the stimulus
u_n', v_n'	Chromaticity coordinates of reference white
s_{uv}	Saturation
C^*_{uv}	Chroma
h_{uv}	hue angle

The color difference in CIELUV between two color stimuli is calculated by:

$$\Delta E^*_{Luv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{\frac{1}{2}} \quad \textbf{(27)}$$

Where,

ΔE^*_{Luv}	is the color difference in CIELUV color space
$\Delta L^*, \Delta u^*, \Delta v^*$	are the differences of CIELUV coordinates between two points

2.4.2 IPT color space

The IPT color space accurately predicts hue without detrimentally affecting other color appearance attributes [24]. IPT is short form for Image Processing Transform and useful for transformations such as gamut mapping. In this color space, I co-ordinate represents the lightness direction, P co-ordinates represents the red-green dimension and T co-ordinate the yellow-blue dimension. The range of lightness axis (I) is from 0 to 1 and the range of the other two axes (P &T) is from -1 to 1. This model is readily invertible [24].

The model in this color space consists of a (3×3) matrix, followed by nonlinearity and another (3×3) matrix as shown in equation 28. The model assumes input data is in CIEXYZ for the 1931 2°observer with a CIE standard illuminant D65.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0.0 & 0.0 & 0.9184 \end{bmatrix} \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix}$$

$$L' = L^{0.43} \; ; L \geq 0$$

$$L' = -(-L)^{0.43} \; ; L < 0 \qquad \textbf{(28)}$$

$$M' = M^{0.43} \; ; M \geq 0$$

$$M' = -(-M)^{0.43} \; ; M < 0$$

$$S' = S^{0.43} \; ; S \geq 0$$

$$S' = -(-S)^{0.43} \; ; S < 0$$

$$\begin{bmatrix} I \\ P \\ T \end{bmatrix} = \begin{bmatrix} 0.4000 & 0.4000 & 0.2000 \\ 4.4550 & -4.8510 & 0.3960 \\ 0.8056 & 0.3572 & -1.1628 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

Where,

L, M, S	are cone type
$X_{D65}, Y_{D65}, Z_{D65}$	are tristimulus value for CIE standard illuminanat D65
I, P, T	are co-ordinates of IPT color space

The first (3×3) matrix converts the tristimulus data into a description that is very near the Hunt-Pointer-Estevez cone primaries normalized to D65 [24]. The compression factor (0.43) is nearly identical to that of the RLAB color space for average surround conditions.

2.5 Chromatic Adaptation

Chromatic adaptation refers to the human visual system's capability to adjust to widely varying colors of illumination in order to approximately preserve the appearance of object colors [21]. In other words, chromatic adaptation is the ability of the human visual system to discount the color of the illumination and to approximately preserve the appearance of an object [25]. For example, a white piece of paper when viewed under sky light and tungsten light appears to be white although the measured tristimulus values are quite different under these illuminants. This is because our eye have adapted under each condition to discount the illuminant difference. However, digital imaging systems like digital camera and scanner do not have the ability to adapt to the light source. Therefore, to achieve the same appearance of original scene under different display conditions, tristimulus value of the captured image have to be transformed to take into account the light source of the display viewing condition. Such transformations are called chromatic adaption transforms (CATs).

There are several chromatic adaptation transforms (von Kries CAT, Bradford CAT, sharp CAT, CMCCAT97, CMCCAT2000 etc.) developed to accurately predict color appearance across a change in illumination. Most of them are based on the von Kries model [25]. Von Kries model assumes that, although the responses of the three cone type (RGB) are affected differently by chromatic adaption, the relative sensitivities of each of the three cone mechanism remain unchanged [26]. The von Kries model states that the trichromatic responses of corresponding surface measurements under two illuminants are simple scaling apart. For example, if R_c, G_c, B_c and R, G, B denote the cone responses of the same observer, but viewed under test and reference illuminants respectively then the von Kries model predicts that

$$\begin{aligned} R_c &= \alpha R \\ G_c &= \beta G \\ B_c &= \gamma B. \end{aligned} \qquad \textbf{(29)}$$

Where α, β, and γ are the von Kries coefficients.

2.6 Color Appearance Model

Color appearance model is abstract mathematical model which describes the way colors can be represented and make various descriptors of color straightforward. It provides mathematical formulae to transform physical measurements of the stimulus and viewing environment into correlates of perceptual attributes of color. Color appearance model predicts the change in color appearance under different viewing conditions such as illuminant, luminance level, background color and surround. CIE Technical Committee 1-34 (TC1-34) describes color appearance model as *"A color appearance model is any model that includes predictors of at least the relative color-appearance attributes of lightness, chroma and hue"* [21].

2.6.1 CIE color appearance models

CIECAM97s and CIECAM02 are two color appearance models recommended by the CIE [6]. Figure 7 shows the input and output parameters of the CIE color appearance model.

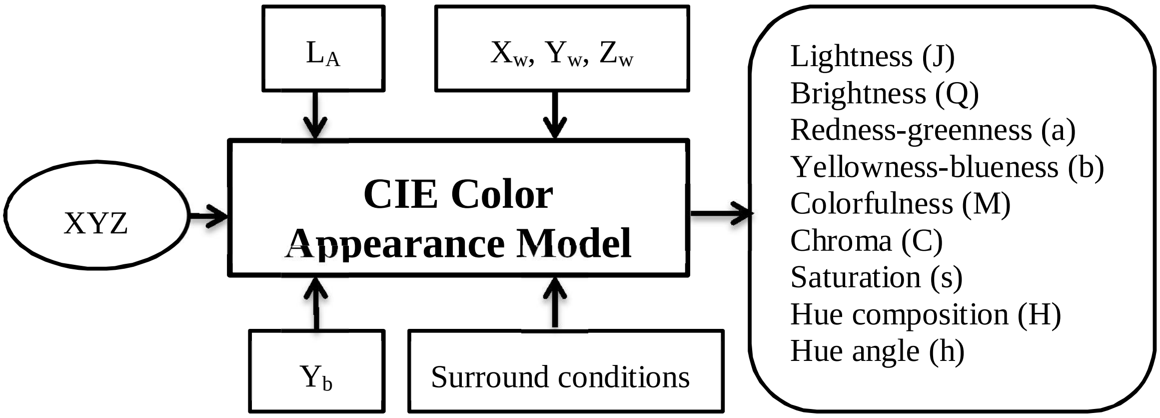


Figure 7. A schematic diagram of a CIE color appearance model **[6]**.

The inputs to the model are:

1. The CIE XYZ values of the stimulus.
2. Viewing parameters X_w, Y_w, Z_w , which are the tristimulus of the reference white under the test illuminant.
3. L_A , which specifies the luminance of the adapting field.
4. Y_b, which defines the luminance factor of the background field.
5. Surround conditions: average, dim and dark.

There are many output parameters from the model which are:

1. Lightness (J)
2. Brightness (Q)
3. Redness-greenness (a)
4. Yellowness-blueness (b)
5. Colorfulness (M)
6. Chroma (C)
7. Saturation (s)
8. Hue composition (H)
9. Hue angle (h)

These output parameters can be combined to form various spaces according to the different application.

2.6.1.1 CIECAM97s color appearance model

During the CIE expert symposium on color standards for image technology in 1996, a decision was made to develop a "CIE color appearance model" based on the 12 principles outlined by Hunt [6]. These principles served as the guiding rules in the formulation of CIECAM97s. CIE TC 1-34 was assigned to develop CIE color appearance model which should combine best features of existing color appearance models and adequately predict all the available data sets [6]. Four color appearance models (Hunt, Nayatani, RLAB and LLAB) were considered to be most advanced at that time. These four alternatives were considered at the May 1997 meeting of CIE TC1-34 in Kyoto and an agreement was reached to adopt a simplified color appearance model named CIECAM97s [27]. However, complexity and problems with CIECAM97s makes barrier for its widespread adoption and use [28].

2.6.1.2 CIECAM02 color appearance model

CIECAM02 color appearance model is improvement of CIECAM97s color appearance model. It gives better predictions of color appearance data, improves accuracy performance, and simplifies the structure of CIECAM97s color appearance model [29]. Input data for the CIECAM02 include the tristimulus values of the test stimulus (XYZ) and the white point ($X_{w,}$ $Y_{w\,,}Z_{w}$), the adapting luminance (normally taken to be 20% of the luminance of a white object in a scene) L_A, the relative luminance of the surround (dark, dim, average), and a decision on whether discounting the illuminant is taking place. CIECAT02 chromatic adaptation transform is used in CIECAM02 which results in a simple model and allows for a simple analytical inversion of CIECAM02 [30]. Redness-greenness components (a), yellowness-blueness component (b), and hue angle (h) in CIECAM02 are calculated using the following equations:

$$a = R'_a - 12\,{}^{G'_a}/_{11} + {}^{B'_a}/_{11} \quad \textbf{(30)}$$

$$b = ({}^{1}/_{9})(R'_a + G'_a - 2B'_a) \quad \textbf{(31)}$$

$$h = \arctan({}^{b}/_{a}) \quad \textbf{(32)}$$

Where,

R'_a, G'_a, B'_a	are post-adaption cone responses
a	is redness-greenness component
b	is yellowness-blueness component
h	is hue angle (between 0 and 360 degree)

The hue composition (H) is calculated by using equation 33 and Table 1.

$$H = H_i + \frac{100(h-h_i)/e_i}{(h-h_i)/e_i + (h_{i+1}-h)/(e_{i+1})} \quad \textbf{(33)}$$

Table 1. Data for conversion from hue angle to hue quadrature **[21]**.

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0	100	200	300	400

Achromatic response (A) is calculated as:

$$A = [2R'_a + G'_a + (1/20)B'_a - 0.305]N_{bb} \quad \textbf{(34)}$$

Where,

A is achromatic response

R'_a, G'_a, B'_a are post-adaption cone responses

N_{bb} is background brightness induction factor

The correlate of lightness is calculated as:

$$J = 100\left(\frac{A}{A_W}\right)^{cz} \quad \textbf{(35)}$$

Where,

J is lightness

A is achromatic response

A_W is achromatic response for white

c is surround factor

z is base exponent

The correlate of brightness is calculated as:

$$Q = (4/c)\sqrt{J/100}(A_w + 4).F_L^{0.25} \quad \textbf{(36)}$$

Where,

Q is brightness

c	is surround factor
J	is lightness
A_w	is achromatic response for white
F_L	is luminance level adaption factor

Similarly, the correlate of chroma is calculated as:

$$C = t^{0.9}(\frac{J}{100})^{0.5}(1.64 - 0.29^{n})^{0.73} \quad \textbf{(37)}$$

Where,

C	is chroma
t	is temporary magnitude
J	is lightness
n	is background induction factor

The temporary magnitude t is calculated by using equation:

$$t = \frac{(50\,000)/13)N_c N_{cb} e_t \sqrt{a^2+b^2}}{R'_a + G'_a + (\frac{21}{20})B'_a} \quad \textbf{(38)}$$

Where,

t	is temporary magnitude
N_c	is a chromatic induction factor for surround
N_{cb}	is a chromatic induction factor for background
R'_a, G'_a, B'_a	are post-adaption cone responses
e_t	is eccentricity factor

The eccentricity factor e_t is calculated as:

$$e_t = {}^{1}/_{4}\,[\cos\left(h\frac{\pi}{180} + 2\right) + 3.8] \quad \textbf{(39)}$$

Where,

e_t	is eccentricity factor
h	is hue angle

The correlate of colorfulness is calculated as:

$$M = C.F_L^{0.25} \quad \textbf{(40)}$$

Where,

M	is colorfulness
C	is chroma
F_L	is luminance level adaption factor

And, the correlate of saturation is calculated as:

$$s = 100(\frac{M}{Q})^{0.5} \quad \textbf{(41)}$$

Where,

s	is saturation
M	is colorfulness
Q	is brightness

2.6.1.2.1 CIECAM02 based color spaces

CIECAM02 includes three color attributes chroma (C), colorfulness (M), and saturation (s). These attributes together with lightness (J) and hue angle (h) form three color spaces (a) J , a_c , b_c (b) J , a_M, b_M *and* (c) J , a_s , b_s .

Where,

$$a_c = C.\cos(h) \qquad a_M = M.\cos(h) \qquad a_s = s.\cos(h)$$

$$\textbf{(42)}$$

$$b_c = C.\sin(h) \qquad b_M = M.\sin(h) \qquad b_s = s.\sin(h)$$

When analysed using large and small color difference data sets, color space derived using J, a_M , b_M gave the most uniform result [6]. To fit all available data sets, various attempts were made to modify J, a_M , b_M version of CIECAM02 and simple equation (43) was developed that adequately fitted all available data [6].

$$J' = \frac{(1+100c_1).J}{1+c_1.J}$$

$$\textbf{(43)}$$

$$M' = \left(\frac{1}{c_2}\right).\ln(1 + c_2.M)$$

The corresponding color space is J', a'_M, b'_M.

Where,

$$a'_M = M'.\cos(h) \text{ , } and \quad b'_M = M'.sin(h)$$

The color difference between two samples in J', a'_M, b'_M color space is calculated as:

$$\Delta E' = \sqrt{(\Delta J'/K_L)^2 + \Delta a'_M{}^2 + \Delta b'_M{}^2} \tag{44}$$

Where,

$\Delta J'$, $\Delta a'_M$, $\Delta b'_M$ are the differences of J', a'_M, b'_M between the standard and sample in pair and K_L is the lightness parameter. Three color spaces CAM02-LCD, CAM02-SCD, and CAM02-UCS were developed for large, small and combined large and small color differences respectively [6].

3 The Official Method of Color Rendering Evaluation

This chapter gives general overview of the current CIE color rendering index (CRI). Limitations and shortcomings with CIE CRI are discussed in section 3.2.

3.1 CIE Color Rendering Index

The CIE has defined color rendering as: *"Effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant"* [17].

The CIE color rendering index (CRI) is the only internationally accepted and widely used metric for assessing the color-rendering performance of light sources. CIE recommended the color rendering index to evaluate color rendering performance of light source in 1965 [9]. The color rendering index is a measure of the degree to which the psychophysical color of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation [17]. This metric is based on chromaticity shifts of samples illuminated by test and reference light sources. A workflow for calculating the CIE CRI is given in the Figure 8.

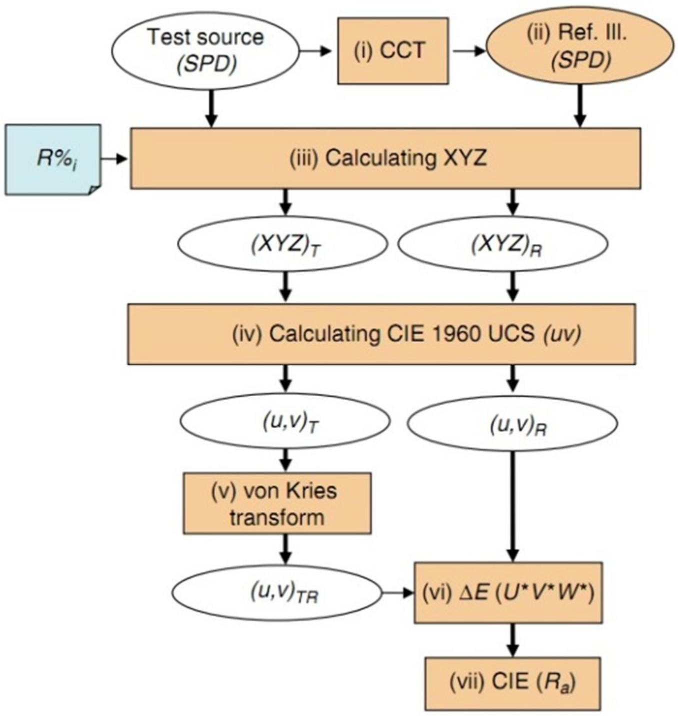


Figure 8. Workflow to calculate CIE CRI **[1]**.

A step-by-step procedure for calculating CIE CRI is given below:

Step 1: Calculation of test source CCT

Calculate the CIE 1931 chromaticity coordinates from the SPD of the test source and then obtain the CCT of test source from the chromaticity coordinates.

Step 2: Selection of reference illuminant

Depending upon the CCT of test source select the reference illuminant. CIE specified that the reference illuminant for test source with correlated color temperature (CCT) below 5000K should be selected from the pool of black body radiators and above 5000K should be selected from the phase of daylight [6].

Step 3: Calculation of tristimulus value

Calculate the XYZ tristimulus values for each test color samples under the test and reference illuminants. Test color samples used to calculate CIE CRI are shown in Table 2. Eight of the 14 test color samples were chosen from the Munsell color order system. These color samples cover the hue circle with moderate chroma and are approximately equal in lightness. The other six test color samples represent four higher chroma primary color (R, Y, G, and B), human complexion, and leaf green. These color samples were added to this method to indicate the color rendering properties of a test light source under extreme conditions

Table 2. CIE test color samples **[9]**.

No.	Approximate Munsell notation	Colour appearance under daylight	
1	7,5 R 6/4	Light greyish red	
2	5 Y 6/4	Dark greyish yellow	
3	5 GY 6/8	Strong yellow green	
4	2.5 G 6/6	Moderate yellowish green	
5	10 BG 6/4	Light bluish green	
6	5 PB 6/8	Light blue	
7	2.5 P 6/8	Light violet	
8	10 P 6/8	Light reddish purple	
9	4.5 R 4/13	Strong red	
10	5 Y 8/10	Strong Yellow	
11	4.5 G 5/8	Strong green	
12	3 PB 3/11	Strong blue	
13	5 YR 8/4	Light yellowish pink (human complexion)	
14	5 GY 4/4	Moderate olive green (leaf green)	

Step 4: Transformation of tristimulus value into CIE 1960 (u, v) chromaticity co-ordinates

Transform XYZ tristimulus values obtained in Step 3 into the CIE 1960 (u, v) chromaticity co-ordinates under the test and reference illuminants using the equations:

$$u = \frac{4X}{X+15Y+3Z}$$
$$v = \frac{6Y}{X+15Y+3Z} \quad \textbf{(45)}$$

Step 5: Transformation of the CIE 1960 (u, v) chromaticity co-ordinates value under the test source to those under the reference illuminants

Transform the CIE 1960 (u, v) chromaticity co-ordinates values under the test source to those under the reference illuminants using the von Kries chromatic adaptation transform given by equation 46. This transformation account for the adaptive color shift due to the different state of chromatic adaption under test lamp (k) and under reference illuminant (r).

$$u_{k,i} = \frac{10.872+0.404\frac{c_r}{c_k}c_{k,i}-4\frac{d_r}{d_k}d_{k,i}}{16.518+1.481\frac{c_r}{c_k}c_{k,i}-4\frac{d_r}{d_k}d_{k,i}}$$
$$v_{k,i} = \frac{5.520}{16.518+1.481\frac{c_r}{c_k}c_{k,i}-4\frac{d_r}{d_k}d_{k,i}} \quad \textbf{(46)}$$

Where functions c and d are calculated for the reference illuminant (c_r, d_r), for the test illuminant (c_k, d_k), and for the test color ($c_{k,i}, d_{k,i}$) using:

$$c = \frac{1}{v}(4 - u - 10v)$$
$$d = \frac{1}{v}(1.708v + 0.404 - 1.481u) \quad \textbf{(47)}$$

Step 6: Calculation of resultant color shift

The u, v chromaticities thus obtained in Steps 4 and 5 are transformed into CIE 1964 uniform color space (CIEUVW) co-ordinates for each test color under the reference and test illuminants using:

$$U^*_{r,i} = 13W^*_{r,i}(u_{r,i} - u_0) \qquad U^*_{k,i} = 13W^*_{k,i}(u_{k,i} - u_0)$$
$$V^*_{r,i} = 13W^*_{r,i}(v_{r,i} - v_0) \qquad V^*_{k,i} = 13W^*_{k,i}(v_{k,i} - v_0) \quad \textbf{(48)}$$
$$W^*_{r,i} = 25(Y_{r,i})^{\frac{1}{3}} - 17 \qquad W^*_{k,i} = 25(Y_{k,i})^{\frac{1}{3}} - 17$$

Subscripts r and k refer to the reference and test illuminants respectively. The values $Y_{r,i}$ and $Y_{k,i}$ must be normalized so that $Y_r = Y_k = 100$. The resultant color shift is calculated using CIE 1964 color difference formula given by:

$$\Delta E_i = \sqrt{(U^*{}_{r,i} - U^*{}_{k,i})^2 + (V^*{}_{r,i} - V^*{}_{k,i})^2 + (W^*{}_{r,i} - W^*{}_{k,i})^2} \qquad \textbf{(49)}$$

Where,

ΔE_i	is the color difference between the color coordinates determined for the same test color sample illuminated by the test and reference illuminant
i	refers to the test sample number

Step 7: Calculation of CIE color rendering indices

a) Special color rendering indices

The special color rendering indices R_i for each test color sample is calculated by:

$$R_i = 100 - 4.6\Delta E_i \qquad \textbf{(50)}$$

Where,

R_i	is special color rendering indices
ΔE_i	is color difference of test color samples under test source and reference illuminant

The scaling factor of 4.6 is derived so that the CIE CRI value of a warm white fluorescent lamp is 51 [31].

b) General color rendering index

The CIE general color rendering index (CIE CRI), is the arithmetical mean of the eight special color rendering indices (R_i) of the CIE test color samples 1 to 8. It is calculated by:

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i \qquad \textbf{(51)}$$

Where,

R_a	is general color rendering index (CIE CRI)
R_i	is special color rendering indices of each color samples

The CIE CRI for a CIE daylight illuminant is set at 100, which is the maximum value of the color rendering index [1]. It is assumed that higher the value of CIE CRI better the light source can render the color.

3.2 Shortcomings and Problems of CIE CRI

The CIE method of measuring and specifying color rendering properties of light sources (CIE CRI) has many deficiencies and limitations. These deficiencies and limitation are explained below.

CIE test sample method requires a reference illuminant and selection of reference illuminant has profound influence in the calculation result [32]. The only criterion to select reference illuminant is CCT of test source. Reference illuminant is selected from the pool of black-body radiators if CCT of test source is below 5000K, and from the phases of daylight if CCT of test source is above 5000K. This means there can be infinite numbers of reference illuminant which lead to the confusion. Matching the CCT of the reference light source to that of test light source is another problem. CIE CRI specifies that the CCT of the reference light source be matched to that of the test source, which assumes complete chromatic adaptaion to any light source CCT. However, this assumption fails at extreme CCT. For example, a 2000K (very reddish) blackbody source and a daylight spectrum of 20,000K (very bluish) both achieves CIE CRI of 100 but the colors of objects illuminated by these sources will appear noticeably distorted [33].

The maximum value of the index is assigned to the reference illuminant which means no light source can render color better than reference source. It limits the innovation of new light sources and motivates lamp manufactures to produce lamps that render object similarly to how they are rendered under daylight or blackbody radiation.

The CIE CRI uses the CIE U*V*W* color space for all calculation. The CIE U*V*W* color space is visually non-uniform, inadequate, and outdated. CIE recommends CIELAB and CIELUV color space for calculating object color differences [33]. The von Kries chromatic adaption transform used in CIE CRI is also considered obsolete, inadequate, and is not applicable for large chromatic difference condition. There are some new chromatic transform like CMCCAT2000, CIECAT02 which perform better than von Kries chromatic adaption transform and provide results more consistent with the human vision [34].

The eight test color samples used in the calculation of CIE CRI have medium lightness and medium saturation. None of them are highly saturated and are available anymore in their original form [34, 35].

These color samples are less relevant to environment rich in saturated colors and can be problematic especially for RGB white LEDs with strong peaks and pronounced valleys in their spectra [33]. It is possible for a light source to render well on non-saturated sample while render poorly on saturated one.

The CIE CRI penalizes light sources for hue, chromatic saturation, and lightness shifts of the test color samples between reference illuminant and test source. However, people sometimes prefer object color to appear different and more saturated than their appearance under reference illuminants. For example skin colors are preferred to appear redder and more saturated than true color under reference illuminants [36]. Green leaves and grass are preferred to appear yellow and slightly more saturated than prefect fidelity [37]. Increases in saturation also give better visual clarity and enhance perceived brightness [38].

For some lamps like low-pressure sodium CIE CRI is negative which is difficult to interpret [39]. Finally, in the CIE CRI, the eight special color rendering indices are combined by a simple averaging to obtain general color rendering index. This makes possible for a lamp to score high CIE CRI even when it renders one or two colors very poorly. This situation is even more likely with SPDs having narrowband peaks [40].

4 Various Metrics for Evaluating Color Characteristics of Light Sources

This chapter discuss the various alternative metrics proposed for assessing color characteristics of light sources. Altogether 14 different metrics are discussed.

4.1 Color Quality Scale (CQS)

Color quality scale (CQS) was developed in National Institute of Standard and Technology (NIST) with the aim of solving the shortcomings of CIE color rendering index. Unlike the CIE CRI, which only considers color rendering or color fidelity CQS integrates several dimensions of color quality including color rendering, chromatic discrimination and observer preferences [33].

The CQS is a test-sample method like the CIE CRI. That is, color differences (in a uniform object color space) are calculated for a predetermined set of reflective samples when illuminated by the test source and reference illuminant. Reference illuminant is selected same as in CIE CRI. None of the eight samples used in the calculation of CIE CRI are highly saturated, but the fifteen Munsell color samples (Table 3) used in the CQS have high chroma and span the entire hue circle in approximately even spacing.

Table 3. Color samples used in CQS with their Munsell notation (hue value/chroma) **[34]**.

No.	Sample	Approximate Munsell Notation
1		7.5 P 4/10
2		10 PB 4/10
3		5 PB 4/12
4		7.5 B 5/10
5		10 BG 6/8
6		2.5 BG 6/10
7		2.5 G 6/12
8		7.5 GY 7/10
9		2.5 GY 8/10
10		5 Y 8.5 /12
11		10 YR 7/12
12		5 YR 7/12
13		10 R 6/12
14		5 R 4/14
15		7.5 RP 4/12

In the CIE CRI, the CCT of the reference source is matched to that of the test source which assumes complete chromatic adaptation to any light source CCT [34]. Because of this, the CIE CRI score can be perfect (R_a = 100) for reference illuminants of any CCT. However, actual color rendering is degraded at extreme CCTs. The CQS addresses this problem using CCT factor which penalizes source with extreme CCTs [34].

The uniform object color space (CIE 1964 U*V*W*) used in the calculation of CIE CRI is outdated, and is very non-uniform. In the CQS, the U*V*W* color space has been replaced by CIELAB, which is currently recommended by CIE and is widely used in many applications [41]. The Von Kries chromatic adaptation transform used in CIE CRI is considered to be incomplete and outdated. CQS uses CMCCAT2000 which is more updated and accurate chromatic transform and has shown to provide results more consistent with the human vision [34].

Another important factor considered in the calculation of CQS is the saturation factor. CIE CRI being a purely fidelity metric penalizes all shifts in perceived object hue and saturation. However, increase in chroma as long as they are not excessive, yields better visual clarity and enhance perceived brightness which is generally preferred [42]. In the CQS, with the implementation of the saturation factor a test source that increases the object chroma is not penalized, but is also not rewarded. Figure 9 shows the effect of saturation factor illustrated in CIELAB color space [33].

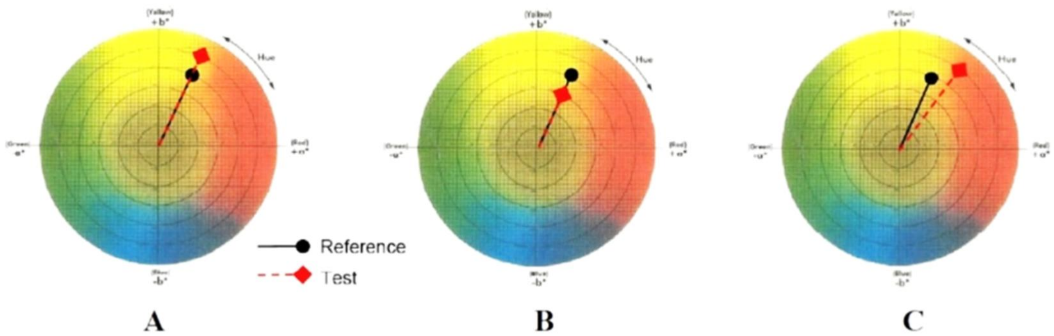


Figure 9. Effect of the saturation factor illustrated in CIELAB color space **[41]**. (A) When the chroma increases under the test illuminant (with no change in hue), there is no change in score. (B) When the chroma decreases under the test illuminant, the score is decreased. (C) When the chroma increases and hue shifts, the score is decreased for the hue shift but not decreased for the increase in chroma.

In this way with the introduction of saturation factor, CQS takes the color preference and color discrimination into account.

In the calculation of the CIE CRI, the eight special color rendering indices are combined by a simple averaging to obtain the general color rendering index. This makes it possible for a lamp to score quite well even when it renders one or two colors very poorly. This situation is even more likely with SPDs having narrowband peaks [41]. RGB LEDs are at increased risk of being affected by this problem because their unique spectra are more vulnerable to poor rendering in only certain areas of color space [33]. To ensure the influence of poor rendering of even a few samples on the results, the root-mean-square of color shifts of each individual sample is used in CQS rather than arithmetic mean.

The procedure to calculate the Color quality scale of the light sources can be described briefly in the following steps:

Step 1: Calculation of color difference and chroma difference

The color difference is calculated for each reflective sample when illuminated by reference illuminant $(L^*_{i,ref}, a^*_{i,ref}, b^*_{i,ref})$ and when illuminated by test source $(L^*_{i,test}, a^*_{i,test}, b^*_{i,test})$ in CIE 1976 L*a*b* color space. The differences in coordinates $(\Delta L^*, \Delta a^*, \Delta b^*)$ are calculated by subtracting coordinates when illuminated by reference illuminant $\left(L^*_{i,ref}, a^*_{i,ref}, b^*_{i,ref}\right)$ from respective coordinate when illuminated from test source $(L^*_{i,test}, a^*_{i,test}, b^*_{i,test})$. After calculating the differences of coordinates, the color difference $(\Delta E^*_{ab,i})$ is calculated as:

$$\Delta E^*{}_{ab,i} = [(\Delta L_i{}^*)^2 + (\Delta a_i^*)^2 + (\Delta b_i^*)^2]^{1/2} \quad \textbf{(52)}$$

Where

$\Delta E^*_{ab,i}$	is the color difference for each sample when illuminated by the reference illuminant and test source
$(\Delta L_i{}^*, \Delta a_i^*, \Delta b_i^*)$	are the differences of the CIE 1976 L*a*b* color space coordinates for each sample when illuminated by the reference illuminant and test source

Similarly, the difference in chroma of each color sample between reference illumination and test source illumination conditions is calculated as:

$$\Delta C^*_{ab,i} = C^*_{ab,i,test} - C^*_{ab,i,ref} \quad \textbf{(53)}$$

Where,

$\Delta C^{*}_{ab,i}$ is the chroma difference of each sample when illuminated by the test source and reference source

$C^{*}_{ab,i,test}$ is the chroma of each sample under test source

$C^{*}_{ab,i,ref}$ is the chroma of each sample under reference source

Step 2: Application of the saturation factor

The saturation factor neutralizes any contribution to the color difference that arises from an increase in object chroma from test source illumination relative to reference source illumination. The color difference of each sample illuminated by the test source and reference source with the integration of the saturation factor ($\Delta E^{*}_{ab,i,sat}$) is calculated by:

$$\Delta E^{*}_{ab,i,sat} = \Delta E^{*}_{ab,i} \qquad if \qquad \Delta C^{*}_{ab,i} \leq 0, \qquad \textbf{(54)}$$

$$\Delta E^{*}_{ab,i,sat} = [(\Delta E^{*}_{ab,i})^{2} - (\Delta C^{*}_{ab,i})^{2}]^{1/2} \qquad if \qquad \Delta C^{*}_{ab,i} > 0 \qquad \textbf{(55)}$$

Where,

$\Delta E^{*}_{ab,i,sat}$ is the color difference of each sample illuminated by the test source and reference source with the integration of the saturation factor

$\Delta E^{*}_{ab,i}$ is the color difference of each sample illuminated by the test source and reference source

$\Delta C^{*}_{ab,i}$ is the chroma difference of each sample illuminated by the test source and reference source

Step 3: Root Mean Square of the color differences

The color differences from all 15 samples are combined by root mean square (rms). This ensures that poor rendering of even a few objects color has a significant impact on general color quality scale. The rms color difference of the 15 samples is calculated using following equation:

$$\Delta E_{rms} = \sqrt{\frac{1}{15}\sum_{i=1}^{15}(\Delta E^{*}_{ab,i,sat})^{2}} \qquad \textbf{(56)}$$

Where,

ΔE_{rms} is the root mean square color difference of the 15 samples

$\Delta E^{*}_{ab,i,sat}$ is the color difference of each sample illuminated by the test source and reference illuminant with the integration of the saturation factor

Step 4: Application of scaling factor

The "rms average" color quality scale score is calculated by:

$$Q_{a,rms} = 100 - 3.1 \times \Delta E_{rms} \tag{57}$$

The constant value '3.1' in equation 57 is scaling factor which was selected so that the average value of the color quality scale for a set of the CIE standard fluorescent lamp spectra (F1 through F12 [43]) is equal to the average value of the CIE CRI (R_a =75) for these sources [33]. This selection was intended to minimize the changes of value from CIE CRI to CQS for traditional light sources.

Step 5: Conversion to 0-100 scale

The calculation of CQS can yield negative value for very poor color-rendering sources, which is not desirable. To avoid occurrences of such negative value following mathematical function is implemented:

$$Q_{a,0-100} = 10\ln\{exp\left(\frac{Q_{a,rms}}{10}\right) + 1\} \tag{58}$$

Where,

$Q_{a,0-100}$	is rms average color quality scale value converted to 0-100 scale
$Q_{a,rms}$	is "rms average" color quality scale score

Figure 10 shows the input and output relation of equation 58. Only lamps with poor color quality (CQS< 30) are affected by the conversion and higher values are hardly affected.

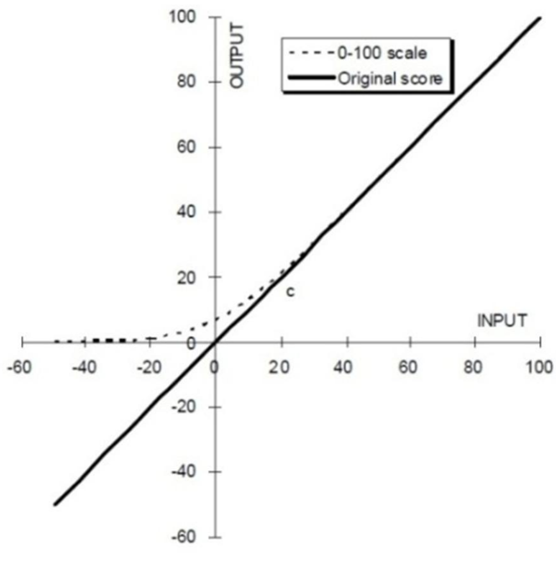


Figure 10. The 0-100 scale function (dashed) used to convert original scores (solid) **[33]**.

Step 6: Application of CCT factor

The problem of imperfect chromatic adaption at extreme CCTs is addressed in CQS with the application of CCT factor. CCT factor penalizes lamps with extremely low CCTs and smaller gamut area [33]. This factor is calculated only from the gamut area of the reference source and is given by:

$$M_{CCT} = T^3(9.2672 \times 10^{-11}) - T^2(8.3959 \times 10^{-7}) + T(0.00255) - 1.612$$

$$(for\ T < 3500K) \quad \textbf{(59)}$$

$$M_{CCT} = 1 \qquad (for\ T \geq 3500K),$$

Where,

M_{CCT}	is the CCT factor
T	is the CCT of the test light source

Figure 11 shows the CCT factor as a function of the color temperature for reference illuminants ≤ 3500 K.

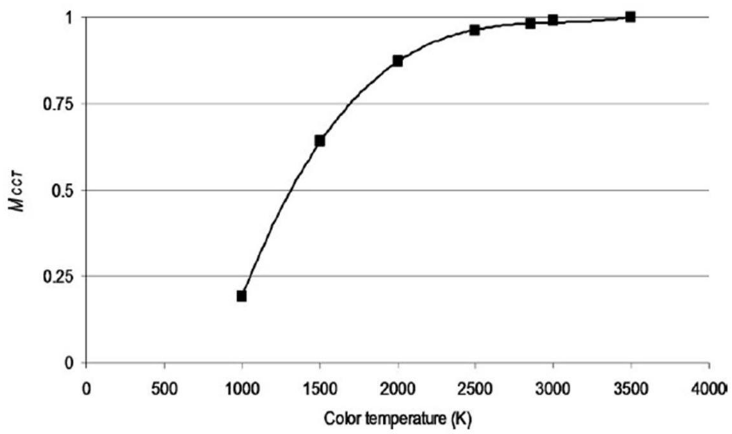


Figure 11. CCT factor (M_{CCT}) as a function of color temperature for reference illuminants≤3500K **[33]**.

As shown in the Figure 11, CCT factor has little impact on white-light sources of practical CCT range but will penalize the light sources having much lower CCTs.

Step 7: Calculation of general color quality scale (Q_a)

Finally, the general color quality scale (Q_a) is calculated as follows:

$$Q_a = M_{CCT} Q_{a,0-100} \quad \textbf{(60)}$$

Where,

Q_a	is general color quality scale (CQS).

Likewise, the special color quality scale (Q_i) for each reflective sample is calculated by:

$$Q_i = M_{CCT}\, Q_{i,0-100} \quad \textbf{(61)}$$

Where,

$$Q_{i,0-100} = 10(\ln exp\left(Q_{i,PRE}/_{10}\right) + 1)$$

$$Q_{i,PRE} = 100 - 3.1 \times \Delta E^*_{ab,i,sat}$$

Additional Scales

There is provision for the additional indices in color quality scale for the expert users and the applications which requires more specific information about the color-rendering properties of light sources. These addition indices are given below.

1. **Color Fidelity Scale (Q_f)**

   This scale is intended to evaluate the fidelity of object color appearances similar to the function of CIE CRI. It is calculated exactly the same procedure as CQS expect that it excludes the saturation factor. Hence, $\Delta E^*_{ab,i,sat}$ is replaced with $\Delta E^*_{ab,i}$ and scaling factor is taken as 2.93 [33].

2. **Color Preference Scale (Q_p)**

   It is based on the notion that increases in chroma is generally preferred and should be rewarded. The calculation procedure for Q_p is same as the CQS Q_a, expect that it rewards light sources for increasing chroma. Thus, $Q_{a,rms}$ in equation (57) is replaced by

   $$Q_{a,rms} = 100 - 3.78 \times [\Delta E_{rms} - \frac{1}{15}\sum_{i=1}^{15} \Delta C^*_{ab} \,.\, K(i)] \quad \textbf{(62)}$$

   Where,

   $K(i) = 1$ for $C^*_{ab,test} \geq C^*_{ab,ref}$

   $K(i) = 0$ for $C^*_{ab,test} < C^*_{ab,ref}$

3. **Gamut Area Scale (Q_g)**

   Gamut area scale is calculated from the relative gamut area formed by the (a*, b*) coordinates of the 15 sample illuminated by the test light source in the CIELAB object color space [1]. It is normalized by the gamut area of D65 multiplied by 100.

4.2 CRI-CAM02UCS Color Rendering Index

Li *et al*. [44] developed the CRI-CAM02UCS color rendering index. This metric predicts the color rendering properties of a light source based on the variation in color appearance of test samples illuminated under the test source and the reference illuminant. The fundamental calculation procedures for CRI-CAM02UCS is same as that of CIE CRI but it is based on CAM02-UCS (uniform color space) which includes the reliable CAT02 chromatic adaptation transform. Reference illuminants selection in CRI–CAM02UCS is same as that of CIE CRI method.

CAM02-UCS is a powerful tool for accurate prediction of color appearance data and color difference data [1]. In their experiment Li *et al.* found that the calculation of color difference based on CAM02-UCS color space, gave the better correlation to the visual results than other previous color difference formulae [44]. Similarly, Sander and Schanda [45] found that the color appearance model based color difference formula gave the best correlation to the visual results. The color difference equation in CRI-CAM02UCS is equally weighted for shifts in lightness, colorfulness and hue of the test samples between the test light source and reference illuminant [44]. Research is going on to improve CRI-CAM02UCS with more comprehensive sample sets [46]. Figure 12 shows the flowchart for calculating CRI-CAM02UCS. It can be seen from Figure 12 and Figure 8 that step 1 to step 3 for calculating CRI-CAM02UCS and CIE CRI are the same. However, other steps are different as CIE 1964 U*V*W* color space is replaced by CAM02-UCS in the calculation of CRI-CAM02UCS.

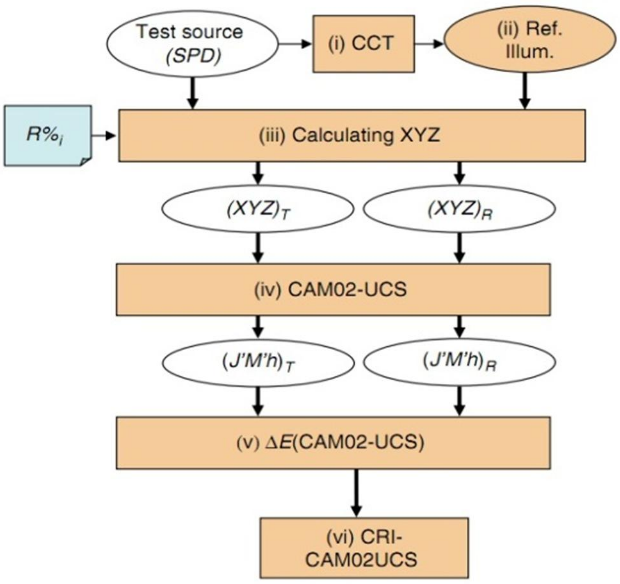


Figure 12. The workflow for calculating CRI-CAM02UCS **[1]**.

Step by step procedures for calculating CRI-CAM02UCS are given below:

Step 1: Calculate the CIE 1931 chromaticity coordinates from the SPD of the test source and then obtain the CCT of test source from the chromaticity coordinates.

Step 2: Depending upon the CCT of test source select the reference illuminant. The criteria to select reference illuminant is that if CCT of test source is less than 5000K then select the reference illuminant from the pool of black body radiators otherwise from the phase of daylight.

Step 3: calculate the XYZ tristimulus values for each test color samples under the test and reference illuminant using equations 1 to 3.

Step 4: Calculate CIECAM02 color appearance model based uniform color space CAM02-UCS attributes J', M' and h values under the test and reference illuminants using:

$$J' = 1.7J/(1 + 0.007J) \qquad J = \text{lightness}$$

$$M' = 43.86 \ln(1 + 0.0228M) \qquad M = \text{Colourfulness} \tag{63}$$

$$a'_M = M' \cos(h) \text{ and } b'_M = M' \sin(h) \qquad h = \text{Hue angle}$$

Step 5: Calculate color difference for each test sample using CAM02-UCS color difference formula given by:

$$\Delta E(CAM02 - UCS) = \sqrt{\Delta J'^2 + \Delta a'^2_M + \Delta b'^2_M} \tag{64}$$

Where,

ΔE (CAM02-UCS)	is the CAM02-UCS color difference for each sample illuminated by the test and reference illuminant
$\Delta J', \Delta a'_M$ and $\Delta b'_M$	are the differences of J', a'_M and b'_M between the test and reference illuminant

Step 6: Determination of CRI-CAM02UCS color rendering index using equation 65.

$$CRI - CAM02UCS = \frac{1}{n}\sum_{i=1}^{n}(100 - 8\Delta E(CAM02 - UCS)_i \tag{65}$$

Where,

$CRI - CAM02UCS$	is the $CRI - CAM02UCS$ color rendering index
$\Delta E(CAM02 - UCS)_i$	color difference for each test sample using CAM02-UCS color difference formula.
n	represents the number of test color samples which are yet to be finalized

4.3 Rank-order based Color Rendering Index (RCRI)

Bodrogi et al. [47] proposed a rank-order based color rendering index (RCRI) which predicts the color rendering rank order of light sources. It is also known as ordinal scale based color rendering index. RCRI predicts the visual rating of perceived color differences between a set of seventeen test color samples (1-12 from Macbeth colour checker chart and 13-17 from NIST colour set as shown in Figure 13) on a five step ordinal rating 'R' when illuminated by the test light and by a reference illuminant. The rating scale R ranges from excellent (R=1) to very bad (R=5). The first rating category excellent (R=1) corresponds to the smallest perceived color difference of a test color sample between the test source and reference source.

Perceived color differences in RCRI are calculated on CIECAM02 color appearance model based uniform color space. RCRI provide easy interpretation value for the non-expert user to assess the equality of test light sources or superiority among a test light source with respect to color rendering properties.

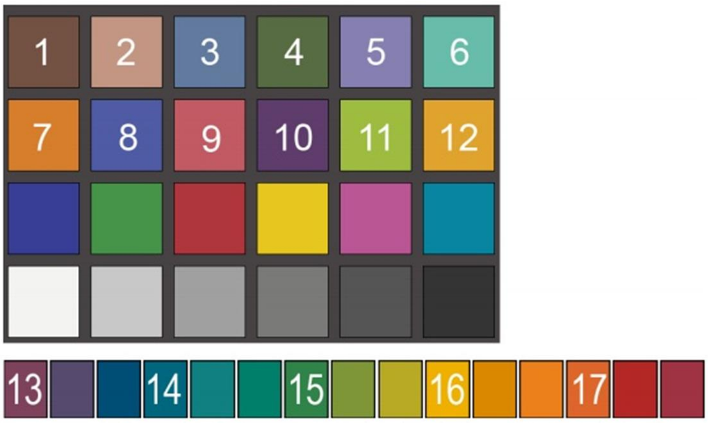


Figure 13. Test color samples (1-17) used in RCRI. Top: Macbeth Color Checker Chart (1-12), bottom: NIST CQS color set (13-17) **[47]**.

The reference illuminants in RCRI are determined using the same methods as that of the CIE CRI. The color difference ΔE_{calc} is computed by the CAM02-UCS formula for each of the seventeen test color sample $((\Delta E_{calc,k}\,; k = 1-17)$ for a given test light source and reference illuminant. The mean value of ΔE_{calc} in each rating category $(\Delta E_{calc,mean,R}; R = 1-5)$ is calculated by using the CAM02-UCS formula and considering the experiment dataset [47]. Table 4 shows the $\Delta E_{calc,mean,R}$ values computed in each rating category and their 95% confidence intervals.

Table 4. Mean values $\Delta \boldsymbol{E}_{\boldsymbol{calc,mean,R}}$ for each rating category (R = 1-5), number of cases (No.), standard deviation (STD) and 95% confidence intervals (Cl) **[47]**.

R	Computed color differences (CAM02-UCS)				
	1	2	3	4	5
No.	163	390	361	300	104
Mean	**2.01**	**2.37**	**3.75**	**6.53**	**11.28**
STD	1.25	1.72	2.58	4.03	5.13
95% Cl	0.19	0.17	0.27	0.46	0.99

Ranking (1 for excellent, 2 for good, 3 for acceptable, 4 for not acceptable and 5 for very bad) is predicted using the criterion: $\left|\Delta E_{calc,mean,i} - \Delta E_{calc,k}\right|$ = minimum. The step by step procedure to compute the rank-order based color rendering index (RCRI) is described below.

Step1: Compute color differences

Calculate the color differences (*$\Delta E_{calc,k}$; k =1-17)* between the given test light source and reference light source for each of the seventeen test color sample using the CAM02-UCS formula given by:

$$\Delta E_{calc,k} = \sqrt{\Delta J'^2 + \Delta a'^2_M + \Delta b'^2_M} \quad \textbf{(66)}$$

Where,

$J' = 1.7J/(1 + 0.007J)$ $\qquad J = lightness$

$M' = 43.86\ln(1 + 0.0228M)$ $\qquad M = Coloufulness$

$a'_M = M'\cos(h)$ and $b'_M = M'\sin(h)$ $\qquad h = Hue\ angle$

Step 2: For every test color sample (k=1to17) compute the following five absolute differences.

$$\begin{aligned} &1^{st} :\left|\ 2.0146 - \Delta E_{calc,k}\right| ;\\ &2^{nd} :\left|\ 2.3681 - \Delta E_{calc,k}\right| ;\\ &3^{rd} :\left|\ 3.7538 - \Delta E_{calc,k}\right| ;\\ &4^{th} :\left|\ 6.5312 - \Delta E_{calc,k}\right| ;\\ &5^{th} :\left|\ 11.2818 - \Delta E_{calc,k}\right| ; \end{aligned} \quad \textbf{(67)}$$

Step 3: Predict the ranking of the test color sample

For every test color sample *(k = 1 to 17)*, determine which one of the five absolute differences in step 2 is smallest. If (for the k^{th} test color sample) 1^{st} difference is smallest then predicted ranking of the k^{th} test color sample is equal to 1. If (for the k^{th} test color sample) the 2^{nd} difference is the smallest then the predicted ranking of the k^{th} test color sample is equal to 2. If (for the k^{th} test color sample) the 3^{rd} difference is the smallest then the predicted ranking of the k^{th} test color sample is equal to 3. If (for the k^{th} test color sample) the 4^{th} difference is the smallest then the predicted ranking of the k^{th} test color sample is equal to 4. If (for the k^{th} test color sample) the 5^{th} difference is the smallest then the predicted ranking of the k^{th} test color sample is equal to 5.

Step 4: Calculate the predicted rankings for every test color sample (k=1 to 17).

Step 5: Count the number N_1 of those test color samples that have predicted ranking equal 1.

Step 6: Count the number N_2 of those test color samples that have predicted ranking equal 2.

Step 7: Compute rank-order based color rendering index (RCRI) from the predicted number of excellent (N_1) and good (N_2) ratings in the following way.

$$RCRI = 100 \times \left[\frac{N_1 + N_2}{17}\right]^{\frac{1}{3}} \qquad \textbf{(68)}$$

Where,

RCRI	is rank-order based color rendering index
N_1	is number of test color sample that have predicted ranking equal 1 (excellent)
N_2	is number of test color sample that have predicted ranking equal 2 (good)

Let *E* denotes the number of samples that do not appear “excellent” and “good “under the test light source compared to reference light source. If the number of E is large, than the test light source gets a low RCRI value. If the number of excellent and good test color sample (N_1+N_2) is large, then the test source gets a high RCRI value.

4.4 Memory Color Rendering Index (MCRI)

CIE CRI and other metrics which evaluate the color rendition properties of light source based on a comparison with a reference illuminant can be considered as color difference indices. Color difference indices only measure the shift in color appearance with respect to an ‘optimum’ reference illuminant [48]. However, many users are often more interested in the perceived color quality of lighting, i.e. how attractive objects look under a given light source than in the color difference with a reference illuminant. It is also problematic to evaluate color quality of light source based on a comparison with a reference illuminant. Because one has to know which illuminant is considered “perfect” and use as a reference as well as which deviations from reference should or should not be penalized.

People consciously or subconsciously judge the color appearance of objects against the colors they mentally associate with those objects [48]. Mentally associated object color or memory color can be possible to use as reference to assess color quality of light sources [48]. Evaluating color quality of light source by reference to memory color has several advantages. First of all the correlation between the visual appreciation of the users and metric predictions should be high because evaluations are based directly on visual assessments of the color appearance of real objects. Secondly, it does not suffer from any of the difficulties associated with reference illuminant.

Smet et al. developed color rendering index based on memory colors called memory color rendering index (MCRI) [49]. The main idea of MCRI is that better the color appearance of an object under a light source resembles with memory color of objects better be the perceived color quality of light source. MCRI assesses the color rendering properties of light sources as the perceived similarity between an object’s colors under the test source with object’s memory colors. MCRI does not need any reference illuminant because all referencing is done to the people’s idea of what certain familiar objects should or can look. It does not depend on chroma/saturation enhancement, but it depends directly on visual appearance rating of a set of familiar objects [50]. MCRI takes directly how good objects look under a given light source rather than only the color difference with a CIE reference illuminant.

Color rendering property in MCRI is assessed as the general degree of similarity between the color appearance of a set of nine familiar objects under the test light source and the memory colors of those objects. The test sources which render the objects colors more similar to their memory colors have the higher color rendering index. The similarity of each object color under the test source with its memory color is calculated using the similarity distributions obtained in a series of psychological experiments [49]. These experiments investigated the color appearance of a set of nine familiar real objects with colors distributed around the hue circle. The nine familiar objects chosen were a green apple, a banana, orange, dried lavender, a smurf figurine, strawberry yoghurt, a sliced cucumber, a cauliflower, and Caucasian skin. Later neutral grey sphere was added to the set of objects [51]. In the experiment each object was presented in approximately one hundred different colors by placing them in a specially constructed LED illumination box as shown in Figure 14. This specially constructed LED illumination box masked any clues to the color of the illumination thereby creating illusion that the objects themselves changed color [51].

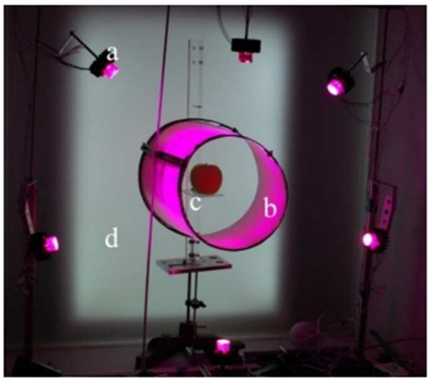


Figure 14. Interior of the LED illumination box. (a) RGBA LED packages to change the object color; (b) Diffusing tunnel to mask the specular reflection; (c) Transparent support for the object; (d) self-luminous back panel to provide a constant adaption point **[49]**.

A group of observers were asked to rate the color appearance of the presented object on a 5 point scale with respect to what they thought the object looked in reality. The pooled observer rating for each object were modelled in the uniform IPT color space by a modified bivariate Gaussian distribution described by the following equations 69 [48].

$$R(P,T) = a_1 + a_2.S(P,T);$$
$$S(P,T) = exp\left(-\frac{1}{2}\left(d^2(P,T)\right)\right); \tag{69}$$
$$d^2(P,T) = (X - X_c)^T.\Sigma^{-1}.(X - X_c);$$
$$X = \binom{P}{T}; X_c = \binom{a_3}{a_4}; \ \Sigma^{-1} = \begin{vmatrix} a_5 & a_7 \\ a_7 & a_6 \end{vmatrix};$$

Where,

$R(P,T)$	is the pooled observer rating for each object modelled in the uniform IPT color space by a modified bivariate Gaussian distribution
$S(P,T)$	is the similarity distribution
$d(P,T)$	is the elliptical d-contours of the bivariate Gaussian surface in IPT color space
X	is the object chromaticity under test light source in IPT color space
X_c	is the distribution centre which represents the most likely location of memory color
$a_1\ to\ a_7$	are similarity distribution parameters

An example of similarity distribution obtained when pooled observer rating of object modelled in the uniform IPT color space by a modified bivariate Gaussian distribution is shown in Figure 15.

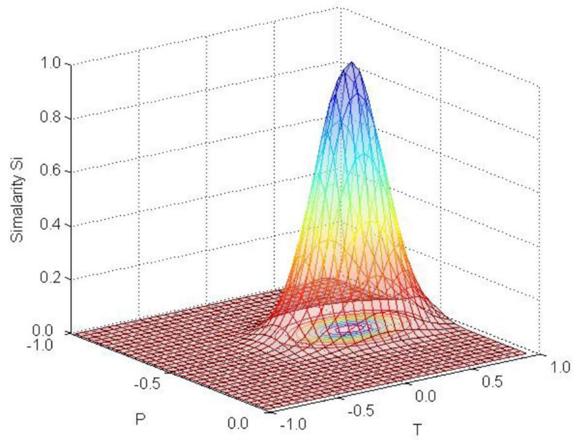


Figure 15. Similarity distribution in IPT color space **[51]**.

This model requires seven parameters: $a_1$and $a_2$to scale the rating and $a_3$toa_7 to describe the similarity distribution S (P, T). The distribution centre X_c which is the most likely location of the memory color is located at (a_3,a_4). The inverse of the covariance matrix ∑ give the shape and the orientation of the shape. The function d (P, T) describes the elliptical d-counters of the bivariate Gaussian surface in IPT color space. The parameters a_3 to a_7 that describe the similarity distribution S_i (P, T) in IPT color space are given in Table 5.

Table 5. Similarity distribution parameters for each of the ten familiar objects in smet et al. experiment [51].

Object name	Symbol	a_3	a_4	a_5	a_6	a_7
Green apple	*S-ap*	−0.0907	0.3906	46.0900	18.9538	−0.2833
Ripe banana	*S-ba*	0.1553	0.3676	66.0833	23.3494	−0.8224
Orange	*S-or*	0.3085	0.4683	40.8171	20.6933	−6.9833
Dried lavender	*S-la*	0.0191	−0.1258	296.9222	127.4322	−52.0363
Smurf®	*S-sm*	−0.1203	−0.2083	112.8298	64.3715	−45.8178
Strawberry yoghurt	*S-sy*	0.1725	0.0162	66.1341	71.8095	−26.2745
Sliced Cucumber	*S-sc*	−0.0329	0.2245	107.4140	36.7800	3.0505
Cauliflower	*S-cf*	0.0390	0.0523	233.1061	60.9832	−40.6899
Caucasian skin (hand)	*S-ha*	0.1481	0.1312	102.3266	81.1393	−21.9418
Munsell N4 grey sphere	*S-n4*	−0.0190	−0.0164	843.3289	342.1807	−261.1875

The bivariate Gaussian distribution R (P, T) and their d-counter ellipses obtained by fitting the pooled ratings in IPT color space for each object used in smet et al. experiment are shown in Figure 16 [49].

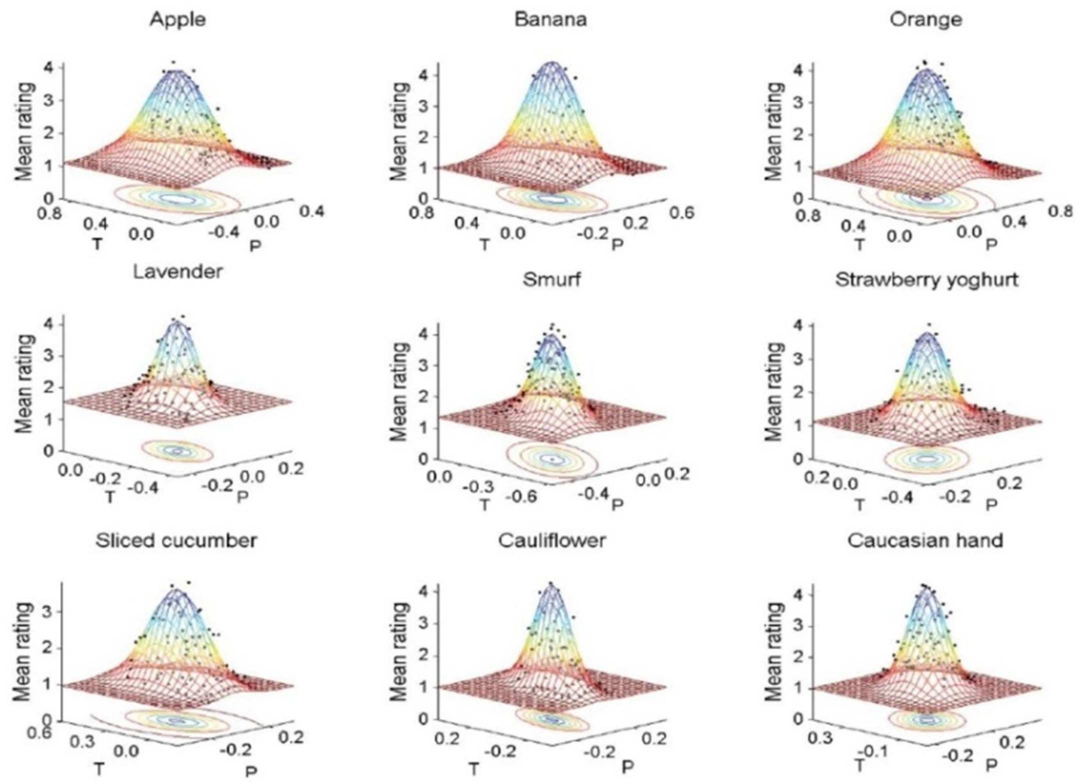


Figure 16. Bivariate Gaussian distributions R (P, T) and their d-contour ellipses obtained by fitting the pooled ratings in IPT color space for each object used in the experiment by smet et al. **[49]**. The mean rating for each illumination setting is also shown as a point to visualize the goodness-of-fit.

The similarity distribution S describes the similarity between any apparent object color and its memory color (centre of distribution). It enables a quantitative evaluation of the color appearance of each of the familiar objects. Based on these similarity distributions, the color quality of light source is estimated using the steps explained below.

Step 1: Calculation of objects tristimulus value under illuminant D65

The tristimulus values for each of the ten familiar objects under the test light source are calculated using the spectral reflectance of the objects and the CIE 10° standard observer. CAT02 chromatic adaptation transform is used to transform these tristimulus values to corresponding values under illuminant D65.

Step 2: The corresponding tristimulus values are transformed to IPT chromaticity coordinates, $X_i = (P_i, T_i)$.

Step 3: Calculation of function values of the corresponding similarity distribution $S_i\,(X_i)$

The function values of the corresponding similarity distribution $S_i\,(X_i)$ are calculated with the object chromaticities X_i as input, resulting in a set of ten S_i values which describes the degree of similarity with each object's memory color [50].

$$S_i(X_i) = e^{-\frac{1}{2}[(X_i - a_{i,3})^T \begin{pmatrix} a_{i,5} & a_{i,7} \\ a_{i,7} & a_{i,6} \end{pmatrix} (X_i - a_{i,4}))]}, \quad (i = 1 \text{ to } 10) \tag{70}$$

The individual values of S_i are in the range of zero to one.

Step 4: Calculation of MCRI

The general degree of memory color similarity S_a (also known as memory color rendering index) is obtained by taking the geometric mean of the ten individual Si values.

$$S_a = \sqrt[n]{\prod_{i=1}^{n} S_i} \tag{71}$$

MCRI score ranges from zero to one. MCRI value of one means that the light source renders all familiar objects exactly as we expect them to look.

4.5 Feeling of Contrast Index (FCI)

The visual clarity of any light source is defined as the impression of clear distinction between the surface colors of various objects under the light source [52]. It is the characteristics of light source which produces the feeling of "clearness" or "distinctness" between object colors under illumination. Hashimoto et al. [38] by using various two-color and four-color combinations studied the relation between visual clarity and feeling of contrast. They found that the visual clarity is closely related to the feeling of contrast between object colors under the illumination used for same observing conditions.

Visual clarity or feeling of contrast is one of the important characteristics of color rendering property of light sources [52]. However, the effect of visual clarity under various illuminations condition cannot be assessed adequately by using the present CIE CRI [38]. CIE CRI has no information whether the light source makes objects colors more saturated or not. Saturation or chroma enhancement is generally considered a positive trait in many lighting applications [10].

Hashimoto and Nayatani first proposed a feeling of contrast index based on the visual clarity or brightness sensation of objects colors in 1994 [52]. It is based on the concept that a light source that increases feeling of contrast also increases the saturation of colored objects which is generally preferred. The 1994 proposal was very complicated and not practically usable because it includes complicated interpolation and predicting the test illuminance E_t (predicated) was very difficult [38]. Hashimoto et al. [38] improved 1994 proposal and proposed simplified method in 2007 [38]. This simplified method makes the tedious computations simple for deriving the feeling of contrast index and uses CIELAB instead of Nonlinear Color-Appearance Model [53]. Also, the gamut area is derived under the same illuminance (1000 lx) irrespective of test and reference illuminants. The complex and complicated interpolation of 1994 proposal is completely excluded in the new simplified method. The computational procedures to derive felling of contrast index (FCI) are explained below.

Step 1: Selection of four-color combination

Highly saturated four-color combinations (5R 4/12, 5Y 8.2/10, 5.5G 5/8, and 4.5PB 3.2/6) with red, yellow, green and blue hues are selected. These four-color combinations can assess effectively the feeling of contrast under various illuminations and represent almost all the hues used in the actual environment [38]. Figure 17 shows the arrangement of each component color of the selected four-color combination with their Munsell notations.

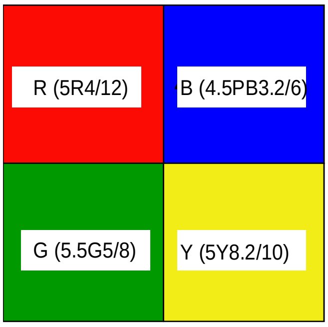


Figure 17. The arrangement of each component color of the selected four-color combination and their Munsell notations **[38]**.

Step 2: Calculation of tristimulus values of each component color of the four–color combination under test illuminant (T)

Using the spectral distribution data of the test illuminant and spectral reflectance data of each component color, the tristimulus values of each component color of the four-color combination under the test illuminant (T) are calculated. The spectral reflectance data of each component color is shown in Table 6.

Table 6. Spectral reflectance data of each component color (red, yellow, green, blue) of the four-color combination used in Figure 1 **[38]**.

(nm)	Red	Yellow	Green	Blue	(nm)	Red	Yellow	Green	Blue
380	0.058	0.078	0.075	0.066	585	0.089	0.749	0.121	0.052
385	0.059	0.084	0.081	0.070	590	0.116	0.746	0.108	0.052
390	0.061	0.092	0.088	0.076	595	0.150	0.743	0.096	0.052
395	0.061	0.099	0.096	0.085	600	0.198	0.738	0.087	0.052
400	0.061	0.103	0.101	0.092	605	0.263	0.734	0.080	0.051
405	0.061	0.106	0.105	0.101	610	0.338	0.729	0.075	0.052
410	0.060	0.107	0.108	0.109	615	0.412	0.726	0.072	0.052
415	0.060	0.107	0.110	0.110	620	0.489	0.723	0.071	0.052
420	0.059	0.107	0.112	0.111	625	0.555	0.721	0.070	0.052
425	0.059	0.108	0.115	0.120	630	0.603	0.720	0.069	0.052
430	0.058	0.109	0.118	0.123	635	0.641	0.719	0.069	0.052
435	0.058	0.110	0.122	0.135	640	0.665	0.718	0.069	0.052
440	0.058	0.111	0.125	0.154	645	0.682	0.718	0.069	0.052
445	0.057	0.113	0.130	0.172	650	0.694	0.717	0.069	0.052
450	0.056	0.115	0.135	0.184	655	0.703	0.718	0.069	0.052
455	0.055	0.116	0.141	0.192	660	0.708	0.719	0.070	0.052
460	0.055	0.118	0.149	0.200	665	0.713	0.721	0.072	0.051
465	0.054	0.120	0.158	0.208	670	0.716	0.723	0.073	0.051
470	0.053	0.123	0.166	0.211	675	0.718	0.725	0.074	0.051
475	0.052	0.126	0.175	0.209	680	0.720	0.727	0.076	0.051
480	0.051	0.130	0.184	0.202	685	0.722	0.729	0.077	0.051
485	0.050	0.137	0.195	0.190	690	0.724	0.730	0.079	0.051
490	0.050	0.148	0.209	0.177	695	0.726	0.732	0.080	0.051
495	0.049	0.164	0.227	0.163	700	0.731	0.734	0.081	0.052
500	0.049	0.194	0.256	0.147	705	0.733	0.734	0.081	0.053
505	0.049	0.240	0.291	0.132	710	0.738	0.735	0.081	0.054
510	0.049	0.298	0.325	0.118	715	0.742	0.735	0.080	0.056
515	0.050	0.376	0.352	0.105	720	0.746	0.734	0.080	0.058
520	0.050	0.451	0.363	0.094	725	0.751	0.734	0.080	0.060
525	0.051	0.529	0.361	0.084	730	0.754	0.736	0.081	0.062
530	0.051	0.596	0.348	0.077	735	0.756	0.736	0.083	0.064
535	0.052	0.645	0.331	0.071	740	0.758	0.740	0.086	0.067
540	0.053	0.684	0.308	0.067	745	0.760	0.742	0.090	0.071
545	0.054	0.710	0.284	0.063	750	0.763	0.744	0.094	0.077
550	0.055	0.726	0.260	0.061	755	0.765	0.747	0.098	0.089
555	0.057	0.737	0.235	0.058	760	0.766	0.747	0.102	0.106
560	0.060	0.743	0.213	0.057	765	0.769	0.749	0.105	0.129
565	0.062	0.747	0.191	0.055	770	0.770	0.750	0.108	0.155
570	0.065	0.750	0.171	0.054	775	0.773	0.750	0.110	0.176
575	0.068	0.750	0.154	0.053	780	0.744	0.749	0.112	0.193
580	0.075	0.749	0.137	0.053					

Step 3: Determination of the tristimulus values of the corresponding colors under the reference illuminant D65

The tristimulus values calculated in Step 2 are transformed to those of the corresponding colors under reference illuminant D65 by using CIE chromatic adaptation transform (CIE 109-1964) [38]. The computational conditions used in the CIE chromatic adaptation transform are:

a) The value of the test illuminance is kept constant at 1000 lx, which is equal to that of the reference.

b) Luminance factor Y_0 of test and reference background is 20.

Step 4: Calculation of gamut area 'G ' (T, E_t = 1000 lx) for test illuminant (T)

The tristimulus values of each component color (red, yellow, green, blue) of the four-color combination are converted into CIELAB coordinates (L*, a*, b*). In the assessment of feeling of contrast for the four-color combination under different illuminations, the red component color is more important [38]. For this reason, the gamut area G (T, E_t = 1000 lx) is computed by the area sum of the two triangles: one consisting of red, yellow, and green; and the other of red, blue, and green as shown in Figure 18.

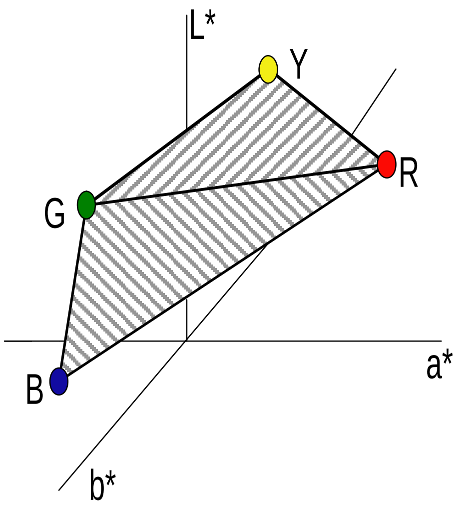


Figure 18. The gamut area in the three-dimensional space, consisting of CIELAB coordinates (L*, a*, b*) of each component color (R, Y, G, and B) of the four-color combination under illumination **[38]**.

Step 5: Calculation of gamut area 'G' (D_{65}, $E_{T=}$100 lx) for reference illuminant D65

Using the spectral distribution data of CIE illuminant D65 and spectral reflectance data of each color, the tristimulus values of each component color of the four-color combination under the reference illuminant D65 are calculated. The calculated tristimulus value are then converted into CIELAB coordinates (L*, a*, b*). The gamut area G ($D_{65}E_t$=1000 lx) for the reference illuminant is calculated by area sum of two triangles (RGY and RBG) similarly as of Step 4.

Step 6: Calculation of Feeling of contrast index (FCI)

After calculating gamut area G (T, E_t = 1000 lx) for test illuminant and G (D_{65}, E_t = 1000 lx) for the reference illuminant, feeling of contrast index (FCI) of the test source is calculated by:

$$FCI = [G(T, E_t = 1000\,lx)/G(D_{65}, E_r = 1000 lx)]^{1.5} \times 100 \qquad \textbf{(72)}$$

Where,

FCI	is feeling of contrast index
G (T, Et =1000 lx)	is gamut-area under the test illuminant (T) at illuminance (1000 lx)
G (D_{65}, E_t=100 lx)	is gamut-area value under the reference illuminant at illuminance (1000 lx)

4.6 Color Harmony Rendering Index

Color harmony is one of the important aspects of color appearance. CIE TC1-69 meeting (2007) in Beijing declared color harmony rendering property as an obserble factors to be considered in color quality of light source [54]. Color harmony rendering index describes how strongly a light source distorts the harmony of colors seen in the environment [54]. The issue of color harmony rendering is not the color differences of samples under the test light source and the reference light source but the general appearance of all colors in the field of view under the test and reference light source (especially the relation between the color samples).

Judd and Wyszecki define color harmony as "*when two or more colors seen in neighbouring areas produce a pleasing effect, they are said to produce a color harmony*" [55]. Granville describes it as the color usage that pleases people [56]. These both definitions imply a strong link between harmony and the emotion "pleasantness" evoked by colors and are emotional terms. Ou and Luo [57] developed a quantitative model for two-color combination based on chromatic, lightness, and hue effect. When the chromatic difference between the constituent colors becomes larger, color harmony decreases. Likewise, less the hue difference between the constituent colors in a color pair, the color pair appears harmonious. Small lightness difference between the constituent colors in a color pair tends to reduce color harmony and high lightness values of the constituent colors tend to enhance the harmony [57]. Ou and Luo combined these three color harmony factors (chromatic effect (H_C), lightness effect (H_L), and Hue effect (H_H)) additively to form a two-color harmony model. The two-color harmony model is given by:

$$CH = H_C + H_L + H_H \tag{73}$$

Where,

CH	is two-color harmony model
H_C	is chromatic effect
H_L	is lightness effect
H_H	is hue effect

Similar to the concept of CIE CRI, color harmony based index indicate the extent of color harmony variations of a set of samples pairs in any direction under a test light source from the reference illuminant. Luo et al. [58] developed a color harmony based rendering index based on Ou´s two-color harmony model. The flowchart for calculating color harmony index developed by Luo et al. is shown in Figure 19.

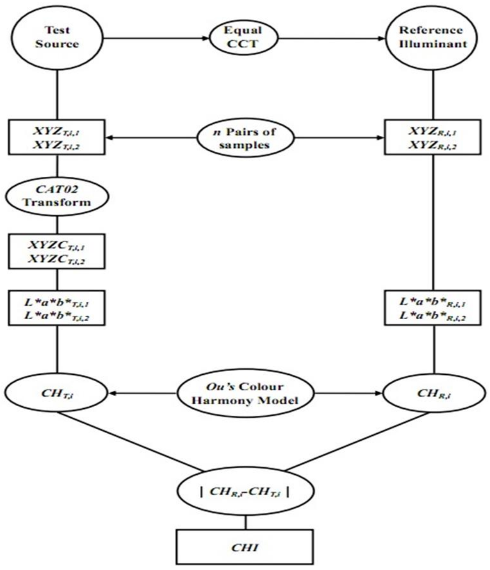


Figure 19. Flow chart for calculating color harmony index **[58]**.

The step by step procedure to calculate color harmony rendering index is described below:

Step 1: Reference illuminant selection

CIE daylight illuminant having the same CCT value as the test source is chosen as the reference illuminant.

Step 2: Test color sample pair selection

There are no recommended test sample pairs so far [58]. Ou et al. used 45 pairs of test sample pairs as shown in Figure 20 to derive color harmony based index.

Figure 20. Images of 45 test sample pairs used for investigation of color harmony **[58]**.

Step 3: Compute the XYZ tristimulus values for each test color sample pairs under the test source and reference illuminant respectively.

Step 4: Calculate CIELAB color space coordinates values (L*, a*, b*) for each test color sample pairs under reference illuminant.

Step 5: Transform the XYZ tristimulus values for each color sample pairs under test source to those under the reference illuminant using CAT02 chromatic adaption transform then calculate CIELAB color space coordinates values (L*, a*, b*) values. The CAT02 chromatic adaption transform is used to bridge the chromaticity difference between the test source and the reference illuminant.

Step 6: Calculate color harmony values of the test sample pairs using Ou´s color harmony model for the test source and reference illuminant respectively. Then calculate color harmony difference in any direction.

Step 7: Compute color harmony rendering index (CHI) using equation:

$$CHI = 100 - k \frac{\sum_{i=1}^{n} |CH_{i,reference} - CH_{i,test}|}{n} \quad \textbf{(74)}$$

Where,

CHI	is Color Harmony Index
$CH_{i,reference}$	is color harmony value of the i^th test sample pair under the reference illuminant
$CH_{i,test}$	is color harmony value of the i^th test sample pair under the test source
k	is scaling factor or constant whose value is 133.44
n	is number of the sample pairs

The value of k is determined so that the average score of the CHI for the CIE standard fluorescent lamps (F1 through F12) is equal to the average score of the CIE CRI (Ra=75) for these sources [58]. This scaling factor maintains consistency of the new colour harmony based index scale with the CIE CRI scale for existing lamps.

Szabo´ et al. carried out computation to investigate and compare Ou´s model with classical color harmony theories and found significant difference between the predictions [59]. Correlation was investigated using visual experiment [60]. Similarly, weak correlation of r^2 =0.30 was found between Ou´s model and Szabo´et al. visual data base [59]. One possible reason for this weak correlation can be the different ethnic origins of observers because in Szabo´ et al. experiment observers were university student from Hungary while in Ou's model they were Chinese [59].

Szabo´ et al. also developed a new quantative color harmony formulae which predict color harmony impression from the CIECAM02 hue, chroma, and lightness correlates of the member colors of the two and three color combination. Color harmony rendering index by using the formula developed by Szabo´ et al. can be calculated by [54]:

$$R_{hr} = 100 + k * \sum_{i=1}^{n} CHF_{i,ref} - CHF_{i,test} \quad \textbf{(75)}$$

Where,

R_{hr}	Color Harmony Rendering Index
$CHF_{i,\,ref}$	is the color harmony formula under the reference light source
$CHF_{i,\,test}$	is the color harmony formula under the test light source
n	indicates the number of test colour pairs (harmonious under the reference light source)
k	is scaling factor or constant whose optimised value is 5

CHF_{2M}, CHF_{2D}, CHF_{3M} and CHF_{3T} (these are color harmony formula see appendix of [54] for details) can be substituted in equation 75 depending on the set of two or three test color combination used. Test color combination shall contain color samples that are often seen together in everyday life and shall span the more harmonious and less harmonious regions of the predictions of the color harmony formulae to describe increasing and decreasing tendencies of color harmony under different test light sources.

4.7 Categorical Color Rendering Index (CCRI)

Categorical color rendering index (CCRI) is based on categorical color name and uses the color appearance model CIECAM97s [61]. It takes into account of color categorization rather than color difference in evaluating color rendering property of various light sources. CCRI measures whether an observed color seen under test source is falling into same category as seen under a reference illuminant or not.

To calculate categorical color rendering index Yaguchi et al. [61] carried out the experiment with four subject, 292 color samples, and fourteen kinds of light sources. Color samples chosen were 292 Munsell color chips found at even value (V) levels, even chroma (C) levels, and hue (H) labelled 5 and 10. Among fourteen test light sources; eight were fluorescent lamps, five were HID lamps and an incandescent lamp. The subjects were asked to sort color samples into eleven basic color categories specified by Berlin and Kay [62] under each illuminant. These color categories are red, green, yellow, blue, orange, pink, purple, brown, white, grey, and black as shown in Figure 21. Sorting of color sample under each illuminant was repeated three times for each subject.

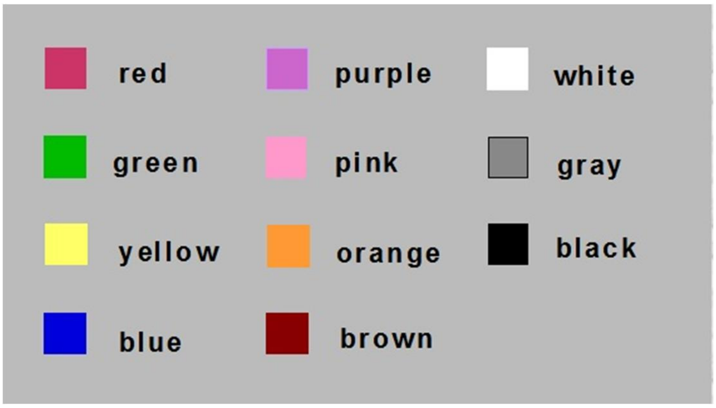


Figure 21. Basic color categories by Berlin and Kay **[63]**.

Color samples sorted into the same color category consistently for all three trials under each illuminant were selected for each subject. Figure 22 shows examples of these color samples in the Munsell hue circle under three different light sources; CIE standard illuminant (D65), the high-pressure mercury lamp (H), and the halogen lamp (IL).

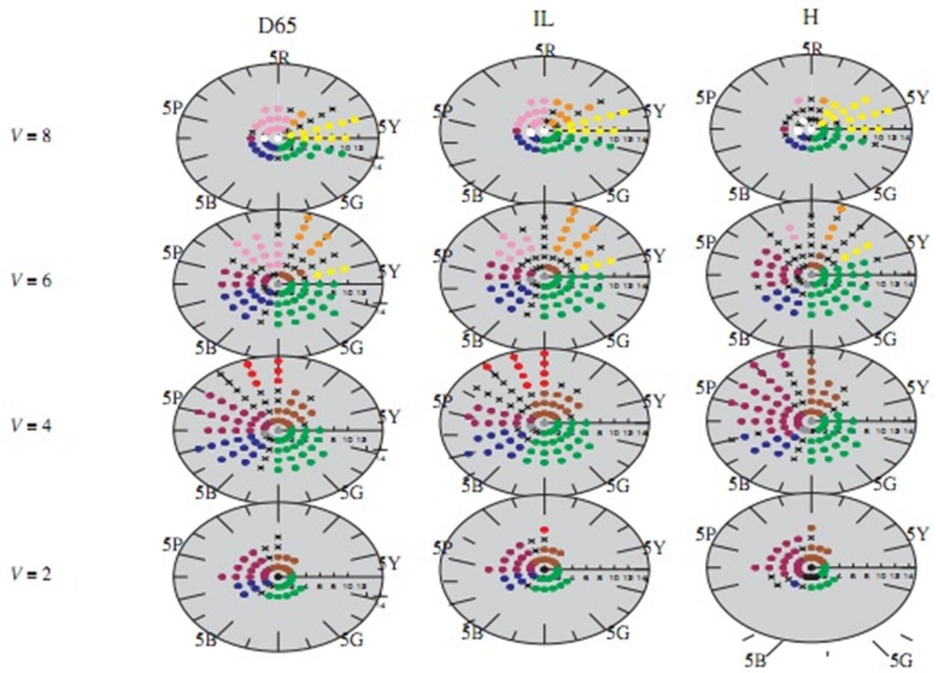


Figure 22. Color samples consistently sorted into the same color category under typical three illuminants: CIE standard illuminant (D65), Halogen lamp (IL), and High pressure mercury lamp (H) **[61]**.

Color name regions in the CIE 1931 chromaticity diagram greatly depend on light sources. Similarly, in the CIELAB color space color name region under a given light source are slightly overlapped with different color name region under the other light source. In order to allocate the basic color name regions in a viewing-condition independent color space, all experiment data were applied to CIECAM97s color appearance model. Lightness (J), chroma (C) and the hue angle (h) of the selected color samples were calculated and plotted in CIECAM97s color appearance model. It is found that the eleven basic color name region are clearly separated in the CIECAM97s space with each other which means that the CIECAM97s provide a good prediction of color name under various light source [61].

Color name regions were determined with color map in the CIECAM97s space and each color name region was allocated by a fan shape area at four different lightness level as shown in Figure 23. The fan shape area for each color name in a map are specified with an maximum and minimum hue angle (H_{max},H_{min}) and maximum and minimum chroma (C_{max}, C_{min}) whose value are shown in Table 7.

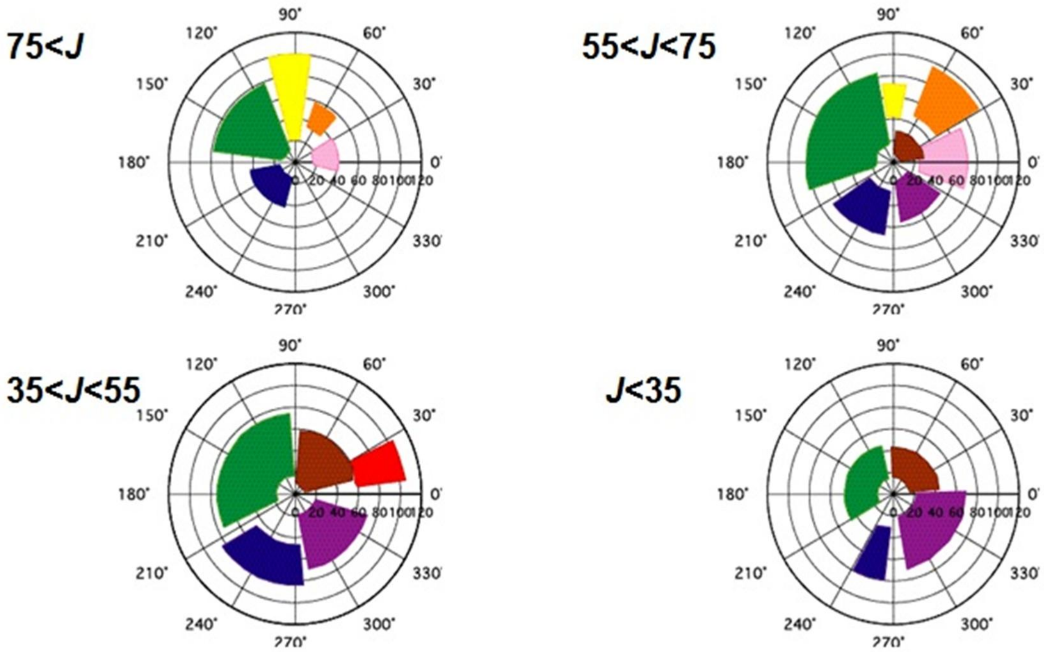


Figure 23. Color name regions in the hue circle of the CIECAM97s space at four different lightness levels **[63]**.

Table 7. Boundaries color name region in CIECAM97s **[61]**

Lightness	Color name	*H*min	*H*max	*C*min	*C*max
75≤ J	pink	350.56	32.42	18.32	42.05
	orange	46.43	71.1	34.85	57.73
	yellow	81.53	104.4	21.72	100
	green	111.69	172.91	12.3	77.88
	blue	191.49	255.56	15.46	43.47
55≤ J<75	pink	341.1	25.74	26.09	72.16
	orange	30.79	66.62	48.22	95
	brown	11.47	84.37	6.79	28.97
	yellow	80.7	97.48	41.98	72.5
	green	100.31	197.28	16.88	83.75
	blue	214.26	263.13	27.5	68.21
	purple	277.26	327.41	17.07	54.52
35≤ J<55	red	6.64	27.49	58.96	105
	brown	11.79	84.45	10.63	58.51
	green	93.33	203.97	17.26	73.61
	blue	218.72	275.34	47.02	83.75
	purple	280.27	343.99	19.84	70.13
J<35	brown	5.55	93.11	15.86	44.36
	green	103.44	210.67	15.13	46.35
	blue	242.36	264.66	31.86	80
	purple	280.71	362.13	22.26	69.04

The evaluation method for the categorical color rendering has an idea similar to percent overlap developed by Boynton et al [64]. The comparison was made between the color category area under the reference source and those of the test sources. Fluorescent lamp simulated as CIE standard illuminant D65 was selected as reference illuminant.

Four color-chips which lie on the boundary of the fun shape area in the hue circle for each of eleven basic categories under the reference source are selected as reference color sample. Let the region of this reference color sample of each color name be S_i (i corresponds to each color name). Lightness (J), chroma (C) and hue angle (h) of these four color sample under the test light source are calculated to obtain region S_t. The overlap region area between S_i and S_t are determined which give the same color under the two different light sources. The categorical color rendering index for each color name is then calculated by using:

$$CCRI_i = 100 * \frac{S_i \cap S_t}{S_t} \quad \textbf{(76)}$$

Where,

$CCRI_i$	is the categorical color rendering for each test sample
S_i	is region of four reference color sample under reference illuminant
S_t	is region of four reference color sample under the test light source
$S_i \cap S_t$	is the overlap region area between S_i and S_t

This index measures the percentage of color samples named with the same color category as those under the reference illuminant.

General categorical color rendering index $CCRI_a$ is calculated by taking the average of CCR_i for eight basic color names (three achromatic color names are not included) and using equation:

$$CCRI_a = \frac{\sum_{i=1}^{8} CCRI_i}{8} \quad \textbf{(77)}$$

Where,

$CCRI_a$	is general categorical color rendering index
$CCRI_i$	is categorical color rendering for each test sample

4.8 Gamut Area Index (GAI)

The gamut area index (GAI) introduced by *Rea and Freyssinier* [11] is based on the work by Thornton on color saturation and hue discrimination [65]. GAI is based on the idea that an increase in the chroma of colored objects or an increase in the color discrimination generally has a positive impact on the perceived color quality [10]. Gamut area means the area enclosed within three or more chromaticity coordinates in a given color space [66]. For color rendering purpose, gamut area of light source is calculated as the area of polygon defined by the chromaticities of the eight CIE standard color samples (same eight color samples used to calculate CIE CRI) in CIE 1976 u´, v´ chromaticity diagram when illuminated by the test light source [10]. Figure 24 illustrates gamut area associated with different kind of light sources. Generally, when the gamut area (GA) of light sources is larger, object colors will appear more saturated under the light sources. Gamut area is more sensitive to hue saturation and hue discriminability than color fidelity [11].

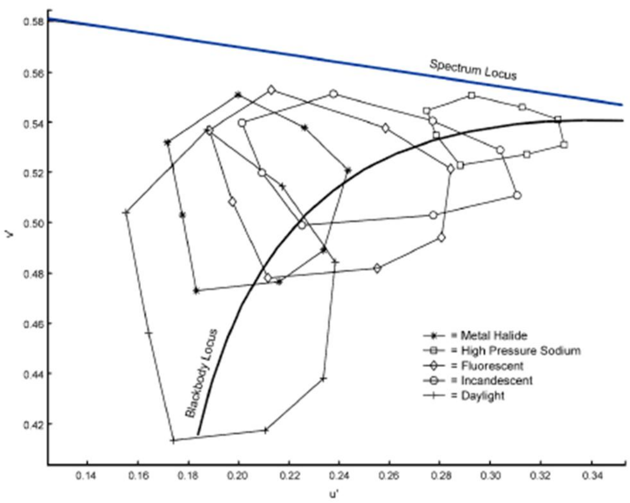


Figure 24. Gamut area of different light sources **[11]**.

To calculate Gamut area index, equal energy stimulus (EES)[1] is chosen as a reference illuminant. A step by step procedure to calculate gamut area index for any light source is shown below:

Step 1: Determine the CIE 1931 tristimulus value (X, Y, Z) for each test color samples under test source by using the equations 1 to 3.

[1]An EES is a mathematically defined illuminant that is used as the reference for GAI and which has a CRI of 95 and a CCT of 5455K.

Step 2: Compute the CIE 1976 u´, v´ values for each test color samples when illuminated by test source by using the tristimulus values obtained in step 1 and using equation:

$$u' = \frac{4X}{X+15Y+3Z}$$

$$v' = \frac{9X}{X+15Y+3Z} \quad \textbf{(78)}$$

Where,

X, Y, Z	are the CIE tristimulus values
u', v'	are chromaticity coordinates of CIE 1976 chromaticity diagram

Step 3: Calculate the gamut area ($GA_{test\ source}$) of the polygon defined by the CIE 1976 u´, v´ values of each test color samples when illuminated by test source.

Step 4: Similarly, using same Steps from 1 to 3 calculate the gamut area (GA_{EES}) of the polygon defined by the CIE 1976 u´,v´ values of each test color samples when illuminated by reference illuminant (Equal Energy Stimulus). Figure 25 shows the chromaticity values of the eight test color sample when illuminated by the equal energy stimulus (EES) in the CIE 1976 u´, v´ diagram. The gamut area of eight test color samples under equal energy stimulus is 0.007354 [67].

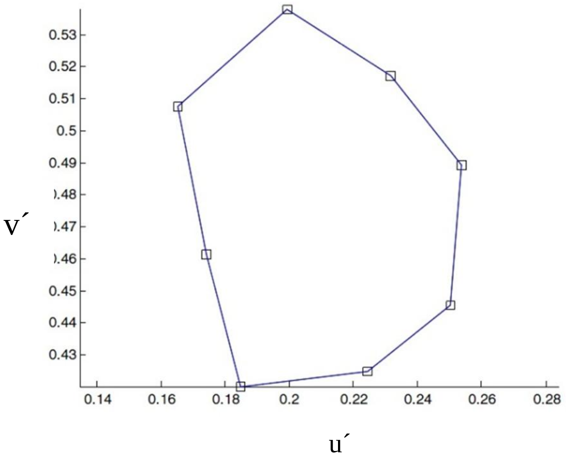


Figure 25. Chromaticity values of the eight test color sources illuminated by the equal energy stimulus in the CIE 1976 u', v' color space **[67]**.

Step 5: Calculate the gamut area index (GAI) of the light source by using:

$$GAI = 100 \times \frac{GA_{test\ source}}{GA_{EES}} \quad \textbf{(79)}$$

Where,

GAI	Gamut area index of the test light source.

$GA_{test\ source}$	Gamut area of the eight test color samples under the test source.
GA_{EES}	Gamut area of the eight test color samples under the equal energy stimulus (EES) which is equal to 0.007354.

GAI value of 100 is assigned to Equal Energy Stimulus and the gamut area of any light source is scaled accordingly. The GAI value of test light source can vary from zero to more than hundred. Rea and Freyssinier suggest that the GAI should be used to complement CIE CRI and reported that light sources with $80 \leq GAI \leq 100$ and CIE $CRI \geq 80$ ensures a natural and vivid appearance of objects [10].

4.9 Monte Carlo Method for Assessing Color Rendering Quality

The CIE CRI determines the degree of color distortions produces by test source for a small number of test color samples of specified spectral reflectance distribution. However, there is no clear objective principle for selecting these few samples and selection process can be characterized as arbitrary.

A Monte Carlo method for assessing color rendering properties of light sources developed by Whitehead and Mossman [68] considers all plausible object reflectance. This method assess the color rendering characteristics of light sources through investigation of very large numbers (one thousand or more) of representative reflectance spectral distributions that span the full multidimensional range of possible spectral distributions and colors.

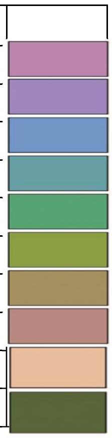
4.10 Flattery Index (FI)

Judd proposed a flattery index in 1967 to supplement the CIE color rendering index because of the concern that the CIE CRI of light source may correlate poorly with public preference of the source for general lighting purposes [37]. Flattery index is based on the work of sanders [36] and Newhall et al. [69] on preferred and memory colors. People remember the color of the familiar objects which are more vivid and saturated and this memory color is consistent with preferred color [70]. For example, skin tones are preferred to appear redder and more saturated than perfect fidelity [36] while color of green leaves and grass are preferred to appear less yellow and slightly more saturated than they really are [37]. However, the CIE CRI penalizes lamp for any distortions from the true color of objects produced by the test light source. Judd idea was that if light source of low CIE CRI was preferred for general lighting to one of high CIE CRI, then some of the distortions were preferred by the observers than the true color of the object [37]. The Flattery index evaluate the degree to which an illuminant succeeds in flattering objects viewed under it and describes whether a light source renders color in a more pleasant (flattery) way than the other or not.

The basis of flattery index is similar to the CIE CRI except that the target colors were not the true sample colors, but instead were the preferred sample colors viewed under the standard reference source. It uses 10 of the 14 Munsell reflective samples (samples 1 to 8 and 13, 14 of the samples used in CIE CRI). Flattery index does not treat all sample color shifts equally instead based on psychological studies, preferred shifts are specified for each sample. Different weights (percentage of the total) of color sample are used to obtain chromaticity difference. About one-third of the total weight is given to human complexion color, another about one-third of the total weight to food color, and the remaining weight is distributed equally among other six text samples not representing human complexion or foods. Table 8 shows the test color samples with their Munsell notation and the weight percentage used to calculate average color difference of each sample.

Table 8. Test samples used in Flattery Index with their Munsell notation and weight percentage **[37]**.

Test Sample	Munsell Notation	weight percentage
1	7.5R 6/4	5
2	5Y 6/4	15
3	5GY 6/8	5
4	2.5G 6/6	5
5	10BG 6/4	5
6	5PB 6/8	5
7	2.5P 6/8	5
8	10P 6/8	5
13	5YR 8/4	35
14	5GY 4/4	15



The flattery index of test source might have higher score than the reference source [37]. The method for selecting the reference illuminant is the same as that used in the CIE CRI. Judd assigned the reference illuminant a value of 90 reserving the value of 100 for a hypothetical ‘perfect’ illuminant. A ‘perfect’ illuminant would be one that would shift the 10 test sample colors to the preferred positions within the 1960 CIE u, v chromaticity diagram.

In order to maintain computational similarity to the CIE CRI and establish value of 90 for reference illuminant, the preferred color shifts were reduced to one fifth of the experimental value. The final formula to compute Judd's flattery index is given by:

$$R_f = 100 - 4.6\left(\overline{\Delta E_{f,k}}\right) \quad \textbf{(80)}$$

Where,

R_f	is the Judd's flattery index for test light source
$\left(\overline{\Delta E_{f,k}}\right)$	is the weighted arithmetic mean of the chromaticity difference between the chromaticities of the ten samples under the test source and the chromaticities of the reference illuminant corrected by one fifth of the preferred chromaticity shift

4.11 Color Preference Index (CPI)

Color preference index introduced by Thornton [71] is based on the work of Judd's on color preference. It is very similar to the Judd's flattery index expect for a few differences as mentioned below [72].

1. Only the first 8 Munsell color samples are used.
   Judd uses CIE test colors 1-8, plus 13 and 14 in the calculation of Flattery index whereas Thornton uses only test colors 1-8 in the computation of CPI.
2. Thornton preserves the original magnitude of the preferred chromaticity difference whereas Judd reduced the chromaticity difference to one fifth of the experimental value.
3. Thornton applies equal weighing to the test sample but in Flattery index Judd applies differential weights to the test samples.
4. Thornton assign a value of 100 to reference illuminant D65 with maximum value of 165 but Judd assigns a value of 90 for reference illuminant with maximum possible value of 100.

Thornton's formula for calculating color preference index (CPI) is given by:

$$CPI = 156 - 7.18(\overline{\Delta E}) \quad \textbf{(81)}$$

Where

CPI	is Color Preference Index
$\overline{\Delta E}$	is the airthematic mean of the color shift in the CIE 1960 uniform color space

4.12 Color Discrimination Index (CDI)

Color discrimination of an illuminant is a measure of the extent to which the illumination allows the observer to discriminate between large varieties of object colors when viewed simultaneously [73]. There are certain visual tasks which require easy discrimination among colors. An example is wiring task with color-coded wires in numerous colors, some of which are not easily and rapidly distinguishable under common light source. Distinguishing the red car in a parking lot lit by mercury vapor lamps and balls at the billiards by means of color illuminated by light composed of a single pure color can be very difficult. Hence, for such and similar tasks a light source affording the observer a maximum of color-discriminating capability is desirable. Perception of color difference is essential in color discrimination.

Thornton recognized the capability of a light source to allow for good color discrimination as an important aspect of color rendition and proposed the color discrimination index (CDI) [73]. CDI is scaled so that reference (CIE illuminant C) has a score of 100 but it is possible for sources to score greater than this reference. CDI is proportional to the gamut area enclosed by the eight test color samples used in the calculation of CIE CRI in the 1960 CIEUCS diagram. Light source yielding a small gamut area implies difficulty in discriminating among the object colors and hence have poor color discrimination capability whereas light source having a larger gamut area implies the better color discrimination capability. Color discrimination of the illuminant depends on the average color contrast between the neighboring objects in the field of view and perception of color [73]. The color discrimination index is given by the equation (3).

$$CDI = \left(\frac{GA_{test}}{GA_c}\right) \times 100 \qquad \textbf{(82)}$$

Where,

CDI	is the color discrimination index
GA_{test}	is the gamut area of the test light source
GA_c	is the gamut area of CIE illuminant C (average daylight) which is equal to 0.005 square units

4.13 Cone Surface Area (CSA)

Cone surface area is a gamut area based index introduced by Fotios [72] in 1997. This metric combines measures of gamut area of the first eight test samples of the CIE CRI with the source chromaticity in the CIE 1976 u´ v´ chromaticity diagram. Cone surface area is the surface area of color cone with a base area of the same size as the octagonal gamut area of the first eight CIE CRI test samples plotted in the CIE 1976 u´ v´ chromaticity diagram and a height equal to w´ in the same color space. The formula to calculate cone surface area (CSA) is given by:

CSA = area of base (gamut area) +curved surface area

$$\text{CSA} = \pi r^2 + \pi r l \qquad \textbf{(83)}$$

Where,

r	is the radius of base of cone which is equal to $\sqrt{\frac{GA}{\pi}}$
GA	is the gamut area in 1976 CIE u´ v´ diagram
l	is the length of the slope of the cone which is equal to $\sqrt{(r^2 + (w')^2}$
w’	is the perpendicular height of the cone and is given by $w' = 1-(u' + v')$

5 Discussion and Conclusion

Color quality of light source is important for its acceptability and usefulness. CIE CRI is the only internationally recognized and widely used metric to evaluate the color rendering properties of light sources. CIE CRI has been used for many years. However, both colorimetry and light source technology have advanced significantly since the development of CIE CRI and various problems with CIE CRI have been identified. Moreover, there are several visual dimensions of color rendition such as color fidelity, visual clarity, color discrimination, color preference, color harmony, color acceptability etc. CIE CRI measures only color fidelity aspect.

CIE Technical Committee TC 1-62 “Colour rendering of white LED light sources” [74] concluded that current CIE CRI does not always describe visual colour rendering correctly, especially in case of white LEDs. In response to the conclusions of TC 1-62, a new technical committee TC 1-69 “Colour rendition by white light sources” was established in 2006. The objective of TC 1-69 is to investigate new methods for assessing the colour rendition properties of white-light sources used for illumination, including solid-state light sources, with the goal of recommending new assessment procedures. TC 1- 69 also agreed that new metric to have one number output (with optional supplementary indices for expert user) with scaling similar to CIE CRI [13]. A wide variety of approaches have therefore been proposed. Some of the proposed metrics address specific aspect of color rendition like flattery index, color preference index, color discrimination index, feeling of contrast index, color harmony index, gamut area index. Other metrics such as color quality scale and memory color rendering index try to represent more than one aspects of color rendition. Those metrics which only addresses specific aspect of color rendition are intended to be used in conjunction with final metric.

The color quality scale is a mixed metric which measure both color fidelity and color preference. It does not penalize light sources for saturation. The CRI-CAM02UCS has many similarities with the CIE CRI, but uses a uniform object color space based on the CIECAM02 color appearance model. The rank-order based color rendering index (RCRI) ranks the color quality of light sources and is easier to interpret for non-professional users. The memory color rendering index (MCRI) evaluates color rendering properties of light source based on how closely rendered object colors match with people's memories for the color of familiar objects. MCRI does not need any reference illuminant. Reference is done to the people idea of what certain familiar objects should or can look. The feeling of contrast index (FCI) is designed to measure the "visual clarity" that a light source makes when illuminating objects. The color harmony rendering index (HRI) measures how pleasing color combinations appear under a test source. The categorical color rendering index (CCRI) assesses lamps color rendering performance based on whether the categorical color names assigned to objects remains the same or changes. GAI is intended to supplement the CIE CRI to ensure a natural and vivid appearance of objects. A Monte Carlo method for evaluating lamp performance considers all plausible object reflectance factors. Flattery index (FI) is intended to supplement the CIE CRI with information on public preference. Color preference index (CPI) is similar to Flattery index which give information on public preference. Color discrimination index (CDI) is a measure of the extent to which the illumination allows the observer to discriminate between large varieties of object colors when viewed simultaneously. Cone surface area (CSA) combines measure of gamut area and the chromaticity of light itself.

At the CIE division 1 meeting held in Princeton, a proposal was made to recommend nCRI-CAM02UCS (CRI-CAM02UCS with revised sample sets) and CQS. There has been disagreement among the experts to accept two recommendations for same purpose. CRI-CAM02UCS is a true fidelity metric, calculations are up to date with improved data and more color samples set, and it does not change the quality score of current lamps. CQS as it is mixed index (fidelity and preference) creating ambiguity about the effect of the light source (no penalty on saturation). Hence, traditional lamp industry concerns that the concept underlying the CQS deviates from the CIE CRI [39].

Smet et al. [46] did experiments to check performance of the proposed thirteen metrics including CRI-CAM02UCS and CQS [15]. Metrics were evaluated by calculating the average correlation of metric predictions with visual scaling of perceived color quality obtained in several psychological studies. Memory color rendering index (MCRI) was found to be statistically better at preference or attractiveness than all other metrics. A metric that combines CIE CRI and gamut area index (GAI) found to be statistically better at predicting naturalness than other metrics. This result shows that other metrics like MCRI and CIECRI+GAI can performs better than CRI-CAM02UCS and CQS. Although, MCRI is promising due to elimination of reference source, it needs more study on memory color of different cultures and scaling. Addition of GAI with existing CIE CRI is simple however existing CIE CRI has many problems and TC 1-69 already agreed on one single number output [75]. Moreover, if two numbers are used general user would be confused about which metrics to be used and what is the difference between them. Hence, without updating or modifying current CIE CRI, two-metric approach by complementing CIE CRI with GAI may not be the best solution.

It is very difficult to integrate every aspects of color rendition into single metric that define overall color quality of light source. Hence, determining which aspects of color rendition corresponds best to people's judgements of color quality is important before finalizing the metric. If color fidelity alone found to corresponds best to people's judgements of color quality, then CRI-CAM02UCS should be choosen as final metric. If intergration of color preference and color discrimination with color fidelity is found to corresponds best to people's judgements of color quality, then color quality scale should be choosen as final metric. However, if comparing an object color under light source with people's memory color corresponds best to people's judgement of color quality then memory color rendering index should be choosen as a final metric. Further research works in the direction of determining which aspects of color rendition corresponds best to people judgements of colory quality is necessary.

A good method for measuring color rendering properties of light sources is necessary to satisfy the consumer expectation of color quality in different applications and to enable the lamp designer to develop light sources having good color quality. If a flawed method is used, light sources with poor color quality may be unknowingly encouraged. New metric should be simple to use, evaluate purely the visual perception and should not limit or affect the choice of technology.

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