Evaluation of Color Rendition indices for LED lighting in merchandising spaces

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Abstract- This paper aims to develop metrics for the evaluation of color rendition of LED light sources in merchandising spaces. Influential factors for a LED light source, such as correlated color temperature, illuminance, and color rendering index (CRI) have been proposed as part of a sustainable lighting application strategy. However, there are several problems with the CRI. The factor analysis used in this research is focused on the properties of the LED light source, and various combinations of twenty existing and proposed alternative metrics were analysed for the LED illumination evaluation method. LED spectral power distribution should be designed for high luminous efficacy as well as good color rendering. Optimised LED light source increases color saturation and has a good color discrimination capability. Our results indicate that two complementary assessments should be developed to characterise the features of a LED light source for merchandising lighting application. Saturation enhancement or hue shift are core common categories for different types of merchandising lighting. For example, a combination of CRI below 80, high enough CRI R9, and Color Quality Scale (CQS) is recommended in supermarkets, while CRI over 80, sufficiently high CRI R9, and Feeling of Contrast Index (FCI) is recommended for lighting in clothing retail stores.
Keywords –Light Emitting Diodes (LEDs); Merchandising spaces; Color Rendering Index (CRI); Color Quality Scale (CQS: Qa, Qf, Qp, Qg); Feeling of Contrast Index (FCI)

I. INTRODUCTION

The U.S. Department of Energy (DOE) has been conducting solid-state lighting (SSL) research and development (R&D) projects since 2000. The central strategy for the research provides analysis and direction to develop SSL technology and maximise energy savings. SSL products are currently on the market that are based on DOE-funded R&D [1] and SSL technology is expected to grow in the future. Usage of developed LEDs means that there is a requirement for an application standard in commercial spaces [2]. LEDs, a type of SSL, are revolutionizing the lighting market [3].

In 2013, the Illuminating Engineering Society of North America (IES) investigated how the light spectrum affects vision, and consequently published IES TM-24-13. According to this publication, which illustrates the standards of LEDs for commercial and industrial interior lighting, correlated color temperature (CCT) and illuminance are two determinants that decide illuminance maintenance recommendations for visually demanding tasks [4]. Illuminance is used to maintain equal spatial brightness perception and visual acuity. Visually demanding tasks, including reading tasks as well as other critical vision tasks, require efficient performance. However, the task performance is also determined by the color-rendering performance. The color qualities of spectrally enhanced lighting are characterised by two attributes: the color appearance of a lamp and the color-rendering capabilities. An International Standard was specified in lighting quality figures for the lighting of workplaces in 2002. That Standard describes the lighting requirements for a sustainable building environment, which includes CCT, illuminance, and CRI [5].

The color rendering index (CRI) is the only international criterion for measuring the effect of an illuminant on the color appearance of objects. The International Commission on Illumination (CIE) established the Technical Committee (TC) to standardise a method of CRI calculation in 1965. The CRI was modified in 1974 and 1995, and its criteria have been continuously updated [6]. The current CRI has limited information to enable light sources to characterise the multidimensional experience of color. Advancements in LEDs have resulted in questions about how we use and consider the CRI [7]. The CRI yields values based on the distributed broadband spectra. The CIE standard illuminant, namely an incandescent lamp, provides the highest level of color rendering [8]. However, a narrow-band LED achieves the highest color rendition available using a different approach, and creates an emission spectrum that is not based on the continuous spectrum [9].

The relationships between CCT and illuminance, and CCT and the CRI are examined in order to predict influential factors in architectural lighting applications. Ohno [10] analysed LED models that should be optimised for both of these aspects. The CIE summarised in a technical report that the CRI alone is limiting for evaluating a light source’s color rendition [11]. To address the problem of the one-dimensional CRI, the CIE founded two Technical Committees, TC1-90 and TC1-91 [12]. The IES developed a two-measure system which considers color fidelity and color gamut type metrics, Rf and Rg [13]. This system is adopted in the IES TM-30-2015 and is proposed for consideration with the CIE. However, the TM-30 method provides evidence beyond average fidelity and average perception-related color quality effects beyond color fidelity [14, 15]. It is less clear how these average measures may translate into value for the end user in an actual application. In addition, in 2017, the CIE published the CIE 2017 Color Fidelity Index for Accurate Scientific Use [16]. However this color fidelity index based on characterizations provided by TM-30 describes an objective aspect of differences between colors as rendered by a test source and reference illuminant. Therefore, the factor analysis in this study has expanded the alternative metrics of the CIE's two TCs. International criteria to complement the CRI have not been established [17, 18, 19, 20, 21]. This study provides recommendations for applying LED lighting by analyzing the metrics to evaluate the factors that influence merchandising lighting.

1.1 Influential factors for merchandising lighting applications

Lighting is an important element integrated with architectural design, as it helps us to "understand" a space and contributes to our emotional and physiological responses [22]. While it is also important to reduce the energy consumed by lighting systems in commercial buildings, making merchandise in a store look good is generally considered more important than energy saving for illuminants [23]. The assessments for lighting systems in commercial buildings are able to be characterised by three attributes: CCT, the CRI, and illuminance. In this study, influential factors for merchandising spaces will be discussed.

1.2 Influential factors: CCT, Illuminance, CRI

In 1931, the CIE recommended three standard illuminants, designated A, B, and C. The CIE illuminant A and D65 are referred to as standard illuminants [24]. CCT together with illuminance has been described by the Kruithof graph as yielding pleasing visual conditions for interior lighting. Combinations of CCT and illuminance have been cited as a design tool. The Kruithof graph gives information for the acceptable color temperature of light sources at various illuminance levels. However, the Kruithof hypothesis was criticised in many research papers as providing insufficient evidence to support the combinations of CCT and illuminance[25]. Fotios studied empirical data to find evidence in favor of Kruithof in a lighting design relation. Table 1 shows that the CCT depends on the categories of retail markets. CCT is classified as low end (mass merchandising), middle end, and high end (exclusive) [22, 23].

Table -1 CCT by categories of retail markets (IESNA)

Category	Retail Market	CCT (K)
Low end	Mass merchandising	3500 to 5000 K
Middle end	General	Neutral
High end	Exclusive (decorative, accent, ambient)	2700 to 3000 K

Note: CCT = Correlated Color Temperature

Illuminance has a major impact on carrying out a visual task. Regarding the recommended illuminance in a merchandising space, merchandise and displays should be at least three times brighter than the general illuminance (which is typically between 300 and 1000 lx). The customer should be attracted to specific merchandise on the shelves. Table 2 lists the current recommended illuminance for merchandising spaces [22, 23].

Table -2 Currently recommended illuminance for merchandising spaces

Areas or Tasks	Description	Type of Activity Area	Illuminance (lux)
Circulation	Area not used for display or appraisal of	High activity	300
	merchandise or for sales transactions	Medium activity	200
		Low activity	100
Merchandise	The plane area, horizontal to vertical,	High activity	1000
	where merchandise is displayed and readily	Medium activity	750
	accessible for customer inspection	Low activity	300
Feature displays	Single item or items requiring special	High activity	5000
	highlighting to visually attract and be set	Medium activity	3000
	apart from the surroundings	Low activity	1500

The CRI was introduced to ensure that colors are rendered naturally in an environment. The color-rendering properties of a light source have a maximum of 100 values to provide an objective indication. The CIE standard illuminants mimic the spectrum of the Sun or a blackbody. Table 3 shows the required values specified by the CIE for the retail and food industry. The recommended minimum value of the general CRI for merchandising lighting applications is given as over 80 [5].

Table -3 Lighting requirements for retail outlets and bakeries (source: ISO 8995:2002(E), CIE S 008/E-2001)

Retail Outlets	Illuminance (lux)	CRI (Ra)
Type of interior, task, or activity		
Sales area – small	300	80
Sales area – large	500	80
Till area	500	80
Wrapping table	500	80
Bakeries		
Type of interior, task, or activity		
Preparation and baking	300	80
Finishing, glazing, decorating	500	80

Note: CRI = Color Rendering Index

1.3 Influential factors for merchandising lighting applications

Lighting design criteria employ CCT, illuminance, and the CRI to determine if the function performs appropriately for environmental architecture lighting. A comprehensive review of relevant papers has been conducted for two aspects: the maintenance and the color aspect of the light and surfaces. In this study, a proposed compromise between the two aspects is investigated.

1.4 Maintained illuminance

The illuminance and its distribution in the task and surrounding areas have a major impact on the visual task. The recommended lighting levels for each task are described as maintained illuminance. CCT and illuminance are related in determining maintained illuminance [5]. Many studies have explored the effect of illuminance on visual response [26, 27, 28, 29].

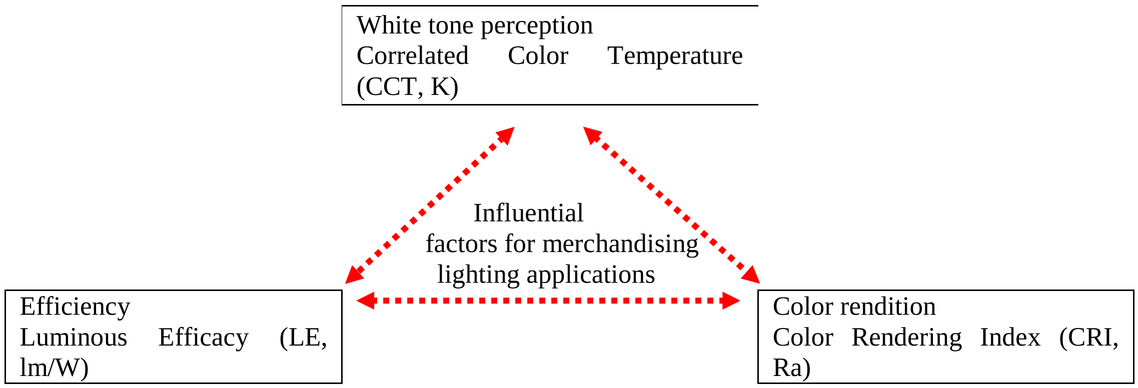
Hu, Houser, and Tiller [26] summarised the significant spectral power distribution (SPD) lumen output effect on lamp brightness. In their psychophysical experiments, CCT and lumen output were not related. An illuminant's spectral properties contributed to the perception of the illuminant's brightness. Houser, Fotios, and Royer [27] investigated the effect of SPD on brightness perception with LEDs. Fotios et al. [28] investigated credible evidence of SPD effect and brightness perception. However, in their study, SPD is not the only determinant that affects brightness perception. Wei et al. [29] found that LEDs with diminished yellow emission make a great contribution to preference and provide higher brightness than a blue-pumped LED at the same illuminance level. Their study was performed to examine how LED sources with spectral optimization can provide higher brightness at a certain illuminance level so that equivalent brightness can be achieved with a lower illuminance level, leading to lower energy consumption.

II. COLOR ASPECT

Another aspect to be considered as a critical principle in merchandising spaces is the color aspect. The CCT is the apparent color of the light emitted [5]. The CRI is an indicator for evaluation of the color-rendering properties of a light source in 1965 [30]. However, the CRI cannot accurately characterise light source spectra from the general point of view of color rendition or color quality. The CIE's CRI considers all CCTs equally. Two sources with the same CCT may look very different. Two directions were used in this study to provide additional information about SPD performance that is unavailable from the CRI. The color discrimination index (CDI) [31] and color preference index (CPI) [32] are indicators for describing complementarity. The CDI quantifies a specific light source that comes with a larger gamut area, leading to higher color discrimination capability. The CPI is an indicator of the ability to enhance the color appearance of illuminated objects. As will be discussed later, the CDI is related to the feeling of contrast (FCI) [18]. The CPI is related to the color quality scale (CQS) [17].

Maintained illuminance and color aspect for LED light sources

The results of factor analysis on lighting applications reveal that the key determinants for LED light sources which foster a sustainable strategy for lighting applications are: CCT, illuminance, and CRI. The three factors can be described by white tone perception, efficiency, and color rendition. This paper concentrates on the lighting quality in relation to the maintained illuminance and color aspect. Both aspects are indispensable requirements for performing tasks in spaces. The difference between luminous efficacy and luminous efficacy of radiation (LER) is addressed as color rendering to characteristics of light sources for general lighting [10]. The U.S. DOE specifies minimum requirements for both the luminous efficacy and the CRI for light sources [1]. As LED technology evolves, it has replaced traditional incandescent, fluorescent, and high-intensity-discharge (HID) lamps [33]. The literature review shows that maintenance and color aspects must be considered together in merchandising spaces. Figure 1 shows a schematic diagram of influential factors for merchandising lighting applications.



Schematic diagram of influential factors for merchandising lighting applications

Reference gamut-based methods for evaluating color-rendering properties of LED light sources

During this study, the CRI and alternative color rendition indices for characterizing LED light sources were analysed in detail. The following review is based on considering previous relevant research, which presents several limitations of the current CRI and the need for improvements, and consequently discusses alternative measures to assess a new method for LED light sources for color rendition.

Problems of the CRI for LED light sources

The CRI has several problems when applied to an LED light source. It does not take account of the accurate rendition of the colors, color preference, or color discrimination capability of a light source. These are noted as poor rendering flaws of saturated red, saturation enhancement, and degraded colors under a CCT of 3500 K [10, 34, 35].

Firstly, the problem with the CRI is that for LED light sources it performs poorly with saturated red colors, but still has high values [34, 35]. Photons of blue light have high energies, while photons of red light have low energies [36]. The energy efficiency of a light source has a problem caused by a decrease in the long wave part of the spectrum, leading to poor rendering of the saturated red color. Ohno proposed LED models to analyze the possible performance of white LEDs. Various LED spectra (multi-chip and phosphor types) were modeled and analysed in comparison with conventional lamps. 3-LED-1 is a three-chip LED model optimised for the highest LER at Ra=80 and 3300 K, and has a very high LER (K=409 lm/W). However, 3-LED-1 exhibits very poor rendering of red. 3-LED-2 has the same CCT and CRI values, but exhibits good rendering of all the four saturated colors. The red spectrum is modified from 605 to 616 nm [10]. However, the lighting quality should always be high enough to be sufficient for visual performance. The luminous efficacy of radiation (LER) does not include color quality information about how natural the colors of objects look under given illumination. Therefore, Table 4 concentrates on the comparison of CRI Ra and CRI R9 for LED light sources. It shows CRI R9 should be considered for evaluating saturated red colors.

Table -4 Comparison of CRI Ra and CRI R9 for different light sources

Light Source	Description	CCT (K)	LER (lm/W)	CRI (Ra)	CRI (R9)	R (9–12)
CIE Standard Illuminant A	Incandescent/Tungsten	2856	248	99		
CIE Standard Illuminant D65	Noon Daylight	6504	248	100		
Monochromatic radiation	507 nm		303			
Monochromatic radiation	555 nm		683			

PHOS-1	Phosphor model, warm white (400–700)	3013	253	99		
PHOS-2	Phosphor model, warm white (450–650)	3007	370	86		
3-chip LED: 3-LED-1	RGB LED (457/540/605)	3300	409	80	-90	27
3-chip LED: 3-LED-2	RGB LED (474/545/616)	3300	359	80	89	88
3-chip LED: 3-LED-3	RGB LED (465/546/614)	4000	370	89	65	64

Secondly, the characterization of LED light sources is not determined by fidelity alone but also by color saturation. The eight-test color samples used in calculating the CRI are medium-saturated colors. A light source can perform well with a desaturated color sample, but poorly with a saturated color sample. Ohno [10] carried out a simulation to improve the color rendering of saturated red colors. Colors of the 14 samples in CIELAB space under illumination by the three-chip LED model (455/547/623) yielding CCT=3300 K, Ra=73, R_9–12_=50, K=363 lm/W, and the reference source (Planckian) are compared. In that study, it was shown that a three-chip LED light source can produce enhanced color saturation.

Thirdly, a different light source will lead to a different spectrum of illumination and, consequently, different discrimination capabilities [31]. The CRI of a light source does not indicate the apparent color of the light source. The color discrimination capabilities of the CRI reference light source are different at varied CCTs. Thornton compared the color discrimination capabilities of different light sources, the CIE’s six illuminants in daylight at ∞ K and 6500 K, and Planckian radiators at 4000 K, 3000 K, 2000 K, and 1000 K. The results showed that daylight, which offers the possibility of obtaining white light, has a high color-rendering capacity [31]. Royer, Houser, and Wilkerson [37] performed a test to examine the capability of LEDs, two fluorescent lights, and one tungsten halogen light. Xu, Luo, and Royer [38] conducted an experiment to predict the discrimination capability of an LED light source. They found that the high discrimination capability of an LED light source was located in three wavelength regions: approximately 425 nm, 505 to 525nm, and 660 nm. Davis and Ohno [39] investigated the color discrimination capability of a reference light source at various CCTs. The results show that the color discrimination performance of the reference source degraded below 3500 K and above 6500 K.

A good CRI score does not always provide a reliable description of the good color-rendering properties of LED light sources. The CRI can give a high score to an LED light source that renders saturated red very poorly. However, LED sources have the potential to achieve better color rendering. The saturation of the objects can be enhanced by spectral adjustment (but this saturation enhancement should not be exaggerated).

III. ALTERNATIVE COLOR RENDITION METRICS

Extensive studies have been conducted to develop CRI complimentary methods for evaluating the color rendition of light sources. In this study, twenty alternative color rendition metrics have been investigated to identify important features, which included the CIE Color Rendering Index (CRI), Flattery Index (Rf) [40], Color Discrimination Index (CDI) [31], Color Preference Index (CPI) [32], Color Rendering Capacity (CRC) [41], Color Surface Area (CSA) [42], CRI-CAM02UCS [43], CRI 2012 [30], Gamut Area Index (GAI) [19], Color Quality Scale, (CQS: Qa, Qf, Qp, Qg) [17], Feeling of Contrast (FCI) [18], Memory Color Rendering Index (MCRI) [20], Harmony Rendering Index (HRI) [44], Preference of Skin Tone Index (PS) [21], IES TM-30 (Rf and Rg) [13]. We supposed that such methods are correlated with the final prediction performance for merchandising lighting applications.

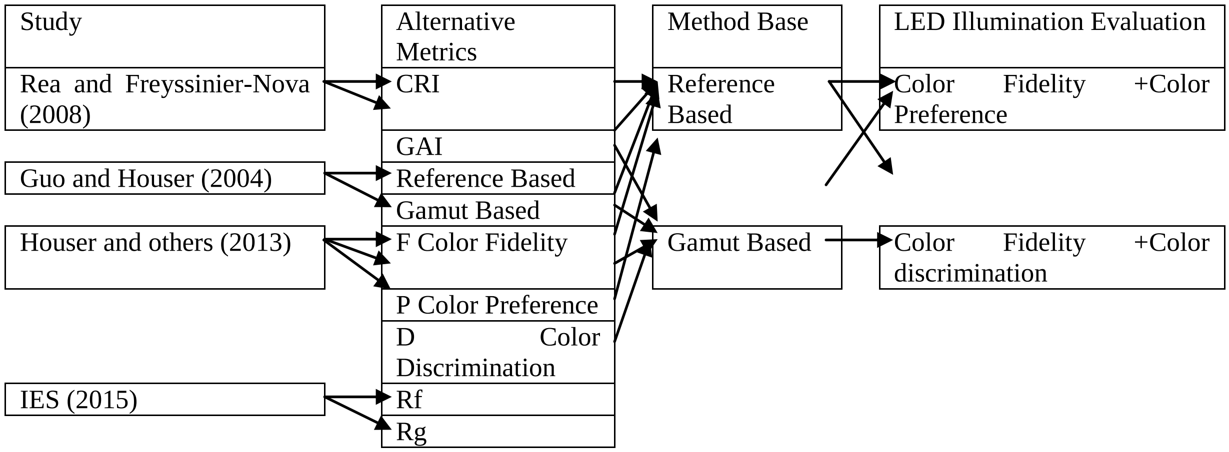
Two complementary assessments for LED light source

Classification of alternative metrics for LED light source

In Rea and Freyssinier-Nova [19], Guo and Houser [45], Houser et al. [46], and IES’s study [13], an indices analysis was performed to investigate a method for evaluating the color rendition of light sources. Rea and Freyssinier-Nova [19] proposed using two measures: CRI for fidelity and GAI for gamut. GAI provides additional information to describe the color discrimination ability of light sources. Guo and Houser [45] distinguished eight measures of color rendition using a two-measure system based on either the reference method or the gamut-based method. Houser et al. [46] reviewed twenty-two measures of color rendition and classified the various indices into three groups regarding the limitations of a single index CRI: color fidelity, color preference, and color discrimination. In that study, the effects of color preference and color discrimination were assessed to characterise overall color rendition. IES [13] developed a two-measure system using color fidelity, Rf, and the color gamut, Rg. This is an improved version of the CIE CRI and the gamut area index.

Previous studies have established a method basis for evaluating the color rendition of light sources. These measures can be grouped into one of three categories: color fidelity, color preference, and color gamut. A method can be grouped into the two-measure system. One is a reference-based method, and the other is a gamut-based method.

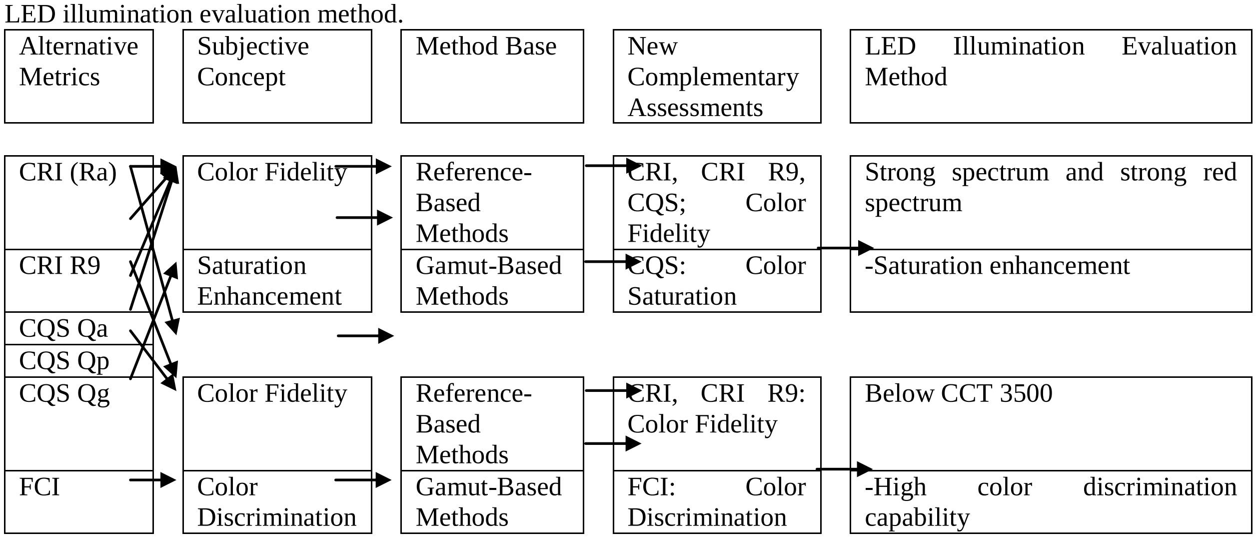
Figure 2 aims to express the two methods for final lighting applications based on a comparison between reference and gamut methods.



An analysis of reference gamut based methods for LED lighting evaluation

The classification of alternative metrics for LED lighting illumination evaluation method

Two complementary assessments in relation to the combination of the reference and the gamut method are developed in order to address the current problems with the CRI in an LED's spectral power distribution. The new assessments help enhance luminous efficacy and improve color rendering by augmenting the color saturation and color discrimination capability. Figure 3 shows two complementary assessments for LED illumination evaluation. Considering the number of limitations faced by the CRI when characterizing a LED light source, a combination of CRI Ra, CRI R9, CQS Qa, Qp, Qg, and FCI is investigated. The first assessment is that CRI, CRI R9, and CQS evaluate the combined effects of color fidelity and color saturation. The second assessment is that CRI, CRI R9, and FCI are set to enhance the improvement color discrimination capability of the LED light source. The abovementioned analysis proves that single metrics have limitations, but the new assessments can be applied to an LED illumination evaluation method.



Two complementary assessments for LED illumination evaluation

Spectral optimization and two complementary assessments to merchandising lighting application

The current CRI cannot characterise light source spectra which have been designed for high luminous efficacy and an improved spectrum for red color. A new metric to be proposed in the present article for evaluating the spectral optimization of LED lighting and two complementary assessments for different categories such as fabrics, fruits and vegetables, meat, and bakery products will be described.

Spectral optimization to merchandising lighting application

Freyssinier, Paul, and Rea [47] discussed how the CRI may be augmented to improve its performance as a merchandising lighting system, and proposed guidelines that combine the CRI with a complementary metric. They found that a light source may make colors either duller or more vivid, and GAI provides valuable information complementary to that of Ra. They contended that the light source for merchandising lighting applications should consider a two-measure system.

Feng et al. [48] studied how LED light sources enhanced the color appearance of illuminated objects. They investigated a method to obtain the desired CRI and GAI for enhancing the color appearance of merchandise and to stimulate purchasing behavior. Two types of CRI, 90 and 80, were designed. Clothing with six common colors was selected for the experiment setup. In their study, an LED light with both high CRI and high GAI was used to improve the color appearance of the illuminated objects. They found that good color rendering can increase the GAI without sacrificing the CRI. This demonstrated that GAI can be a useful supplement to the well-established CRI in ensuring that clothes appear more vivid and saturated.

Ohno and Davis [49] conducted studies with fruits, vegetables, and skin tones to verify the CPI while enhancing the saturation of the colors, which led to a higher preference for the objects. The results of the experiment showed that subjects' desire is increased much more by color-enhancing light (Ra=71, Qa=83) than color-desaturating light (Ra=82, Qa=74).

Two complementary assessments of merchandising lighting application

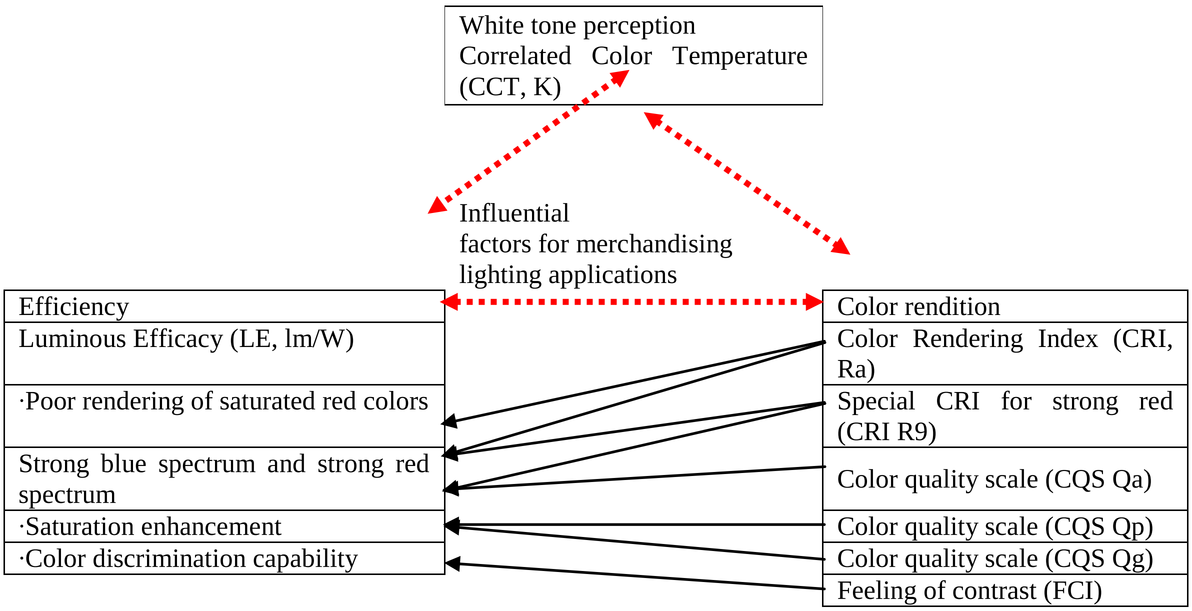
Szabó et al. [50] studied optimal SPDs for shop environments. The focus of their experiment was on the selection of different cloths, fruits and vegetables, and meat and bakery products. They found that subjects preferred an LED light source with a higher FCI when choosing a fabric because of the increased saturation indicated by the higher FCI of the LED light source. However, subjects preferred an optimised LED light source with a high CQS Qp and a high CQS Qg in the fruits and vegetables category because it enhances saturation, and created a higher preference for the illuminated objects. Meat and meat product lighting preferences were different from the other categories which had an optimal LED light source as opposed to a color quality index. A light source that mimicked existing meat SPDs from either a conventional lamp with a filter or an existing LED spectrum was most preferred. Different color quality metrics did not correlate well with the preference evaluation of meat products. However, an LED light source with a low CCT in the bakery product category was rejected by the test subjects. They preferred a reasonable enhancement of the saturation in the bakery product category.

Wei et al. [29] conducted an experiment with two LED light sources in two full-sise side-by-side rooms to test the color preference for illuminated objects. The objects included a mirror, a red apple, a red pepper, an orange, a lemon, a green apple, a cutting board, a bamboo bowl, bamboo utensils, hardwood floors, flowers, towels, and place mats. One room was lit by a typical blue-pumped phosphor product (BP-LED), and the other room had a purposefully designed diminished yellow emission (YD-LED) at 3000 K. Subjects preferred the YD-LED illuminated room. That study found that most color measures characterizing color preference (CRI R9, Qa [CQS 9.0], Qp, Rf, CPI, FCI94, FCI02, MCRI) and gamut-based measures (Qg, CDI, CRC, CRC_Volume, CSA, FM Gamut, GAI) were able to predict the higher overall preference for YD-LED.

Lin et al. [51] investigated the preferred LED light source at 4000 K for three lighting applications: a restaurant, a clothing retail store, and a supermarket. They found that single-value measures could not predict preferences for different lighting applications because color preference is more likely to be a combination of hue shifts and saturation changes. For the restaurant and the clothing retail store, an LED light source with a CRI above 80 and little chroma enhancement was preferred. In the supermarket, an LED light source with a CRI below 80 and the full chroma enhancement was preferred. Such results show that an LED with a CRI value of 80 or more is required in both instances. An analysis of two complementary assessments for LED light with enhanced color saturation was investigated, as shown in Table 5.

Comparison of spectral optimization and two complementary assessments

The purpose of merchandising lighting is to make merchandise look good (David and IESNA 2011). Lighting must be designed to attract customers to a store and allow them to appraise merchandise. This study examined the factors influencing merchandising lighting and compared them with the improved LED illumination evaluation method. The schematic diagram in Figure 4 shows three influential factors for merchandising lighting applications. Two complementary assessments for LED lighting evaluating resulted in order to address the current problems with CRI in LED spectral optimization.



Schematic diagram for spectral modification and two complementary

Many studies that evaluate the color rendition of LED light sources support the two assessments analysis. According to data analysis, one assessment is for evaluating supermarket LED lighting, while the other assessment is for clothing retail lighting. By contrast to the current CRI 80 standard used for all merchandising spaces, as a result of this analysis, CRI values were found to be different for each category. The CRI values were lower than 80 for fruits and vegetables. CRI R9 and CQS (Qa, Qp, Qg) were used to complement CRI, and were tested along with a CRI over 80 and CRI R9, FCI in regards to clothing retail optimization. The recommendation for the lighting of fresh meats was to use CRI values over 80. The result is that the new assessments can be applied to different types of merchandising environments.

IV. CONCLUSION

Several problems with the CRI have been mentioned by different research groups. Various LED models based on literature reviews have had their color-rendering performance compared to their energy efficiency aspects. The shortcomings of the CRI that have been identified are its inability to measure the poor rendering of red, increased color saturation, and color discrimination below CCT 3500 K. These results indicate that a better method for evaluating the color rendition of a LED light has become the focus point of a number of researchers since 2007. The alternative metrics proposed have focused on CIE methods. However, it is too complicated to measure the multidimensional properties of the LED light source. No single metric has been adapted for international use.

For the different types of merchandising lighting applications, this paper has discussed influential factors and comprehensive color rendition indices. The guideline for the complementary assessments has shown that the CRI needs to perform under spectral optimization with high luminous efficacy as well as provide a good rendering of red. In this study, combination metrics were developed based on a comprehensive analysis of LED light sources. Twenty alternative metrics complementary to CRI were compared and grouped into two complementary assessments between reference and gamut methods. The metrics determined whether the saturation of fruits and vegetables is enhanced in the supermarket while the saturation of fabrics is increased in clothing retail stores. The results showed that the combined metrics of low CRI, high CRI R9, and CQS values (CRI below 80) exhibited the recommended values for supermarkets, while high CRI, CRI R9, and FCI values (CRI over 80) are proposed for clothing retail outlets. It was found that the new color-rendering assessments for the technological properties of LEDs are required for the lighting applications in merchandising spaces, where goods should look appealing to customers.

This paper may be valuable for both lighting specification and to help designers gain an overall understanding of the development of alternative metrics for LED lighting evaluation in merchandising spaces. CCT, illuminance, and CRI were discussed in detail to investigate factors that affect lighting assessment methods. Two categories of maintenance and the color aspects of LED lighting were also analysed. In addition, the relationship between energy efficiency and color rendering were examined to identify which sustainable lighting application could be assessed by these methods. Customers will choose appropriate lighting where it is applied in a complementary way. Supermarkets and clothing retail stores should be optimised separately.

It is recommended that the poor rendering of red and saturation enhancement aspects be evaluated as complementary assessment criteria for an LED illumination evaluation method in order to obtain a more comprehensive and thorough review of the project.

V. ACKNOWLEDGEMENTS

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