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An overview for colour rendering indices in Solid State Lighting

1. INTRODUCTION

The solid-state lighting (SSL) has now reached considerable efficiencies that make it suitable for different applications, from general office lighting, retail spaces, without forgetting the possible applications in the domestic sector.
The LED technology has already satisfied the demands of the market and the lighting's designers concerning luminous flux and efficiencies and now the new challenge is represented by the color quality of the emitted light.
The new technologies have provided the opportunity for manufacturers to customize different aspects of a lighting product:

- The intensity distribution in photometric space
- The spectral distribution both in terms of color temperature, and optimizing the color rendering in according to specific lighting application.

The first question to answer is if there are any appropriate instruments for the assessment of the chromatic color rendering, which can be also applicable to new solid state lighting source.
In general we can say that the color rendering index represents the ability of a light source to reproduce the colors of various objects in comparison with a natural or ideal source.
The International Commission on Illumination (CIE), has defined the color rendering index as the effect of lighting on the chromatic appearance of objects (in a conscious or unconscious way) rather than the chromatic appearance under an illuminant reference [1].
The latest (and currently in force) version of CRI (Color Rendering Index) follows CIE's proposed method and it is described in the 1995 publication 13.3, *"Method of measuring and specifying color rendering properties of light sources".*
The CIE color rendering index is based on the direct comparison of a set of eight color samples, each illuminated by two sources, the first one is the light source under test and the second is the reference with equal correlated color temperature.
The test procedure involves comparing the appearance of eight color under the tested light and a reference light source. The average differences measured are subtracted from 100 to get the CRI. Using this method, small average differences will result in a higher score, while larger differences give a lower number.
If the test light's CCT is lower than 5000 K, the reference light source of equal correlated color temperature (CCT), is selected within the Planckian's radiator group, otherwise from illuminants of D-series (which should approximate the spectrum of natural light in several hours of the day).
The R_a value, usually provided by the manufacturers, represents the average of the indexes R_i of the first 8 samples.
The CIE publication 177 (published in 2007) reports the results of some perceptive experiments and of the simulation on the color rendering: on the basis of those experiences, the technical committee CIE TC 1-62 of Division 1, *"Vision and Colour"*, has established that the color rendering index CIE CRI is not generally applicable to establish the color rendering rank order of a set of light sources when white LED light sources are involved in this set. [2].
Also, the calculation of the CRI was designed many years ago, according to sources with continuous and regular spectrum. With the LEDs is now possible to create light sources that have a wide variety of different light spectra. One can create a light source that matches very well only the color samples of Munsell system used for calculating the CRI, thus obtaining a high CRI, although for other colors the color rendering can instead be very low.
This recommendation is based on a survey of numerous academic studies that considered three different type light sources: phosphor-coated white light LEDs, red-green-blue (RGB) LED clusters and traditional lamps (fluorescent). Most of these investigations involved visual experiments where observers ranked the appearance of illuminated scenes (containing real object or color samples) using lamps with different CRIs. On the basis of result obtained, in general, we can say that there was poor correlation between these rankings and the order produced through the calculated CRI values. In fact, many RGB-based LED sources show low values of R_a index, yet the objects appearance is reported to be acceptable by the observers.
All the new proposed indices fall in one of three basic categories of color rendition:

- The accurate rendition of color as they appear if they would be lighted under a reference light source (color fidelity index)

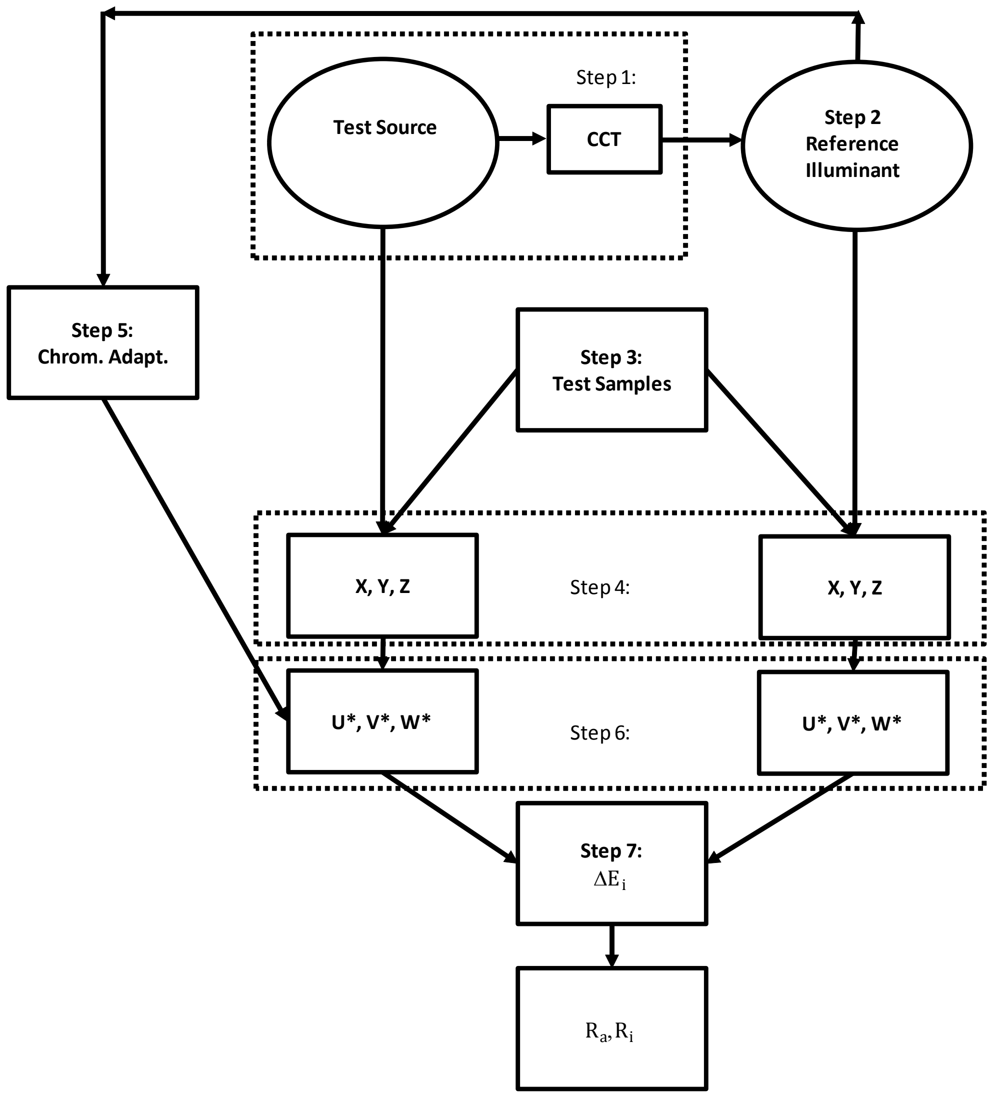


Figure 1 - Workflow for calculation the color rendering index R_a, defined by the CIE publication 13.3 (1995)

- The light source ability of rendition of objects appearance like if they appear *"vivid"*, *"pleasant"*, or *"flattering"* (color preference index)
- The ability of light source to allow an observer to distinguish colored parches when they are viewed simultaneously (we reference to this dimension of color rending as *"color discrimination"*)

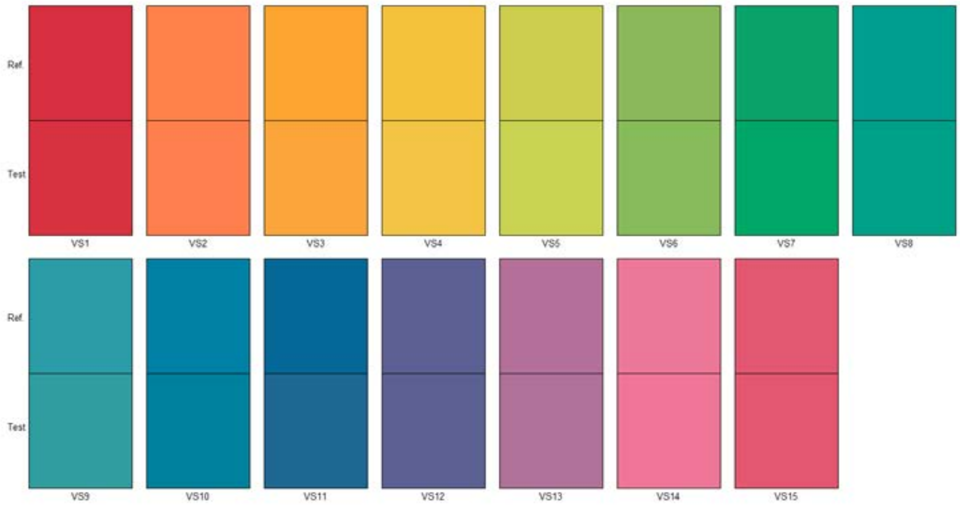
Each color rendering index proposed in scientific literature can be classified into one of the three categories: the particular application should suggest the proper color rendering characteristic that a lighting design project is called to meet and consequently the designer must choose the most appropriate rendering index for the evaluation of the light sources used.

2. UPDATE CIE COLOR RENDERING INDEX

The CIE standard method has some defects and shortcomings:

- Reference illuminant: the choice is between black body radiator and daylight phase of the same CCT as the test source. However, there is no evidence that these reference illuminant is the most optimum source in terms of naturalness and other subjective aspect of color quality [7][8]. Furthermore, no source can render the colors better than the reference, a situation that represents a limit to the development of new sources.
- The set of used samples (8 de-saturated color + 6 saturated samples) were extracted from the Munsell's Atlas, but are no longer commercially available. In addition, selected samples do not cover the gamut of possible colors in proper manner as instead can make color samples extracts from other collections like Macbeth Colour Checker. Davis and Ohno show that a light source can perform well with the standard eight color sample (desaturated) employed for calculation of actual CIE rendering index,

Figure 2 - CQS color sample



but the same source perform poorly when used in connection with saturated color sample. The same authors, show that the contrary (better result with saturated sample and poor results with desaturated ones) is never true [9].

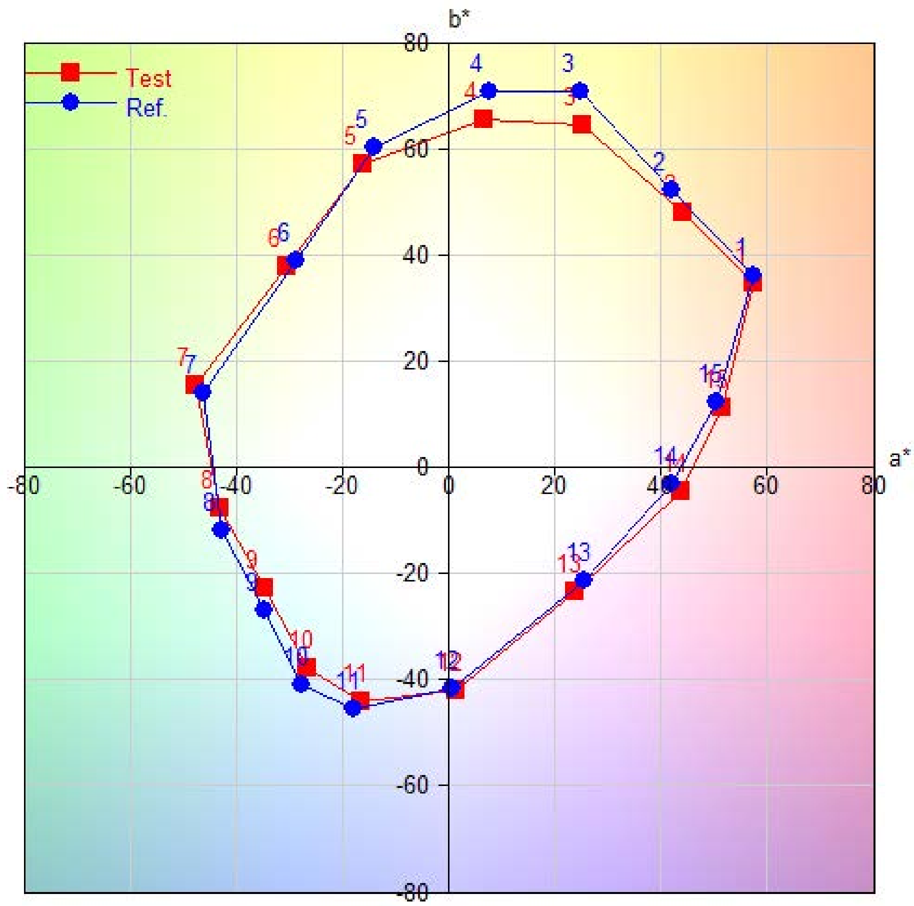
• The used formula to take into account Chromatic Adaptation in illuminant change (switching from a sample lighted by reference lamp to a new situation where the same samples are now lighted by test lamp) has proved to be inapplicable for large chromatic differences.

• The color space U*, V*, W* is not perceptually uniform in relation to other color spaces defined more recently by CIE, and even the suggested mathematical relation for color difference evaluation appears to be obsolete and inadequate.

• The use of a single value average, fails to explain the differences in color rendering of two different sources that have the same general index value, but different values in the special color rendering index (R_i).

• Some researcher expressed a preference that the special color rendering index should not go below

Figure 3 - Gamut area in CIELab color space: in red Test lamp, in blue Reference lamp.



the zero: the main idea is that a scale between 0 and 100 would be less confusing for non-expert users[9], even if there isn't a special meaning associated with the zero value.
For some type of discharge lamps, such as low pressure sodium, the value color rendering index R_a is negative and thus difficult to understand for non-expert users.

The National Institute of Standards and Technology (NIST)[9] developed CQS (Color Quality Scale): like R_a, CQS is based on the comparison to a reference illuminant with the same CCT. QCS is a new color rendering metric Qa that updates CRI R_a in several aspects:

- Better chromatic adaptation model (CMCCAT2000)[18]
- A new set of 15 saturated test color sample were chosen
- Illuminants are not penalized for increase of chroma
- The more up-to-date CIE L*A*B* uniform color space is used to measure the color shift between the test illuminant and reference illuminant
- Colour differences for each sample are not simply averaged as in CIE R_a, but they are combined by root mean square: all 15 test color samples are used to evaluate the general CQS score through a weighted root mean square (RMS) approach for better statistical properties
- The light sources that show a very low correlated color temperature are penalized because they have a small gamut area (introduction of CCT factor)
- A scaling factor is introduced so that the 12 reference fluorescent lamps have the same score using CQS metric or R_a
- CQS values are in the range from 0 (very poor color) to 100 (perfect color): a sigmoid function is introduced to translate negative values (of special indexes) to low values (below 20)

Different formulation of this index is proposed by the author. Seven of the 15 test-color sample have been changed during the evolution of indices, CCT factor was removed, in the last version Q_f (gamut area index) is evaluated on the base of reference illuminant with equal CCT. In this index several sub-indices were be proposed, in order to do a proper evaluation of different aspect of color rendering problem:

- Q_g: evaluated as relative gamut area formed by (a*,b*) coordinates of the 15 color samples in CIELAB space normalized to a gamut area of a reference illuminant at the same CCT and multiplied by 100. The value of Q_g could be greater than 100 and the last version of the method doesn't employ any chromatic adaptation transformation. The first version of this index used a fixed reference illuminant D65.
- Q_f computed by the same scheme of Qa, except the exclusion of saturation factor: it is a pure fidelity index, in similar way to R_a. The result is scaled between 0 and 100 so that reference fluorescent lamp have equivalent value of Q_f and R_a.

A promising candidate for substitution of CIE color rendering index is proposed by K. Smet et al [14]: it is a color fidelity index and it is based on the previous work and experience of numerous working group inside TC-169, the CIE technical committee dealing with color rendition of white LED light source.
The computational structure is similar to traditional CIE R_a index, but same of important improvements are proposed to overcome weaknesses and problems listed above.
This rendering index, called CRI2012 (previously called nCRI) is a color difference metric that presents the following major feature:

- The outdate color space for color shift evaluation and chromatic adaptation transformation are replaced by color appearance model CIECAM02/CAM02-UCS[10][11].
- Averaging of partial indices and linear scale are replaced by RMS (root mean square) and by a non- linear function which tends to saturate the limits of intensity range: this behavior should better reflect the features of human perceptual response.
- A new scale factor is introduced so that standard CIE illuminants F1 to F12 have the same average value using Ra metric and $R_{a\ 2012}$.
- The previous set of 14 color samples are changed in two different way: the standard eight samples, used for R_a calculation, are replaced by an imaginary (mathematically defined) set of color samples; the special color index are replaced by a set of 210 real reflectance function, characterized by low and high color constancy, so it is possible to obtain detailed hue-specific information (the set should properly sample the entire gamut volume).
- The reference illuminant is selected through the same rule adopted for R_a: blackbody radiator for test source with

CCT below 5000 K, daylight illuminant for others.

- The test sample chromaticity is now evaluated by CIE 10° standard colorimetric observer because of well-known inaccuracy of CIE 2° standard colorimetric observer in the blue region of visible spectrum.

The influence of the spectra of test samples on the calculated color rendering index is a long time open question: due to a small number of samples, lamps manufacturers are able to tailor the light sources spectral distribution to yield high CRI value, even if the visual impression of color rendering is considered poor[12][13]. In particular, tri-phosphor fluorescent lamp (warm white) is overrated by the current formulation of rendering index as suggested by the visual experiment.
The inadequacy of the current set of test colors is shown by the observation that special rendering index Ri changes if a near metameric test sample are used in calculation instead of original set [14].

3.TWO METRIC APPROACH

The main idea is that only one number can't include the multidimensional problem of color rendition, but on the other hand lighting industry and designers need simple and clear tool to evaluate the color rendering of light sources.
Another interesting method for evaluating color rendering performance of SSL source, is to use a two-metric approach that combines CRI and GAI (for gamut area index) [19].
Index based on Gamut area evaluation has been used as a predictor of user's preference or color discrimination, but it's an imperfect solution for both features.
In case of preference, for example, too large gamut area makes object color too saturated so they appear unnatural and not preferred [15][16].
In case of color discrimination, the increase of saturation, which leads from large gamut area, is sometimes followed by hue shift of several sample (even in this case, if the color distortion is too high, then the user's preference will be very low)[9].
Gamut Area Index (GAI) uses the same eight test color samples as CRI: the index is based on evaluation of the polygon's area (called "Gamut area") described by eight test color samples in the CIE u'v' color space. To calculate the GAI value, the gamut area of the test color samples is compared to that of an equal energy spectrum source. A GAI score of 100 means that the gamut area is of the same size as the equal energy source: a light source with a good CRI score and a good GAI score (between 80 and 100) is considered to have good *"color fidelity"* and *"color vividness"* .
A light source with a low GAI score produces poor rendering on saturated colors, whereas a large GAI score indicates an overly saturated rendering.
Rea and Freyssinier-Nova suggest numerical recommendations about the value of GAI index: if the applications (for example retail) require high features for color rendering, the light source should have both Ra of between 80 and 100 and GAI between 80 and 100.[3][4]
An important notice is that in GAI, the evaluation of the correlated color temperature of reference light source is fixed and independent from that of the source under test: this solution can involve distortions in the judgment of the light sources with low values of correlated color temperature that can still have excellent color quality including good color discrimination performance, despite the low value of the gamut area.

Recent research suggests that the lighting designer community should develop a two-metric system for color rendering of light source: the idea is the combination of an index representing the color fidelity aspects with a measurement of gamut [5].
Experts can manage multiple index without any kind of problem, but for other users it's still necessary to summarize the information into a limited number of measures: when two measures are used, there is enough information in relation to lighting design applications.
The proposal considers a color fidelity based index (we can have information about the fidelity of light source in rendering a set of color sample in comparison to a reference lamp whit the same CCT) and a measure connected with the gamut area evaluation.
Houser et al. suggest that the couple of indices to be considered are Q_a and Q_g, where Q_a is the fidelity component and Q_g is the gamut area evaluation.
For Houser et al. the color fidelity component should not be a pure fidelity index as suggested by other researcher previously[6]: this kind of metrics penalize all color shift and may incorrectly penalize illuminants that favorably increase the chroma (for this reason the proposal is Q_a index).
Even traditional gamut measures (GAI) present the same problem because of their dependence upon CCT: the proposed metrics is Q_g because it's an existing measure of relative gamut and because shares some computation features with Q_a, such as color sample.

4. CONCLUSION

The color rendering of the sources in solid state lighting is a very complex problem which has to take in account different requirements and constraint.
It is possible that in the future there will be different types of indices, depending on the applications that the lighting designers have to face: in any case it seems that the solution of the problem will be proposed shortly.
The approach through the use of two metrics seems to offer greater flexibility and completeness, but only a perceptual experiment can fully assess the effectiveness of this solution. A simple word scale has the capability to capture overall color quality of a light source and it would be especially useful for end-users to proper rate a solid state light source in comparison to others. Bodrogi et al., developed a formula (based on series of visual experiment carried out with a color similarity judgment task on ordinal rating scales, as well as on interval rating scale labeled by categories of color similarity) to predict a category of color similarity from an instrumentally measured color difference: this formula was applied to interpret the values of the new Colour Rendering Index (CRI2012) in terms of semantic categories taken for everyday language (excellent, very good, good, moderate, low, bad, very bad)[17].
This solution enable end-users and lighting designers to understand the metric values of CRI2012, and the importance of difference of different magnitude inside the CRI2012 scale index.
If the assessment of color rendering (for reasons of simplicity and tradition) must be reduced to a single number, the sophisticated models used in the most recent versions of the index, will end up providing to the end users the same level of knowledge of the previous indices and the latter improvements introduced, will become marginal.

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