# Evaluation and Improvement of the CIE Metameric and Colour Rendering Index


**ABSTRACT**

*All artificial light sources are intended to simulate daylight and its properties of color rendering or ability of colour discrimination. Two indices, defined by the CIE, are used to quantify quality of the artificial light sources. First is Color Rendering Index which quantifies ability of light sources to render colours and other is the Metemerism Index which describes metamerism potential of given light source. Calculation of both indices are defined by CIE and has been a subject of discussion and change in past. In this work particularly, the problem of sample number and type used in calculation is addressed here and evaluated. It is noticed that both indices depends on the choice and sample number and that they should be determined based on application.*



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**KEY WORDS**

*Color Rendering Index, Metemerism Index*

First recieved: 18.05.2015.
Accepted: 21.09.2015.


## Introduction

The CIE colorimetric system is based on colour stimulus that is described as a combination of light source, object and an observer. Being three –chromatic in nature, Human Visual System can have same response on physically different stimuli (i.e. different spectral reflectance) which can be significantly higher in dimensionality. This fact is especially true with artificial light sources where it is, with current state of technology, very difficult to have spectral power distribution of standard illuminats defined by CIE. However, these light sources are designed to provide good colour rendering. How well they do it and with what Spectral Power Distribution (SPD) is that achieved is quantified by CIE Color Rendering(CRI) and Metamerism index (MI). The CRI is a well-known descriptor for the colour rendering properties of light sources. Being a single number the CRI is rather loose figure of merit and the accuracy of the CRI in predicting specific colour rendering aspects is relatively low. CRI is an average of only eight colours and accounts only for the magnitude of the colour shift. On the other side MI is calculated by five metamer sets defined by the CIE. Therefore, this work address problem that might come with limited sample set for these two indices and perform analysis with different (extended) sample set.

### Colour Rendering Index

In everyday colour judging situation, either in industry or in everyday experience, the illumination greatly affects our perception of colour. However, some colour judgment situations are more critical than the other. Highly accurate colour communication in industry is one of the cases. There, some measure that quantifies quality of the illumination source must exist. For this purpose, CIE has defined a colour rendering index for light sources (Lee 2005). The measure of goodness of a light source is a correlation between colour rendering of reference illuminant (or illumination source), and given light source. The correlation is expressed as colour difference of rendered colour patches. There are several concerns with this definition:

- Which source should be used as a reference source?
- Which test samples (patches, objects) should be used in evaluation?

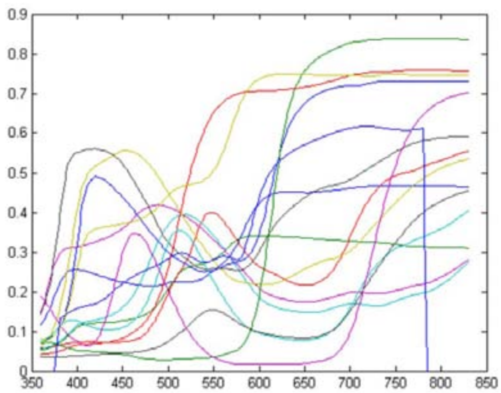
There is also a question of which chromatic adaptation should be applied when a change of illumination is introduced as well as which colour difference formula to use and how it should be weighted.

The compute colour rendering index, one must acquire a Spectral Power Distribution (SPD) of the test and reference light source, as well as spectral reflectance of the test patches. The CIE XYZ tristimulus values are then computed for CIE1931 standard observer and for both reference and test light source. For the reference light source, (CIE publication 13.3) recommend standard illuminants, resembling daylight, fluorescent light sources and incandescent light. The daylight illuminants are identified based on their Correlated Colour Temperature (CCT). The CCT provides an insight of the illuminant's bluishness and yellowishness (Hunt, 2004). The CCT of an illuminant or illumination source resembles the same chromaticity coordinate as the Planckian radiator but different SPD. For a test source with CCT below 5000K, the reference illuminant should be a Planckian radiator with same colour temperature. If the test illumination source is over 5000K, then one of the CIE standard daylights illuminants should be used as a reference.

Therefore, CIE recommends usage of standard illuminants to evaluate quality of the real light sources. The need for such recommendation came from the lighting industry (Schanda, 2007). The characterization and classification of the daylight simulators and other light sources needed to be done based on some standardreference source. Although real light sources up to this date are not able to approximate SPD of CIE standard illuminants, they are able to match in CCT. Therefore, an evaluation of how these light sources render colours in regard to the reference illuminant with which they share CCT, becomes measure of quality the light sources. First methods to characterize colour rendering capabilities of light surces were based on spectral band methods. Here, SPD is sampled and divided into sections which are compared to the standard illuminant. This was the first CIE colour rendering evaluation method. The problem with this method is that it did not correlate well with visual perception. To tackle this problem, the CIE body came with the method based on colour difference calculation. The method established in 1974 is still in use. Full description of this method can be found in (Schanda, 2007,Ohta, 2006).

Computations with this method are performed within CIE 1964 UCS colour space. More recently, newly derivedcolour spaces can be also used, although there is no significant difference that could guide change of the method. The second method is based on CIELUV and CIELAB colour space while colour difference formula and chromatic adaptation is not strictly defined. Briefly described, old method uses selected Munsell patches that sample the colour space. It is 14 colours, approximately resembling primaries of a colorant system and samples of human skin and green leafs (Figure 1).

Second method specifies usage of the Gretag Macbeth Colour Checker for test samples. The patches on this colour target are similarly distributed as Munsell patches and second method shows high correlation with the first, but do not offer an improvement.




» **Figure 1:** *Munsell samples for CRI computation*

In evaluation of CRI, one can compute both general (Ra) and special colour rendering index (Ri). The latter is the CRI computed for each colour sample separately while former is the average score for all patches.

$$\boldsymbol{Ri} = 100 - 4.6\Delta Ei \ \ and \ \ \boldsymbol{Ra} = \frac{1}{8}\sum_{i=1}^{8} Ri$$

The problem here is that in most cases, the CRI does not correspond to the visual colour difference (Sandor and Schanda, 2006). This has significant consequence in applications where people make quite critical decisions about colour. To tackle the problem, the reference illuminant should be considered from real light sources where these should be selected based on application. Other problem that current methodology exhibits is its age and lack of robustness toward new light sources such are LEDs. Later, another experiment was set (Li, et al., 2011) where they have tackled the problem of chromatic adaptation using more recent CAT02 instead of Von Kries. The problem in first experiment was the simultaneous stimuli observation which usually leads to undetermined and poor adaptation. Chou et.al., 2011 also evaluated sample number and type influence of the CRI applied in graphic arts environment. There, they have selected 273 samples with two different Chroma levels, three Lightness levels and hue angles at 10 intervals. By working with CIECAM02 colour appearance model and by using selected range of samples they have proposed CRI-CAM02UCS metric for evaluation of the general colour rendering index. This has shown significant improvements in evaluation of the solid state (LED based) illumination sources and shows better correlation with visual colour difference. The colour sample set used in experiment included: 219 evenly distributed samples and many real world materials like textiles, prints, plastics, skin. Such sample set should provide enough sampling points to evaluate uneven energy levels per wavelength of daylight simulators, spiky illumination sources and LED based illumination. The one issue remains even with proposed new CRI metric; it is still one number that is a figure of merit. Using CIE recommended method averages across only 8 samples where new suggested methods are quite complex and computationally intensive. To tackle this problem, Burgt and Kemenadeevaluated how the colour set influence the colour shifts induced by narrow band SPDs of illumination sources. A number and representatives of colour samples are directly influencingprediction of colour rendering properties. The method used is called CRV or colour rendering vectors and has been described in CIE 13.3 publication.According to the publication, the colour shift in a three- dimensional space are the vectors with directions. For the experiment, they have used a set of 215 colours uniformly distributed across the space with average magnitude of colour difference similar to those of the CIE recommend 8 colours set. They have concluded that as some hues do not contribute equally to the average value of the CRI, some hue angles has to be more sampled or sample colours must be properly selected. The final selection is based on an average magnitude of the colour shift.

However, all mentioned metrics and methods proposed is to derive a better single number that should be a merit of the light source quality. Although this is a useful guidance for lighting industry, it does not provide an insight of how the illumination source would render colours of the specific application. As mentioned before, colour sample selection involves many different application areas such are: textiles, print, plastic, home interior, office lighting, viewing cabinets, etc. therefore, this work has an aim to experiment with CRI within a single application area. The field of spectral printing is one of the application areas that could benefit from such information, not just directly by evaluating illumination source colour rendering properties, but indirectly too, in optimization of a workflow for given application area of spectral printing.

Spectral printing utilizes multichannel printing systems to better reproduce input reflectance and to avoid as much as possible the metamerism. More degrees of freedom one has, the greater the possibility to achieve desired results. As spectra of the objects are significantly different to one of printing inks, it is more possible to have a multi-illuminant match than to have a spectral match. Therefore, both reproduction goals and multi-illuminant gamut mapping(Urban and Berns, 2011) should benefit from the information of illumination sources for which the system is optimized. Chen et.al.2003used colour inconstancy index to optimize multi-ink colour separation based on maximal colour constancy.

This work will evaluate CRI and MI of the common daylight simulators and other illumination sources used in common viewing cabinets used in graphic arts. Instead of using CIE recommended colour set or any recently suggested methods, this work will calculate CRI by using only prints made with hi-fi printer. Expectations are that the CRI can be directly associated with colour rendering of the printed materials on a paper. Therefore,it is the goal of this project to test whether CRI and MI could be indicators of how good are lamps for viewing printed material only and whether numbers differ from CIE recommended method.

### Metameric Index

Grasmann's second law indicates that two lights or two stimuli can match in colour appearance when though their spectral selectivity is different (Kang, 2006). The two stimuli are then called metamers and are basis for CIE colorimetric. The CIE colorimetric system is based on colour stimulus that is described as a combination of light source, object and an observer. The light source with specific spectral power distribution illuminates a spectrally selective object and the result is spotted by an observer. The result is expressed through CIE Tristimulus values. Previously, the standard observer has been defined for 2°, 10°. Also CIE defines set of standard illuminants spectral power distributions that represent proportion of total light emitted, transmitted or reflected by an object at every possible wavelength.

Metamerism is a basic and most important aspect of colour reproduction with limited number of channels. As HVS is equipped with three colour receptors, metamerism occurs as each type of receptors responds on the cumulative energy from a range of wavelengths. This reduced degree of freedom exploited tri-chromatic characteristic of human visual system and give a rise to the trichromatic or metameric colour reproduction workflow. Metamerism always involves at least two pair of objects or stimuli. The metameric match is achieved if two objects produce same colour sensation under specific illuminant for the standard observer. The metameric objects therefore have different spectral distributions but perceived as same colour under given illuminant. The match may not hold under second (other) illuminant or illumination source.

Metameric matches of objects are common near neutral and dark areas of a colour space. These are usually achieved using multiple colourant combinations with subtractive colour mixing.

The illuminant metamerism is a situation where two samples matches under one light source but do not under other. Artificial light sources have very different SPD than natural daylight. For latter it can be say to show rather broadband nature while former exhibit narrow band (spiky) nature. Measurements of the illuminant metamerism are through CIE defined procedures that yield Metamerism Index (Mi) which is the mean colour difference of the eight metameric colours illuminated with test source. Metameric colours naturally match under reference illuminant.

However, as MI is the average value of 5 metamers under daylight it does not provide with an insight of real metamerism potential. Also, index is only specified for change of illuminant from daylight series to whatever testing illuminant or illumination source. With approach presented in this work, it is also possible to choose an illuminant or illumination source under which metamer set can be extracted. Here, the Metamer set (metameric black decomposition) is used to estimate a reflectance set from single XYZ values. It is out of the scope of this work to describe in detail this method and detailed description is given in (Finlayson and Morovic, 2001).

## Methodology

### Testing Illumination Sources

The selected light sources for experiment were D50 Daylight simulator (5000K), Incandescent light (2865), Cool-White Fluorescent (4100K), and UL30 store illuminant (3000K). This set is selected due to its white spread use in industry. Many environments where colour judgment is important are equipped with same or similar illumination sources.

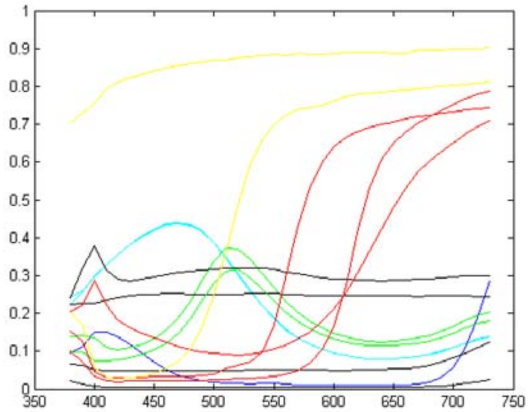
### Printing patches

A multichannel printer has been chosen for its extended gamut and possibility to hard proof any other printing technology. The test printer was ink- jet HPZ3200 which is equipped with 12 channels out of which seven are independent (CMYKRGB). All channels are directly controlled via Caldera RIP and its n-channel workflow, where multichannel tiff separations were sent as a binary code. The separations have been pre-halftoned with DBS algorithm. Also through the RIP, it is possible to control transitions (e.g. from light magenta to magenta). Each channel has been calibrated (linearized) for a dot gain to provide linear output to provided nominal dot coverage. The test patches were ramps of 7 primaries with addition to secondary ramps of CM, CY and MY. All ramps had eleven linear steps which makes all together 111 patches that samples the space in all dimensions of Hue, Chroma and Lightness.

### Measurement

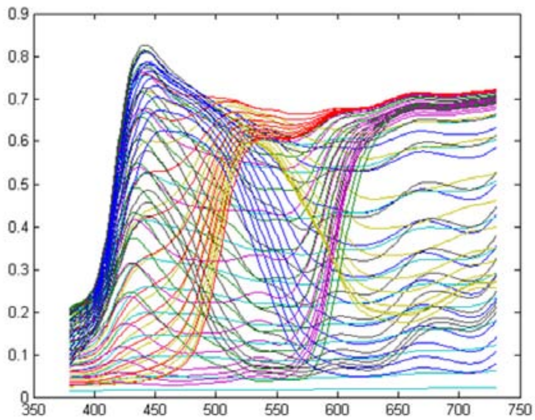
Measurements of printed ramps are done with Datacolour 650 with 20mm aperture (16mm measurement radius).Average of five measurements is taken for further calculation. The average repeatability for this instrument is 0.02 in ΔEab.

Inter-instrument agreement is recorded by measuring BCRA tiles that are provided with reference data. The mean ΔEab value for used measuring instrument is 0.2 while maximum is 0.7 for 12 BCRA tiles. Measured spectral reflectance of 12 BCRA tiles are given on Figure 2.

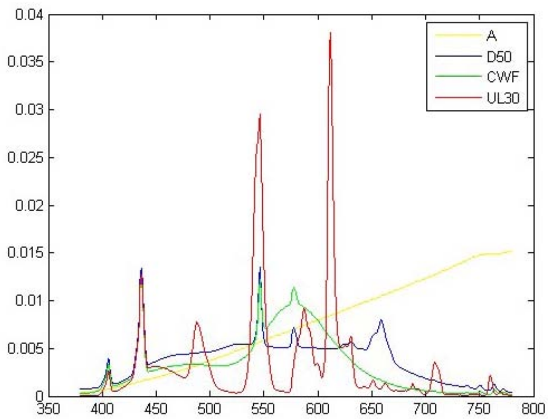



» **Figure 2:** *Measuremnts of BCRA tiles with Datacolor 650*

The instrument has effective measurement resolution of 10nm. For further computations, all measurements have been interpolated to 1nm in Matlab using spline interpolation. Spectral reflectance curves of printing ramps are shown on Figure 3.




» **Figure 3:** *Reflectances of the printed ramps*




» **Figure 4:** *SPDs of tested illuminants*

The measurements of the SPD of the tested light sources are done with Minolta CS1000 tele-spectroradiometer where BaSO4 tile has been used as a diffusor. The instrument has resolution of 1nm which is needed to accurately represent peaks of the expectedly spiky daylight simulator and fluorescent light sources. Average of five measurements is taken for further computations. Measurements of all SPDs are shown on Figure 4.

## Computations

All computations are done in Matlab. To compute CRI, the CIE still valid recommendation is followed. Although many more recent methods are suggested, in this work it is not method itself which is evaluated. It is rather change of the sample set used for computation of indices targeting to have application dependent indication of light source quality and metamerism potential. Therefore, samples described in previous paragraph are used instead of Munsell patches for computation of general and special CRI. Computation is as followed (Ohta, 2006):

First, three colorimetric values of the 1964 UCS, W*, U*, V* are computed as:

$$W = 25\, Y^{\frac{1}{3}} - 17$$

$$U = 13\, W(u - u_n)$$

$$V = 13\, W\,(v - v_n)$$

whereu ($u_n$ illuminant) and $v$ ($v_n$ illuminant) are chromaticity coordinates of CIE 1960 UCS diagram and are computed with XYZ values as:

$$u = \frac{4X}{X + 15Y + 3Z} = \frac{4X}{-2x + 12y + 3}$$

$$v = \frac{6Y}{X + 15Y + 3Z} = \frac{6y}{-2x + 12y + 3}$$

As chromaticity coordinates of the test light source do not match one chosen as reference illuminant, it has to be compensated with chromatic adaptation. Therefore, chromaticity coordinates for test and reference source are corrected by:

$$u'_k = u_r$$

$$v'_k = v_r$$

$$u'_{k,i} = (10.872 + \frac{0.404 c_r c_{k,i}}{c_k} - \frac{4 d_r d_{k,i}}{d_k})/(16.518 + 1.481\, c_r \frac{c_{k,i}}{c_k} - \frac{d_r d_{k,i}}{d_k})$$

$$u'_{k,i} = 5.520/(16.518 + \frac{1.481 c_r c_{k,i}}{c_k} - \frac{d_r d_{k,i}}{d_k})$$

where uk’ and vk are the chromaticity coordinates of the test source after applying the chromatic adaptation correction; ur and vr are the chromaticity coordinates of the reference illuminant; uk,ian vk,iare the chromaticity coordinates of the test colors after applying the chromatic adaptation correction; crand dr are coefficients computed as:

$$c = (4 - u - 10v)/v$$

$$d = (1.708v + 0.404 - 1.481u)/v$$

To compute CRI, the tristimulus values Xr,i, Yr,i and Zr,i , as well as Xk,I ,Yk,i and Zk,i are obtained from the spectral distribution Sr(λ) and Sk(λ), respectively, where i is the number of color samples used for calculation. Coordinates of the 1964 UCS space are calculated as:

$$W_{r,i} = 25(Y_{r,i})^{\frac{1}{3}} - 17$$

$$U_{r,i} = 13W'_{r,i}(u_{r,i} - u_r)$$

$$V_{r,i} = 13W'_{r,i}(v_{r,i} - v_r)$$

$$W_{k,i} = 25(Y_{k,i})^{\frac{1}{3}} - 17$$

$$U_{k,i} = 13W_{ki}(u^{'}_{k,i} - u^{'}_k)$$

$$V_{k,i} = 13W_{ki}(v^{'}_{k,i} - v^{'}_k)$$

The colour difference is computed then as:

$$\Delta E_i = ((U_{r,i} - U_{k,i})^2 + (V_{r,i} - V_{k,i})^2 + (W_{r,i} - W_{k,i})^2)^{1/2}$$

From here, the CRI is gained as:

$$\boldsymbol{Ri} = 100\ - 4.6\Delta Ei\ \ and\ \ \boldsymbol{Ra} = \frac{1}{n}\sum_{i=1}^{n} Ri$$

Metamerism Index is computed according to (CIE 015:2004) and it represent average colour difference for the change of illuminant. In this work CIEΔ2000 is used as a colour difference formula. In order to create additional sample set, three primaries at 100% effective coverage are selected and subsequent metamer set has been extracted. Further on, each of this set has been used to compute Mi where average colour difference of the set has been reported. Computation method is identical to one recommended by CIE - publication 15.3 with the change of metamer set (5 metamers under D65 are recommended by CIE, many more obtained through optimization for theoretical metamer set). To extract a metamer set, a method described in (Kang, 2006)is used and is based on metameric black idea and constrained optimization to compute all possible metamers of a given XYZ value. The whole concept is based on Matrix R theory described in detail in [12] and is onlybrieflydiscussed here.

The color matching matrix A is defined as:

$$A = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ x_n & y_n & z_n \end{bmatrix}$$

where n is the number of sampling points.
A set of mutual metamers will yield:

$$\boldsymbol{\eta}_1 A^T = \boldsymbol{\eta}_2 A^T = \boldsymbol{\eta}_3 A^T \ldots \boldsymbol{\eta}_n A^T = T$$

where n1,n2,n3 are mutual metamers that map to same T=XYZ values. Further on, Matrix R that splits metamer  on it fundamental component and residual (called metameric black) is given as:

$$\boldsymbol{R} = \boldsymbol{A}(\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T$$

Fundamental component and metameric black can be then expressed as:

$$\acute{\eta} = R\eta_i$$

$$\mathbf{k} = \eta_i - \acute{\eta} = \eta_i - \mathbf{R}\eta_i = (\mathbf{I}-\mathbf{R})\eta_i$$

where $\eta_i$ is the reflectance of the stimuli, ŋ’ is the fundamental metamer and k is the metameric black component. From here, stimuli can be recovered as:

$$\eta_i = \acute{\eta} + \mathbf{k} = \mathbf{R}\eta_i + (\mathbf{I}-\mathbf{R})\eta_i$$

This provides with general principle of metamer set recovery. To obtain proper (e.g. all positive) reflectance set, the smoothness is added (Finlayson and Morovic, 2005) and positivity constrain in optimization routine to estimate realistic metamer set.

## Results and Discussion

As mentioned, the CRI was be computed using standard Munsell set of 13 colours and will be compared with CRI obtained from 111 printed patches. It is a desire to evaluate whether there is any difference when more application specific indices are needed. In Table 1 the results of computed general CRI are presented.

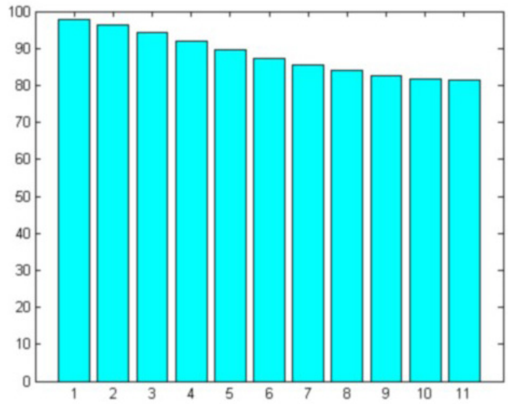
**Table 1**

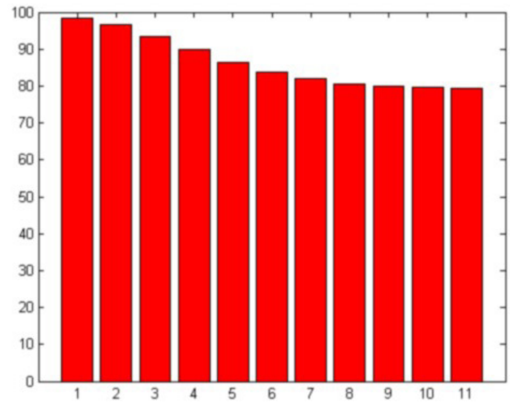
CRI computed with Munsell set and Printed sample set

| Illumination source | Munsell set | Printed set |
|---|---|---|
| D50 light source | 90.76 | 88.14 |
| Incandescent light | 93.23 | 91.78 |
| Cool White Fluorescent | 59.21 | 53.73 |
| UL30 | 71.05 | 74.55 |

As Table 1 shows, there is a small difference between using two methods. This is mostly seen with CWF and UL30 light sources which are not developed to render printed material. Due to its rather smooth SPD, incandescent light is performing well with printed material which has also smooth reflectance curves. D50 light source is optimized to work well within graphic arts environment which is also shown in the Table 1.

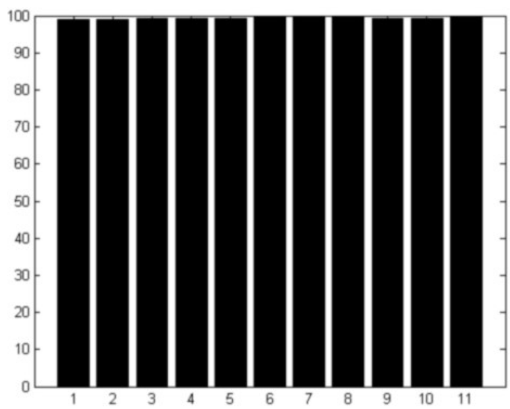
One of the characteristics of multichannel printing utilizing light colours is smoothness of tone transitions from light to mid-tones. Therefore, special CRI might give much better insight of colour rendering the smoothness. Ramps are printed with 10% of dot area coverage increase which is in Chroma direction. Results for cyan, red and blackfor incandescent and D50 illumination sources are given here (Figure 5).

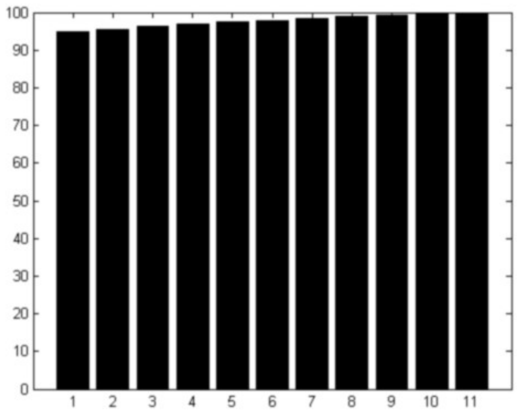




» **Figure 5:** *D50 - Rendering of the transitions*

Special CRI for two printed ramps, cyan and magenta, shows how selected light source renders transitions. Higher the Chroma of the channel, less CRI score it achieves.



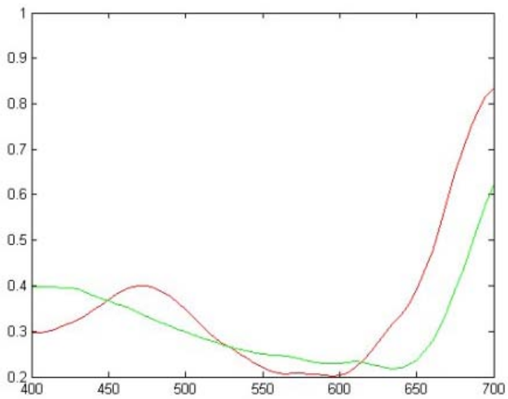


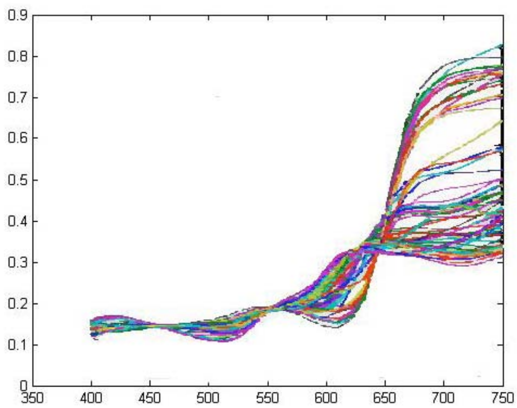

» **Figure 6:** *Incandescent (previous page bootom right) and D50 (above) illumination sources rendering of neutrals*

Although this trend is the same for D50 light source, rendering of the neutrals is slightly different with incandescent and D50 illumination sources (Figure 6).

### Metamerism Index

Metamerism index for same illumiantnts is computed using recommended CIE method and compared with using metamer set as the samples.




» **Figure 7:** *Metameric pair (above) and metamer set (bellow) that maps to same XYZ values under D65 illuminant*

The metamer set is computed under D65 illumination and then computation follows recommended method. Aim of this approach is to see to what extend metamerism can theoretically pose a problem, especially in reproduction. Therefore, such information can serve well within spectral reproduction workflow and gamut mapping. A trade off with using this method is rather complex and computationally intensive procedure which might not be suitable for industrial application. An example metamer set that extracted from a single XYZ value is presented in Figure 7. This set is gained as an addition of fundamental metamer and metameric black space of vectors.

Further on, visible MI is computed for all selected illumination sources and compared with metamer set extracted from fivecolours (e.g. primaries of the printer).

**Table 2**

Metamerism Index comparison using two different data set; standard metameric pairs specified by CIE and metamer set extracted from printing primaries

| Illuminant | Mi | | Metamer set Mi | |
|---|---|---|---|---|
| | Avg | Max | Avg | Max |
| D50 | 0.99 | 2.1 | 8.91 | 17.38 |
| A | 3.13 | 7.13 | 14.7 | 31.28 |
| CWF | 1.86 | 2.51 | 12.23 | 20.44 |
| UL30 | 2.3 | 4.48 | 14.2 | 24.3 |

It is worth noting that metamer set approach is rather theoretical and there is no guarantee that all reflectances from set are reproducible. However it does provide an insight on the magnitude of illuminant-metamerism and should provide very useful data for optimization of the printing system.It is also worth noting that metamer set is computed under D65 illuminant altohogh this approach can be applied to any desired reference illuminant or illumination source.

## Conclusion

The Colour Rendering and Metameric Index are developed to rate light sources according to their correlation with standard illuminants. Therefore they provide relative measure of goodness that is expressed as quality or metameric abilities of the source.

There have been many attempts to improve still existing CIE recommended methodology for computation of indices. Expansion of solid state illumination challenged current methodology as it did not provide visual correlation.  Still, only a single number of CRI and MIis a description of the light source characteristics.

In this work, a specific sample set for evaluation of CRI and Mihas been created. This set is a representative of printing technology and has the intention to evaluate illumination sources that are commonly used in graphic arts. The indices gathered this way give a better information of the rendering and metameric capabilities of the light sources. It can be concluded that for colour rendering, the printed sample set gives similar score to the one obtained with standard method. However, same cannot be said for MI computation. The sample set for standard method is rather small and does not give a good insight on magnitude and diversity. Intention is that with application specific CRI and MI, the reproduction system can be optimized and proper illumination selected.

## References


1. Chen, Y., Berns, R.S., Taplin, L.A., and Imai , F.H. (2003), Multi-Ink Colour-Separation Algorithm Maximizing Colour Constancy, IS&T/SID Eleventh Colour Imaging Conference, pp 277-281
2. Chou, Y.F.,Luo, M.R., Schanda,J.,Csuti,P.,Szabo,F. and Sárvári, G. (2011), Recent Developments in Colour Rendering Indices and Their Impacts in Viewing Graphic Printed Materials, Nineteeth Colour and Imaging Conference: Colour Science and Engineering Systems, Technologies, and Applications San Jose, California; November 2011; pp. 61- 68
3. Commission Internationale de l'Eclairage: Method of measuring and specifying colour rendering properties of light sources. Publ. CIE 13.3-1995
4. Commission Internationale de l'Eclairage, CIE 015:2004: Colorimetry, 3rd Edition
5. Finlayson, G.D., and Morovic, P. (2005), Metamer Set, Journal of Optical Society of America, Vol. 22, No. 5,pp.810-819
6. Hunt, R.W.G. (2004), The Reproduction of Colour, 6th Edition, Wiley
7. Kang, H.R. (2006), Computational Colour Technology, SPIE Press Monograph, Vol.PM159
8. Lee, C.H, 2005, Introduction to Colour Imaging Science. Cambridge University Press
9. Li, C., Luo, M.R., Cui, G. and Li, C. (2011), Evaluation of the CIE colour rendering Index, in Colouration Technology, Society of Dyers and Colourists, pp. 129-135
10. Ohta, N. and Robertson, A.R. (2006), Colourimetry: Fundamentals and Application, Wiley
11. P.J.M.van der Burgt, J.T.C. van Kemenade, About colour rendition of light sources. The balance between simplicity and accuracy, Philips Lighting, The Netherlands, Avalible online: http://cie2.nist.gov/TC1-69, [last accessed 13.05.2015]
12. Sandor, N., and Schanda, J. (2006), Visual Colour-Rendering Experiments, Lighting Res. & Technol. Vol. 38/3, pp. 225-239
13. Schanda, J. (2007), Colourimetry: Understanding the CIE system, Wiley
14. Urban, P., Berns, R.S. (2011).Paramer Mismatch-based Spectral Gamut Mapping, IEEE Transactions on Image Processing, Vol.20, Issue 6, pp.1599 – 1610