A NEW METHOD FOR QUANTIFYING COLOUR RENDERING

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ABSTRACT
This paper is aimed to develop some new measures for quantifying colour rendering between a reference and a test illuminant. In addition, CIE colour rendering index (CRI) and Colour Quality Scale (CQS) were evaluated using different sets of testing samples in order to reveal whether the two measures are sample dependent or not.

Keywords: Colour Rendering Index, Colour Quality Scale, Colour Gamut, Colour Volume and Area

1. INTRODUCTION
Colour rendering is defined as “effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant”. The currently recommended colour rendering index (CRI) [1] calculation method was officially introduced in 1974 and has been widely used in the lighting industry. More recently, some attempts [2-5] have been made to either improve its performance or to bring it in line with the modern colorimetric practice.

However, more experimental results [2,3] show that the CRI does not correlate well with visual colour rendering, especially in the case of LEDs. Sandor and Schanda [2], and Li et al [5] found that this could be improved when using the CIECAM02 based colour difference [6] in the CRI calculation. Davis and Ohno [4] proposed the Colour Quality Scale (CQS) for evaluating the colour rendering properties of the light sources. The calculation of the CQS is different from that of CRI mainly in three aspects. Firstly, 15 test reflectance functions were selected, which are different from those of the 14 CIE test samples used in computing CRI. Secondly, the colour difference was calculated based on CIELAB colour space [7] rather than CIE U*V*W* space [7], and the colour difference is further modified based on a saturation factor. Finally, a correlated colour temperature (CCT) factor was introduced to reflect the quality of the test light source against the CIE D65 illuminant. The CCT factor is defined as the ratio of the areas of the colour gamut in CIELAB space, formed by the 15 samples under the test and D65 illuminants respectively.

The aims of this paper are twofold. New measures based on the volume and area of a real surface colour gamut are derived for quantifying colour rendering between a reference and a test illuminant. Then the CRI and CQS are further evaluated against different test samples to reveal whether the sample sets used will affect their performances.

2. DATA COLLECTION
The data accumulated are categorised into two different types of data: colour coordinates and reflectance functions. The former includes the 576 colour coordinates (under the combination of CIE illuminant C and 1931 standard colorimetric observer) which defined the colour gamut boundary obtained by Pointer [8] in 1980, and the 684 colour coordinates which defined the colour gamut boundary standardised by ISO [9] in 1998. The latter includes the reflectance functions from Munsell Color Book, NCS colour atlas, DIN colour system, Munsell Limit Color Cascade, Dupont spectro-master, natural colours such as flowers and foliage, and also a data set provided by Sun Chemical [10]. The total number of reflectance functions is 32487.

3. NEW GAMUT BOUNDARY BASED ON SPECTRAL REFLECTANCE FUNCTIONS
A new gamut boundary was derived by using all the data in the above two types of data. Various methods such as segment maxima method (SMGBD)[11,12] have been used for defining gamut boundary. The surface of the gamut based on the collected data is shown in Figure 1, for which the real world surface colour gamut boundary was derived in terms of CIELAB L*, C* and h under CIE illuminant D50 and 1931 standard colorimetric observer. However, if another illuminant other than D50 is considered, the colour gamut boundary will be changed. This creates a problem to...
describe the new colour gamut boundary. One solution is to define the gamut boundary in terms of reflectance functions.

A new method for reconstructing reflectance functions is developed based on colour coordinates of a given set of gamut boundary. The reflectance function can be reconstructed using the techniques of localised basis vectors [13], smoothest conditions [14], and colour constancy [15] constraints. There are 684 (36 x 19) boundary points for the new colour gamut shown in Figure 1. Thus, 684 reflectance functions were generated.

Figure 1: The gamut of the real surface colours

4. NEW MEASURES FOR COLOUR RENDERING

Four new colour measures were derived. They are Volume, Shared Volume, Shared Area in L*C* plane and Shared Area in a*b* plane.

4.1 Colour Volume

The size of colour gamut shown in Figure 1 represents the volume of colour space that can be realised under any particular light source. The physical measure for the size of the colour gamut is its volume, which is used to quantifying the quality of colour rendering. The volume of the 3-D colour gamut can be considered as the sum of volumes of tetrahedrons. All the tetrahedrons have a common vertex, which is located in the middle of neutral axis (i.e., L*=50).

4.2 Shared Area and Shared Volume

Figure 2 shows one cross-section of the solid volume of the gamut with L*=50. The area enclosed by the full curve boundary corresponds to the reference D65 illuminant and the area enclosed by the dotted curve boundary corresponds to a test lamp. The quantity R is defined by:

\[ R = A_S / A_R \]  

where \( A_S \) is the shared area (shaded region in Figure 2) and \( A_R \) is the reference area. It is clear that \( R \) is less than or equal to 1. If the test boundary is very displaced compared to the reference boundary, there will be less shared area, hence \( R \) will be smaller. In addition, it is possible to have many cross-sections of the solid gamut, not only with a fixed \( L* \), but also cross-sections with a fixed hue angle. Similarly, a shared volume can be defined. The shared colour gamut will have a smaller, but similar to that given in Figure 1, hence the shared volume can be computed as a sum of volumes of tetrahedrons.

4.3 Comparing new measures with CRI and CQS

D65 illuminant and its six simulators were used in this investigation. These are VeriVide (VV), GretagMacbeth Spectral Light II (GM), Philips (F20T12/D), an LED daylight simulator based on 8 LED clusters (LED), a Yellow-Blue white LED (W. LED) and a simulator with Fluorescent lamps together with 3 LEDs (F.LED). The four new measures together with the CRI and CQS were evaluated and the results are listed in Table 1.

All the values for the new measures were normalised against corresponding values under D65, and then multiplied by 100. It can be seen from Table 1 that CRI and CQS gave roughly the same results for each light source. This can be seen in Figure 3, where the horizontal values are CRI values for the 7 light sources tested, and where the vertical values are the results of all the measures. The straight line is the 45° line. The CQS (dotted) curve is below the 45° line, but closer to the 45° line. The curve is also monotonically increasing. The other curves corresponding to new measures are all located above the 45° line and the curves are decreasing in certain parts and increasing in the other parts. These imply that CQS and CRI are roughly the same and the
new measures are somehow different from CRI. Through all measures indicate the light sources of Philips and White LED performed the worst, the new measures gave much higher values than CRI and CQS values, especially the measure of shared area in L* C* plane. The results based on the four measures were agreed with the data generated by Li et al [5] where their results showed that white LED gave similar performance as LED simulator and fluorescent LED.

Figure 2: Gamut boundaries of the reference illuminant (D65, full curve) and a test lamp (Philips, dotted curve) plotted in a* b* plane with L*=50.

Figure 3: All the new and CQS measures versus CRI values

Table 1: Performance of D65 simulators under various measures

<table>
<thead>
<tr>
<th>Illuminants</th>
<th>CRI</th>
<th>Colour Volume</th>
<th>Shared Volume</th>
<th>Shared Area (L*C)</th>
<th>Shared Area (a<em>b</em>)</th>
<th>CQS</th>
</tr>
</thead>
<tbody>
<tr>
<td>D65</td>
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<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>VeriVide</td>
<td>98.2</td>
<td>100.1</td>
<td>98.6</td>
<td>98.8</td>
<td>98.5</td>
<td>98.4</td>
</tr>
<tr>
<td>GretagMacbeth</td>
<td>97</td>
<td>99.6</td>
<td>98</td>
<td>96.8</td>
<td>98.1</td>
<td>96.8</td>
</tr>
<tr>
<td>Phillips</td>
<td>75</td>
<td>90.8</td>
<td>85.5</td>
<td>91.9</td>
<td>86.6</td>
<td>74.7</td>
</tr>
<tr>
<td>LED simulator</td>
<td>98.4</td>
<td>101.1</td>
<td>98.3</td>
<td>99</td>
<td>98.3</td>
<td>99.1</td>
</tr>
<tr>
<td>White LED</td>
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<td>86.3</td>
<td>92.4</td>
<td>86.5</td>
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<tr>
<td>Fluorescent LED</td>
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<td>101.5</td>
<td>99.3</td>
<td>99.5</td>
<td>99.2</td>
<td>97.6</td>
</tr>
</tbody>
</table>

5. EVALUATING CRI AND CQS WITH DIFFERENT SETS OF SAMPLES

This section tests the performances of CRI and CQS using different datasets. Four sets of reflectance functions were used. They are the set of 14 reflectance functions recommended by CIE [1] for computing CRI, the set of 24 reflectance functions in the GretagMacbeth ColorChecker Chart [16], recommended by CIE [3] for improving the calculation of CRI, the set of 15 reflectance functions proposed by Davis and Ohno [4] for computing CQS, and the set of 684 reflectance functions of the present study. Figure 4 shows the values of CRI and CQS for the 7 light sources calculated using each of the four sets of reflectance functions. It can be seen in Figure 4 that:

a) the values of CRI and CQS calculated using the set of 15 reflectance functions show large difference from those calculated using the set of CIE 14 reflectance functions;

b) the values of CRI and CQS calculated using the set of 15 reflectance functions are similar to those calculated using 684 reflectance functions generated from this study;

c) no matter which set of reflectance function is used, they give the same rankings for the light sources tested.

6. CONCLUSION

Four new measures for quantifying colour rendering were proposed. These were tested together with the CRI and CQS. A test was carried out using 6 D65 simulators. The results showed that rankings from the new measures are not much different from those of CRI and CQS, but they gave some higher values for the two lower ranking light sources tested. These predictions agree
with a new set of results by Li et al [5]. Furthermore, the sample dependent property for CRI and CQS was tested. The results showed that both measures can have very large changes for certain light sources when the test set of reflectance data is changed. However, the results showed the sets of 15 and 14 reflectance functions have large difference, and the sets of 15 and 684 reflectance functions gave the similar performance for the CRI and CQS.

Figure 4: Values of CRI (a) and CQS (b) for the light sources under four sets of reflectance functions

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