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A COLOUR GRAPHIC FOR REAL COMPLEX SCENES: APPLICATION TO LED ILLUMINANTS

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Abstract

This paper presents a new colour graphic informing on the colour rendition properties of light sources and glazing, in context. Instead of making predictions based on a predefined set of colour samples, the colour content of complex scenes is analysed. The main calculation steps of the proposed colour graphic are described with particular emphasis on the division of the colour space, based on colour naming, and on the processing of scenes' achromatic content. Then, the paper illustrates the interest of the proposed method for assessing colour rendition of LED sources in comparison to the IES TM30-18 colour vector graphic for two complex scenes. The results show that even if for most sources the colour shift tendency predicted by both method is similar; some differences support the interest to use real scene colour content to characterize accurately colour rendering.

Keywords: Colour rendering, colour shift, complex scene, LED illuminants

1 Introduction

During the past decades, limitations of the General Colour Rendering Index have been welldocumented with criticisms on being a one number output and not being able to represent all dimensions of colour quality (Davis and Ohno, 2010; Smet et al., 2010; van der Burgt and van Kemenade, 2010; Jost-Boissard, Avouac and Fontoynont, 2015, 2016). To deal with this issue, different indices of colour quality have been proposed (Hashimoto et al., 2007; Davis and Ohno, 2010; Smet et al., 2012; IES, 2015) and graphical representations have been developed (Davis and Ohno, 2010; van der Burgt and van Kemenade, 2010; IES, 2015, 2018; CIE, 2017; GLA, 2018). Since then, they became very useful and used to interpret and model the results of psychophysical experiments. However, some very recent studies have demonstrated that people's judgement for colour rendition varies with the type of objects present in the scene and with the lighting application (Royer et al., 2016; Lin et al., 2017; Wei et al., 2017) making objects dataset used in an experiment a critical point to avoid mischaracterisations (Royer and Wei, 2017). Although all these graphics are essential to characterise, visualise and understand the colour rendition properties of light sources, they are indeed not calculated for specific colour contents. As a consequence, they are not expected to accurately predict perception of specific objects and might not provide a reliable description of the effects of light sources over real scenes. Indeed, it is possible that a source with low theoretical rendition renders specific objects well and vice versa.

To improve colour rendition accuracy for real environments, we developed a new colour graphic for light source and glazing (Cauwerts and Jost, 2018). Instead of making predictions based on a predefined set of colour samples, the colour content of complex scenes is analysed. The graphic provides intuitive information about which colours of the scene are impacted and what kind of distortion should be expected. This paper aims particularly at:

- presenting improvements of the colour graphic;
- illustrating the interest of the proposed method for assessing colour rendition of LED sources in comparison to existing graphical representations.

Colour graphics will be tested on CIE illuminants including the nine LED illuminants recently recommended by CIE TC1-85 in the revision of CIE 15 technical report on colorimetry (CIE, 2018). This set of nine spectra represents all types of commercial LEDs found on the market, it was determined in the frame of the European research project "Future photometry based on solid-state lighting products" (EMPIR PhotoLED) from a collection of approximately 1500 commercial LED products of different types (Jost *et al.*, 2017).

2 Colour graphic

2.1 Overview of existing colour graphics

Colour graphics provide information on the magnitude of expected colour shifts for a predefined or standardised set of colour samples, and illustrate how different ranges of hue are typically affected by some light sources. In general, whatever the colour graphic and the colour space, vectors symbolize colour shifts. The starting point represents the colour under the reference illuminant and the end point, the colour under the test source. The length of the arrow represents the magnitude of the colour shift and its direction gives an estimate of the type of distortion. Pointing toward the origin means that the colour will lose chroma (with no change in hue). Pointing outwards indicates the opposite. Radial deviations signify shifts in hue.

A difference between "colour shift" graphics and "colour icon" or "colour distortion" or "colour diagram" graphics is that in the second type of graphics, colours are in general averaged into hue bins and colour coordinates of the reference source are normalized to a circle. For instance, colour shifts can be averaged for 36 hue segments of 10° each (van der Burgt and van Kemenade, 2010), or for 16 hue bins as in IES TM-30-18 (IES, 2018), or in eight hue bins of 45° each as in CIE224:2017 (CIE, 2017).

2.2 Proposed colour graphic

This section summarizes main calculation steps of the proposed colour graphic (Figure 1). For further details on the methodology, the reader can refer to the above-mentioned publication (Cauwerts and Jost, 2018).



Figure 1 – Main calculation steps of the colour graphic

For characterizing colour shifts, the colour graphic requires XYZ tristimulus values of the original scene and the distorted one. XYZ tristimulus values of real scenes can be obtained with an imaging colorimeter, a calibrated HDR camera, a hyperspectral camera or with a lighting simulation software. XYZ tristimulus values of shifted scenes can be obtained with the same instruments (without moving the viewpoint for the scene capture but changing the light source) or by computation. In this second case, the spectral power distributions (SPDs) of the sources (original and tested) and spectral data of original scene should be known.

For taking into account both colour appearance and spatial phenomena, iCAM06 (Kuang, Johnson and Fairchild, 2007) is first applied to the scenes. iCAM06 was chosen among several colour appearance models because it was developed specifically for complex stimuli. The prediction of the three attributes of colour (lightness, chroma and hue) is given in the IPT colour space which has a very good hue uniformity (Ebner and Fairchild, 1998). Therefore, our colour graphic represents colour shifts in the PT plane of the IPT colour space.

NOTE I channel of IPT color space is the intensity; P is the red-green colour opponency and T, the blue-yellow.

To facilitate the interpretation of scenes' colour content, we divided the PT plane in colour categories corresponding to six principal hues (orange, yellow, green, blue, purple and red). Unlike other graphical representations, the division of the space is not equally distributed but is determined based on colour naming (to help communication). For increasing the precision, each principal colour category is then divided in three bins of same angle. For instance, the orange bin is divided in an orange-yellow, an orange and an orange-red sub-category.

The studied scenes can be analysed by "colour category" or by "element". Each point of the colour graphic is either an average of the pixels belonging to each colour category or an average of the pixels of each studied element. Colour shifts are represented by vectors that begin with the mean hue and mean chroma of the original scene (empty symbols) and end at the mean hue and mean chroma of the distorted scene (plain symbols). When the scene is analysed by colour category, two circular histograms complement the graphic. They represent the proportion of pixels assigned to each colour bin and aim at describing the colour distribution of the two scenes (original and distorted). The histograms give the end-user the opportunity to evaluate whether the colour shifts impact a lot of pixels or not, and to determine which colours appear in or disappear from the scene. Empty histograms are for the original scene and plain histograms for the distorted scene (Figure 1).

2.3 Improvement of the colour graphic

Three experiments were conducted for validation purposes (Cauwerts and Jost, 2018). They highlighted a need for re-defining the boundaries between colour categories, and for distinguishing chromatic and achromatic content.

2.3.1 Division of the PT plane in colour categories

As mentioned before, for a matter of communication, the PT plane of the proposed colour graphic is divided into six main colour categories based on colour naming. In the previous version, the boundaries between these six colour bins were set based on the work by Hansen et al. (Hansen, Walter and Gegenfurtner, 2007). The centre of the yellow, orange, red, purple, blue and green bins matched with Munsell 5Y, 5YR, 5RP, 5P, 5B and 10GY respectively (Table 1).

	Previous division			New division		
	Centre	from	to	Centre	from	to
Orange	5YR	0.457 (5R)	1.265 (10YR)	5YR	0.730 (10R)	1.265 (10YR)
Yellow	5Y	1.265 (10YR)	1.689 (10Y)	5Y	1.265 (10YR)	1.689 (10Y)
Green	10GY	1.689 (10Y)	3.441 (5BG)	5G	1.689 (10Y)	3.703 (10BG)
Blue	5B	3.441 (5BG)	4.368 (5PB)	5PB	3.703 (10BG)	4.851 (10PB)
Purple	5P	4.368 (5PB)	5.822 (10P)	5P	4.851 (10PB)	6.066 (2.5RP)
Red	5RP	5.822 (10P)	0.457 (5R)	5R	6.066 (2.5RP)	0.730 (10R)

Table 1 – Centre and boundaries and of each colour bin. The centre is given in Munsell notation, the boundaries are given as an angle in radians (PT plane) and in Munsell notation. Bold values indicate modifications with the previous division of PT plane.

The boundaries between colour categories were defined in plotting Munsell samples under D65 in the IPT colour space and determining the Munsell hue the closest to the hue that is halfway from the centres of two neighbour bins. For validating these boundaries, a scene containing typical colour samples (a Macbeth Colour Checker (MCC), some fruit, vegetables and cans – Figure 2) was analysed through our colour graphic. The results questioned the definition of red and blue bins. Indeed, as shown in Figure 2, red elements were at the limit between red and orange bins and some blue elements were in the purple bin. We determined new boundaries using Munsell 5R as red centre, 5PB as blue centre and 5G as green centre that better match with NCS primaries (Table 1). The original boundary between the green and yellow bins was

kept to 10Y. The other boundaries were defined with the method described above. As illustrated in Figure 2, this new definition improves the categorisation of elements.



Figure 2 – Previous and new colour graphic for elements of a scene lit by a 6500K LED source. □ MCC line 1, + MCC line 2, ■ MCC line 3, ■ MCC line 4, ◆ cans, • fruit/vegetables.

2.3.2 Exclusion of achromatic and low saturated content

In our previous work (Cauwerts and Jost, 2018), consistency was observed between histogram distribution produced by the colour graphic and by people judgments. Small differences have been interpreted as due to achromatic content and presence of vegetation. Indeed, we observed that even in natural scenes, a large part of the scene colour content was identified by people as achromatic while the colour graphic did not include any achromatic bin. The colour graphic was refined in order to tackle the problem of achromatic content.

The scenes (IPT matrices) were first normalized using the white element identified as the brightest (no direct sun, no emitting source). Then, pixels with low chroma (C<0.05) in the original scene were removed from the analysis "by colour category". Objects with low chroma can still be plotted when the analysis is done "by element". Figure 3 illustrates that excluding achromatic content improves the match between histogram distribution produced by the colour graphic and by people judgments. Remaining differences are probably due to the presence of *ochre* façade in scene A (interpreted as yellow or as orange by people, and orange by the metric) and vegetation in scene B, judged as green by people, but analysed as yellow or orange by the colour graphic.



Figure 3 – Comparison between scenes' colour content as described by people and scenes' colour distribution determined by previous and new versions of the colour graphic (Y, O, R, P, B and G stands for yellow, orange, red, purple, blue and green bins respectively, achrom is for achromatic content). Error bars are SE of the mean.

3 Application

3.1 Comparison with the IES TM30-18 colour vector graphic

To test the relevance and interest of the developed colour graphic, it was compared with the mostly used IES TM30-18 colour vector graphic (IES, 2018). We analysed the rendition of 11 CIE illuminants: one illuminant representative of the fluorescent technology (FL12), one representative of high-intensity discharge lamps (HP2) and nine white LED illuminants recently recommended by CIE (CIE, 2018). Among these LED illuminants, there are five representatives of the widespread blue-phosphor technology (B1, B2, B3, B4, B5), two highly-structured LED illuminants (RGB1, BH1), and two violet-phosphor LED sources (V1, V2). Figure 4 presents, for eight of the studied illuminants, both colour graphics.



Figure 4 – IES vector graphics versus our colour graphics, for eight SPDs among the 11 analysed. In our colour graphic, empty symbols represent the reference scene and plain symbols are for the tested illuminant. Grey point means that less than 2% of the scene pixels are in the colour bin.

Contrary to the IES TM30-18 colour vector graphic which uses a standardized set of colours for calculations, our colour graphic requires XYZ values of a complex scene as input. We captured by hyperspectral imaging a scene (Figure 2) containing a MCC, four cans and some fruit and vegetables (red and green pepper, two red, one yellow and one white onions, a kiwi, a garlic, a potato, a green apple and a green pear, an orange, a clementine and two tomatoes). As shown in Figure 2, the objects are rather well distributed in hue and chroma allowing a comparison with IES TM30-18. Our choice of scene and sources seems relevant in view of the work carried out by Royer and Wei on the influence of object dataset on colour metrics (Royer and Wei, 2017). Our colour graphic gives the user the opportunity to choose the reference scene. In order to facilitate its comparison with the IES TM30-18 colour vector graphic we compared the 11 selected CIE illuminants to their reference illuminant (Planckian or daylight illuminant at the same correlated colour temperature (CCT)) and we presented colour shifts "by colour category".

Figure 4 illustrates that our colour graphic indicates the same tendency for colour shifts than the IES graphic except for B5, V1 and FL12 for which the shapes of the predicted colour gamuts are different. Among the five studied blue-phosphor LEDs, B5 is the only SPD leading to different tendencies in both graphics (we observed a small increase in chroma for red pixels and a hue shift toward orange that is not predicted by the IES method). For V1, which has a quite good colour fidelity index (Rf=87), the size of the colour shifts given by both indicators are in the same range but the orientation of the shift is different for nearly all colours. Concerning FL12, the chroma increase in yellow and green predicted by the IES method is not observed in our graphic.

Though RGB1 and BH1 are highly-structured LED sources, both graphics are quite similar but some difference can be observed occasionally. For instance, for BH1, there is an increase in chroma for red with our method while IES predicts a slight decrease in chroma and a small shift in hue. This is probably due to the fact that object dataset used by each method are different and not distributed in the same way providing different averaged values. Analysing the scene "by element" (Figure 5) highlights that neighbour red samples can shift differently: while a red element slightly shifts in hue (towards orange) and not in chroma, its neighbour slightly shifts in chroma and not in hue.



Figure 5 – Colour graphic "by element", for BH1

3.2 Analysis of a complex scene (computer-generated image)

As mentioned above, our indicator was developed for application to complex scenes and enables to choose which scene is taken as reference contrary to conventional rendering metric that uses Planckian or daylight illuminant at the same CCT. For these reasons, it is very attractive for lighting refurbishment as illustrated in this second application.

Figure 6 compares two lighting refurbishments of a scene originally lit under FL12. In the first proposition, FL12 is replaced with RGB1. B1 is proposed in the second case. Both proposed sources have a CCT similar to the original source (~3000K). A colour graphic is given for each

refurbishment (RGB1 versus FL12 on the left, B1 versus FL12 on the right). A visual rendering of the original and the distorted scenes complements the colour graphics.



Figure 6 – Application of the colour graphic for lighting refurbishment

The pixel colour distribution of the colour graphic shows that the scene is mainly composed of orange and red, and in a smaller amount of blue. The histograms indicate an increase of the red content with RGB1 and a slight increase in orange with B1. With RGB1, a slight hue shift toward red is observed for orange and red content, with a small increase in chroma. All other colours (present in smaller quantities in the scene and represented in grey) shift toward green making blue content more saturated and more cyan. This can be visually validated in analysing the pillow, the chair and the door in the renderings. B1 source reduces the chroma of orange content while the chroma of yellow, less present in the scene, increases (visually validated with the comparison of the yellow book). According to our graphic, RGB1 will produces less distortion on the studied scene than B1. The comparison of IES colour vector graphics for RGB1, B1 and FL12 (Figure 4) would suggest that FL12 is closer to B1.

4 Discussion and conclusion

This paper is written in the frame of a research aiming at developing a colour graphic informing on the colour rendition properties of light sources and glazing, in context. Instead of making predictions based on a predefined set of colour samples, the colour content of complex scenes is analysed (using computer-generated images or pictures of built environments). Another originality of the method is to divide the chromatic plane, in which colour shifts are plotted, based on colour naming. Indeed, it improves communication. After presenting new improvements in the development of the colour graphic since its first publication, this paper illustrates its interest with two applications.

A comparison of colour rendition predictions made by our colour graphic and by the vector graphic of IES TM30-18 was done for 11 CIE illuminants including nine LED sources. It shows that even if for most sources the colour shift tendency is similar with both methods, differences can be observed and might lead to mischaracterisations. The divergences might be due to the colours present in the scene. Even if they are well distributed in hue and chroma, they do not have identical spectral distribution functions and do not cover the same repartition as the 99

samples of the IES. It is important to keep in mind that it is the interaction between the SPD of a light source and the reflectance function of the objects that determines colour shifts. Therefore, different sets of colour can lead to different colour shifts. And set of colour samples are a critical component of any colour rendition measure (Royer and Wei, 2017). General indices and graphics are not supposed to predict the perception of a specific real scene or a particular object because the objects in question do not match the standard data set. Our graphic permits to simulate how the colours present in a scene will be, in average, distorted by a light source. The graphic by elements could also precisely indicate what element will be shifted and how, giving a complete view of what could influence observer judgements. In that sense, this kind of graphic could help the interpretation of psychophysical experiments and prevent erroneous modelling due to inaccuracy of measures.

The application of the colour graphic for lighting refurbishment illustrates that another advantage of our graphic is to compare the rendition of former and prescribed sources in a real environment. While other existing methods give information on how a light source will render colours in comparison to an ideal illuminant at the same CCT, the proposed colour graphic offers the opportunity to determine the shift between two sources. While it is not the aim of conventional colour rendering metrics, it could be useful in building design to illustrate, for end-users, the difference of colour appearance produced by two light sources. For instance, our graphic, could compare a scene under daylight at daytime and under electric light at night-time. The case study also points out that contextualizing colour shifts can lead to a different decision from that based on existing indicators. This result highlights the interest of using real scenes instead of test colour samples to characterise the colour rendition of light sources in context.

Standardised measures and recently developed graphical representations are essential for characterising colour rendition properties of light sources. However, independent of the situation, they only provide a first approximation of colour shifts. In taking into account real colour content, our method could improve the accuracy of the prediction. Moreover, the ultimate goal of our work is to develop a graphical indicator that predicts people preferences for colour shifts. For this purpose, the contextualisation is needed as the application influences people judgment. The validation of the proposed colour graphic will continue through psychophysical experiments. At last, to the best of our knowledge, few datasets include spectral reflectance functions of objects typical of real indoor environments. In the frame of this research, we initiated a database of hyperspectral images. We propose to pursue its development to be as representative as possible to multiple real life environments.

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