

Measuring Colour Rendering – A New Approach II

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MEASURING COLOUR RENDERING – A NEW APPROACH – II

Michael R. Pointer

Abstract

Following a summary of the status of the current CIE Colour-Rendering Index, this report presents a method of measuring a coloured sample giving numbers which correlate highly with the appearance of that sample when it is viewed under a defined illuminant. It is shown how these numbers, relating to the hue, lightness, and chroma of the sample, can be combined to provide a measure of the differences between a set of coloured samples viewed first under a reference lamp and then under a test lamp. Four hue/lightness/chroma indices are calculated for each of the four unique hues, red, yellow, green, and blue. These indices are combined to give mean hue, lightness and chroma indices, and an overall index. This final index may be considered analogous to the present CIE colour-rendering index. The procedure was first published in 1986 and the opportunity has been taken to revise the philosophy behind the method and to implement the use of the latest CIE recommendation on colour appearance models.

MEASURING COLOUR RENDERING – A NEW APPROACH – II

MICHAEL R POINTER

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1. INTRODUCTION

Aristotle was acquainted with the problems of colour rendering for he states: “There is an indescribable difference in the appearance of colours in woven or embroidered materials when they are differently arranged; for instance purple is quite different on a white or black background, and variations of light can make a similar difference.¹” This observation, coupled with Lord Kelvin’s statement that “when you can measure what you are speaking about and express it in numbers, you know something about it.²” provides a good reason to want to attempt to measure the perceived changes in appearance of coloured objects when they are viewed under different light sources.

1.1 CIE Colour Rendering Indices

The CIE test method to calculate a colour-rendering index of a test lamp has a long and somewhat chequered history^{3,4,5}. The original 1948 recommendation⁶ was based on an eight-band method that had been proposed by Bouma in 1937⁷. It was subsequently pointed out by Crawford, while working on the subject at the National Physical Laboratory in the UK, that the contribution of two of the bands to the index was of little consequence because they represented light in the near ultra-violet, on the very edge of the visible part of the spectrum. They thus contributed little or nothing to the colorimetry of test objects⁸.

Crawford went on to devise a six-band method⁹ that found acceptance in a number of applications in the UK but did not achieve worldwide approval. The method requires the calculation of the percentage luminance in each band for the test lamp and comparing it with that of the appropriate band for the reference lamp. Thus, the percentage deviation from unity for each band can be obtained. The excess of this deviation over a tolerance, which Crawford determined from experimental observations, is then calculated and summed over the six bands to give a figure of demerit.

At the same time as Crawford was working in the UK, a considerable amount of work was being done in the USA, the Netherlands and Germany on an alternative method for assessing colour rendering. The method was based on the principle of assessing the magnitude of the change in chromaticity produced when a coloured sample is viewed first using a test lamp and then a reference lamp. Ouwletjes¹⁰, Münch¹¹, Münch and Schultz¹², and Nickerson¹³ used a large number of Munsell samples in their researches and finally concluded that eight samples would be sufficient to describe the general colour-rendering properties of a lamp. The results of this work were used by the CIE Technical Committee E-1.3.2 *Colour Rendering* in 1965 to develop a recommendation for a CIE General Colour Rendering Index, R_a ¹⁴. The method involved calculating the colorimetry of eight Munsell test colours, first using the spectral power distribution of the test lamp and then using the spectral power distribution of a reference lamp. This reference lamp was selected to have the same correlated colour temperature (CCT)[#] as the test lamp and be either a Planckian radiator (CCT < 4999 K) or a daylight distribution (CCT > 5000 K). Since the chromaticities of most test lamps would not fall on either the Planckian or the daylight locus, it was necessary to incorporate a chromatic adaptation transform to correct for the difference. The difference in chromaticity between the test lamp and the reference lamp can be perceived as having two components¹⁵: the adaptive colour shift, which is corrected by the chromatic adaptation transform, and the illuminant colour shift which is that part of the difference which remains

[#] The temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions.

and is not corrected. The colour difference for each sample pair was then calculated using the CIE 1964 $U^*V^*W^*$ colour-difference equation and the eight values averaged and scaled such that a warm white fluorescent lamp with a correlated colour temperature of approximately 3000 K has a General Colouring Rendering Index of 50. Exact reproduction by the test lamp, of the colorimetry obtained using the reference lamp, would give an Index of 100.

In 1974, the CIE published a revision of the 1965 method, incorporating a number of improvements to that method¹⁶. A revised chromatic adaptation transform, of the von Kries type, was included and the method of calculating the index slightly modified. Greater emphasis was placed on the Special Colour Rendering Indices, R_i , derived from the colour difference for the eight separate test colour samples, as well from an additional 6 Munsell coloured samples that could be used to calculate Special Indices that pertained to discrete parts of colour space. This method has now found international acceptance and is included in a number of standards and commercial lamp specifications. Several reprints of this recommendation were subsequently published and in 1994, a further up-dated version was published as CIE Publication 13.3 – 1994¹⁷: this represents the current CIE thinking on colour rendering.

The history of colour science has not stood still however, and there have been a number of developments that have a bearing on the calculation of the colour-rendering index. The most important of these developments are:

- The replacement of the u, v uniform chromaticity diagram, used in the calculation of the correlated colour temperature, with the u', v' diagram¹⁸.
- The introduction of two new uniform colour spaces, CIELAB and CIELUV, to supersede the $U^*V^*W^*$ space used in the calculation of the present indices¹⁸.
- The recommendation of a new chromatic adaptation transform by the CIE in 1994¹⁹.
- The commercial non-availability of the Munsell test colour samples.

Thus in 1991, the CIE established a new Technical Committee, TC1-33 *Colour Rendering*, to investigate the whole process of calculating a colour rendering index to evaluate light sources. This committee was not successful in its purposes mainly due to the disagreement between those who advocated including the advances of science and those who recommended that industry did not want change. The paths taken by this committee, and the reasons for its lack of success, are summarised in a review report²⁰.

1.2 Modern Light Sources

The whole concept of a colour-rendering index was originally devised to promote the use of fluorescent lamps over those employing tungsten filaments. With the continuing development of new man-made light sources, such as new fluorescent lamps, mercury vapour lamps, metal halide lamps and, more recently, Light Emitting Diodes (LEDs), the problem of assessing the colour rendering properties of these sources has become of even greater importance. Many artificial sources are designed to provide near daylight-quality illumination in shops, factories, etc. Historically it was often the case that the colour of the light emitted closely resembled the colour of some phase of daylight. While this is still the case for LEDs, values of correlated colour temperature considerably higher than 6500 K are often encountered.

It is still true however, that the relative spectral power distribution provided by most artificial daylight sources does not compare well with that of natural daylight of the same or similar colour. This difference in spectral power distribution causes objects illuminated by the artificial source to be perceived as having different colours from when they are illuminated

by real daylight, which itself leads to a need to ‘measure’ the colour rendering capability of a light source.

It is often the case that light sources are deficient in energy in the long wavelength, ‘red’ region, leading to poor rendition of red objects. Lamp manufacturers are aware, of course, of the problem and have tried to improve the colour rendering properties of their lamps by introducing various blends of phosphors to increase the output of luminous flux in the long wave part of the spectrum. But unfortunately an improvement in colour rendering usually means a lowering in efficacy, that is a loss in light output for a given input of electrical power. Thus, it can be the case that two lamps with the same correlated colour temperature, can have very different values of colour rendering index, especially for saturated colours.

The problem appears especially acute with so-called white LEDs that can be constructed using a ‘blue’ LED, with a peak wavelength at approximately 460 nm, and a yellow phosphor with a peak at approximately 560 nm. In order to obtain a relatively high correlated colour temperature, ‘blue-white’, appearance, the ratio of blue to yellow light must be high: this however, reduces the relative amount of energy in the long wave part of the spectrum. Reducing the ratio improves the colour rendition of red coloured samples, but lowers the correlated colour temperature of the source. Equally, a ‘white’ LED can be constructed from three coloured LEDs, a red, a green and a blue and the positions of the peak wavelengths will be critical to the quality of the colour rendering, especially that of the red peak. If the peak is at a wavelength less than approximately 620 nm then the rendering of red colours will be very deficient. As the value of the peak wavelength is increased then the rendering will improve, but it is quite possible that the value of the general index remains approximately constant²¹.

CIE has now become active in the field of colour rendering. A specific Technical Committee, TC1-65, is looking in to the present problems associated with the application of the colour rendering indices to white light sources. Once their work is completed, and the problem and its cause documented, a new Technical Committee will be established, probably in 2005, to work on the derivation of a revised index. This work can only be successful if it is supported by experimental observations. A CIE Expert Symposium was held in Tokyo in June 2004, at which a number of groups described such observations^{22, 23, 24, 25, 26}.

1.3 Colour Appearance

There are many difficulties involved in developing a comprehensive method of appearance and one of the main problems has been the lack of a system for measuring the appearance of the colours of a series of test samples as they are viewed in a defined environment.

The aim of this report is to outline a useful method of measuring the appearance of these colours, and to apply it to provide quantitative measures that assess the colour rendering properties of a light source. The procedure described for calculating a series of indices, was first published in 1986²⁷. Since that time a number of changes and improvements have been made to the colour appearance model on which the calculations are based, the concept of indices has been thoroughly investigated by application to the quality of colour reproduction systems and some changes have been made to the philosophy of the formulation of the indices.

Traditional colorimetry has been with us for a long time – the 1931 Standard Colorimetric Observer celebrated its 70th birthday in 2001. The CIE system of colour measurement, based

as it is on the colour matching functions which represent the standard observer, has stood the test of time and proved to be immensely valuable in helping to solve many measurement problems. As one of the 'fathers' of the Standard Observer has so aptly pointed out however, "The definition of a colour C by the equation

$$C \equiv X(X) + Y(Y) + Z(Z)$$

expresses the fact that a certain mixture of three reference stimuli will produce the same colour sensation as C when both are seen under the same viewing conditions. Although this specification involves an observer and is therefore a subjective relationship, it does not in itself define the appearance of C ...²⁸.

Thus, the situation can be imagined where there are two colours, both specified in terms of their tristimulus values, and it is required to know the difference in their appearances when viewed under the same specified viewing conditions. Some approximate estimates can be obtained by transforming the tristimulus values to chromaticity coordinates and plotting these coordinates on a chromaticity diagram together with the position of the appropriate white point. In this way a relative idea can be obtained as to whether one sample is, for example, redder than another, and which sample has the higher purity. No information is available, however, as to their absolute colour appearances.

2. COLOUR APPEARANCE MODELS

In 1982, Hunt published a landmark paper describing a model of colour vision that provided a basis for predicting colour appearance which agreed well with established colour order systems (for example, the NCS System)²⁹. The basic model was subsequently extended to provide predictions of colour appearance using illuminants other than the daylight used in the original formulation³⁰. The steps involved in the model are out-lined in Figure 1.

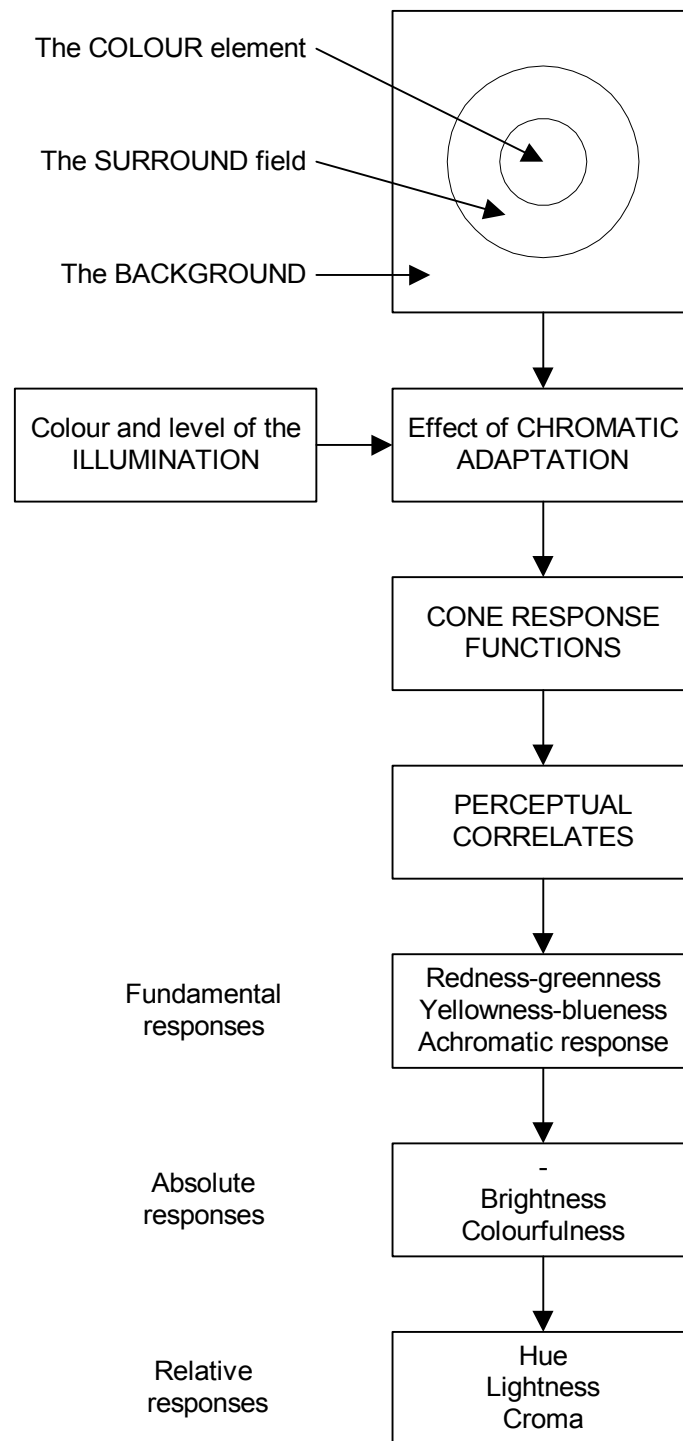


Figure 1. Block diagram showing the components of a colour appearance model.

The output of the model consists of several parameters including the relative perceptual responses, the hue, the lightness, and the chroma, of the measured sample. The hue of any colour can be expressed in terms of the psychological primaries red, yellow, green, and blue. These four unique hues can be represented as points on a hue circle, Figure 2. The hue of a colour can then be expressed as a unique hue, e.g. 100% red, or as a mixture of two adjacent unique hues, e.g. a turquoise (cyan) colour may be 50% blue and 50% green. The hue can also be expressed, as an angle, on a continuous scale from 0 to 360 degrees: 20.13 represents unique red, 90.00 unique yellow, 164.24 unique green, and 237.53 unique blue. On this scale,

the hue of the turquoise example above would be 208. The spacing of the unique hue lines is a consequence of the model.

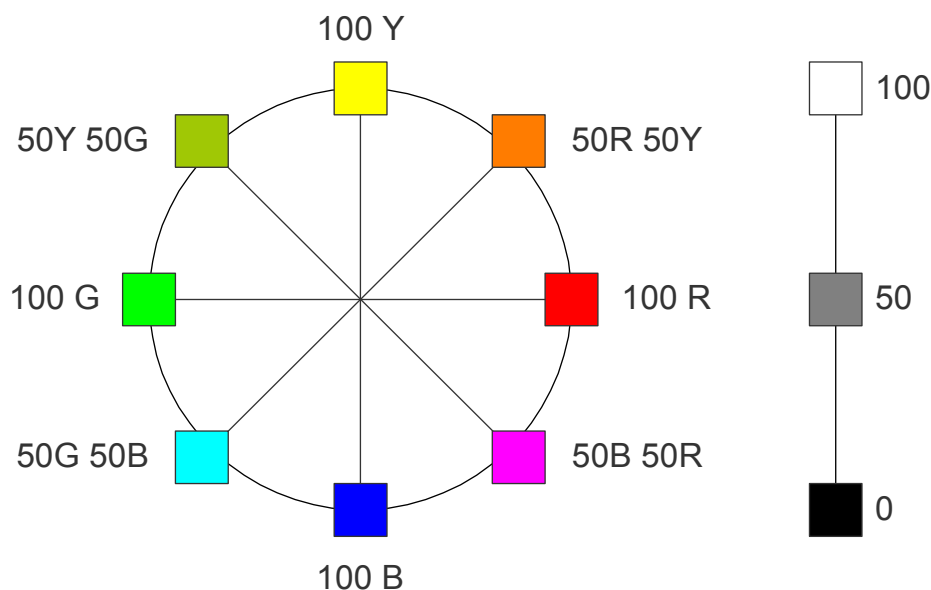


Figure 2. Diagrammatic representation of the scales defining the perceptual concepts of hue (circle), chroma (radii) and lightness (linear).

The lightness may be thought of as a measure of relative brightness, i.e. the brightness of a colour relative to the brightness of a similarly illuminated white in the same scene. If lightness is scaled as 100, all other colours can be attributed numbers between zero (black) and 100.

The chroma is a relative measure of the amount of chromatic colour, or colourfulness, in a sample. In the hue circle of Figure 2, chroma is represented by the distance along radii. Thus, a set of concentric circles represents contours of constant chroma. (For a more formal set of definitions of these attributes, see the Appendix.)

The model can be applied to the problem posed above, if the two samples had the following colorimetric specification (calculated from measurements of the spectral reflectances and using CIE Standard Illuminant D65):

	u'	v'	x	y	Y
Sample 1	0.149	0.474	0.253	0.295	27.04
Sample 2	0.150	0.520	0.357	0.454	14.13
D65	0.198	0.468	0.313	0.328	100.00

Then applying the model gives the following appearance measures:

	Hue angle	Hue	Chroma	Lightness
Sample 1	182	72G 28B	35	48
Sample 2	145	80G 20Y	37	33

Thus it is now possible to say immediately that both samples are predominantly green but that, while Sample 1 exhibits 28% of blue, Sample 2 exhibits 20% of yellow; Sample 2 has a chroma 2 units higher than that of Sample 1, Sample 2 is 15 units darker than Sample 1.

If now the first sample is viewed first under Illuminant D65 and then under CIE Standard Illuminant A, resulting in the following colorimetric data:

	u'	v'	x	y	Y
Sample 1(D65)	0.149	0.474	0.253	0.295	27.04
D65	0.198	0.468	0.313	0.328	100.00
Sample 1(SA)	0.189	0.527	0.357	0.454	23.93
SA	0.256	0.524	0.447	0.407	100.00

then the model gives the following appearances:

	Hue angle	Hue	Chroma	Lightness
Sample 1(D65)	182	72G 28B	35	48
Sample 1(SA)	190	61G 39B	40	46

which shows that the sample, as viewed under illuminant SA, is 11 units bluer, 5 units higher in chroma, and 2 units lighter, than when it is viewed under illuminant D65. Thus, it is possible to calculate numbers representing the absolute appearance attributes of particular samples as seen under defined viewing conditions.

During the years, since the publication of Hunt's paper, there have been many changes and improvements made to the structure of the colour appearance model³¹. This period of evolution culminated in the recommendation by the CIE, in 1997, of CIECAM97s, the CIE Colour Appearance Model 97s – the 's' stood for 'simple', implying that the model was limited in application to the photopic range^{32, 33}. This model found great application in the colour imaging industries and, with the generation of considerably more data^{34, 35} it was revised in 2002 to give the current CIE recommendation for a colour appearance model: CIECAM02³⁶.

3. A NEW COLOUR RENDERING INDEX

The colour rendering properties of a light source can be considered on both an absolute basis and on a relative basis. In the former situation, the colour appearance model is able to give measures which relate to the absolute appearance, in terms of the hue, lightness and chroma, of a colour as viewed under a particular light source. In the latter case, comparison is usually made between a reference source and a test source. In the present method of measuring the colour rendering index the chromaticities and luminance factors of a set of test colours, calculated with respect to the test lamp are compared with the chromaticities and luminance factors calculated with respect to a reference lamp.

As described above, this reference lamp is defined as having the same correlated colour temperature as the test lamp, and a Planckian spectral power distribution if this colour temperature is below 4999 K or a reconstituted daylight distribution if it is greater than this value. Comparisons of this type can be made using the new measures.

It is often more meaningful however, to make comparisons not with a hypothetical reference illuminant but with a real reference illuminant, or source. This could be a source of the same colour temperature and, perhaps, manufactured using a different technology; it could be a reference illuminant which is available as a source and used in a practical viewing situation, e.g. a light booth; or it could be a standard reference illuminant, for example, CIE Standard Illuminants D65 or SA. There is some merit in having only a small number of reference illuminants or perhaps only one.

The indices to be outlined below attempt to provide numbers which give measures of the differences between a 'reference' situation and a 'test' situation. They should enable the comparisons outlined above to be made on a systematic basis.

It is proposed that there be four hue, four lightness, and four chroma indices relating to red, yellow, green, and blue, respectively. These twelve indices are to be considered as vectors in that the calculations provide both the mean magnitude and the mean direction of the colour differences.

The four hue indices can be combined to provide a mean hue index, the four lightness indices combined to provide a mean lightness index, and the four chroma indices combined to provide a mean chroma index; the mean hue, lightness and chroma indices can be further combined to produce an overall colour rendering index.

4. CALCULATION OF THE MAIN INDICES

4.1 Definition of the reference and test situation

As an example, let the reference situation be a GretagMacbeth ColorChecker™ Chart³⁷ illuminated by CIE Standard Illuminant D65 (representing typical daylight). The test situation could be the same chart illuminated by a fluorescent lamp simulating illuminant D65 – CIE F7¹⁸.

4.2 Computation of the colorimetric data

The chromaticities, u' , v' , and the luminance factor, Y , of each coloured sample in the reference and test charts are calculated from measurements of the spectral reflectances of those samples and with a knowledge of the spectral power distribution of the illuminant. If one of the CIE standard illuminants is used as a reference illuminant, the spectral power distribution is available as a table of data; otherwise, the spectral power distributions of this, and that of the test illuminant, must be measured using a spectroradiometer.

4.3 Computation of colour appearance data

The colorimetric data are transformed to colour appearance data using the CIECAM02 Colour Appearance Model.

4.4 Computation of weights

The hue and chroma differences are to be weighted to produce the mean values. The weights are calculated according to the amount of red, yellow, green and blue present in each coloured sample in the reference chart. For example, if the hue of a sample is given by 70% green and 30% yellow, the red weight is zero, the yellow weight 30%, the green weight 70%, and the blue weight zero. Thus, this particular coloured sample does not contribute to the red

or blue indices, but does contribute to the green and yellow indices with weights of 0.7 and 0.3 respectively.

4.5 Computation of hue indices

The differences in hue are assessed in two ways. First, the weighted mean absolute hue difference is calculated as the difference between two hue angles. This gives a measure of the mean total hue error irrespective of direction, i.e. irrespective of whether, for example, one red has been rendered too blue and another too yellow. Second, the mean weighted relative hue difference is calculated. This takes into account the direction of the error so that if in the above example one red rendered 10 units towards the blue, while the other rendered 5 units towards the yellow, the mean absolute red hue error would be 7.5 units, but the mean relative red hue error would be -2.5 and the direction of the red index quoted as Red to Blue. Four pairs of indices are calculated, one pair for each of the four unique hues.

4.6 Computation of lightness indices

These indices are calculated exactly analogously to the hue indices. The weighted mean absolute lightness difference is a measure of the total difference between the reference and test charts. The mean weighted relative lightness difference is used to calculate the mean direction of the differences; i.e. an increase or decrease in lightness. Again four pairs of indices are calculated, one pair for each of the four unique hues.

4.7 Computation of chroma indices

These indices are also calculated exactly analogously to the hue indices. The weighted mean absolute chroma difference is a measure of the total difference between the reference and test charts. The mean weighted relative chroma difference is used to calculate the mean direction of the differences; i.e. an increase or decrease in chroma. Again four pairs of indices are calculated, one pair for each of the four unique hues.

4.8 Scaling and combination of the indices

The hue, lightness, and chroma indices can be scaled by subtracting their values from 100. This provides a scale on which 100 represents a perfect match between the reference and test charts, i.e. the test lamp renders the colours to have the same appearance as the reference lamp.

The hue indices can be combined by finding their weighted mean values, the weights being the number of test colours in the chart that contain each of the four unique hues. (These weights are different from those used to calculate the indices above). Similar weighted mean lightness and chroma indices can be calculated using the same weights. The use of weights in this way implies that the colours in the test picture are distributed in a meaningful way. This would be true of, for example, the GretagMacbeth ColorChecker Chart.

Finally, the mean hue, lightness and chroma indices can be combined to provide an overall rendering index. If required, this combination can also be weighted on the grounds that hue errors might be considered more important than lightness and chroma errors. Thus, for example, a weighting of 2:1:1 might be used.

5. A WORKED EXAMPLE

5.1 Definition of reference and test situation

Let the reference chart be a GretagMacbeth ColorChecker Chart illuminated by CIE Standard Illuminant D65.

Let the test situation be the same chart illuminated by a fluorescent lamp having a correlated colour temperature of approximately 4220 K – CIE fluorescent lamp F2¹⁸: Figure 3 shows the relative spectral power distributions of this lamp and CIE illuminant D65.

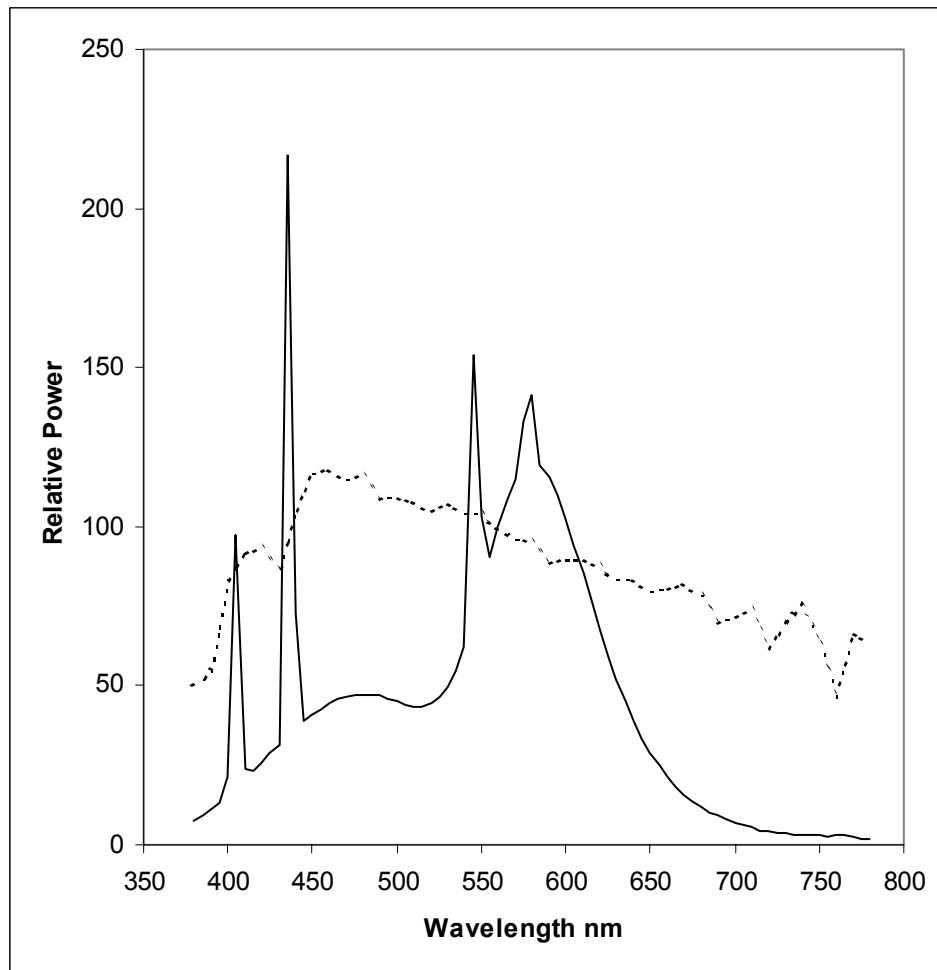


Figure 3. The relative spectral power distribution of the reference illuminant, CIE Illuminant D65 (dashed), and the test lamp (full line), both normalised to a value of 100 at 560 nm.

The ColorChecker Chart comprises 18 coloured samples and 6 neutral samples: Figure 4 shows the layout of the chart. While there is no inherent reason why the neutral samples should not be included in the index calculations, only the 18 coloured patches are used in the example presented here.



Figure 4. Layout of the GretagMacbeth ColorChecker Chart.

5.2 Computation of colorimetric data

The chromaticities u' , v' and the luminance factor, Y , were calculated from measurements of the spectral reflectances of each of the coloured samples in the reference and test charts. The spectral power distribution of the reference and test illuminants were available as tables of data. The data derived for the reference and test situations are given in Table 1.

Table 1. Colorimetric data of the samples calculated using the reference and test illuminants.

	Reference illuminant			Test illuminant		
	CIE D65			CIE F2		
	x	y		x	y	
	0.3127	0.3290		0.3721	0.3751	
Sample	Reference chart			Test chart		
	x	y	Y	x	y	Y
1	0.4006	0.3608	10.39	0.4446	0.3996	10.91
2	0.3807	0.3554	35.41	0.4311	0.3930	36.11
3	0.2458	0.2616	19.05	0.3021	0.3052	17.24
4	0.3371	0.4312	13.16	0.3893	0.4600	13.19
5	0.2699	0.2536	23.74	0.3247	0.3001	22.36
6	0.2602	0.3558	42.95	0.3257	0.3998	40.22
7	0.5050	0.4077	30.39	0.5191	0.4312	34.70
8	0.2114	0.1828	12.03	0.2576	0.2215	10.62
9	0.4593	0.3127	19.29	0.4935	0.3492	19.52
10	0.2906	0.2204	6.92	0.3356	0.2627	6.54
11	0.3743	0.4950	44.89	0.4217	0.5037	46.45
12	0.4747	0.4415	42.19	0.4937	0.4593	48.28
13	0.1842	0.1365	6.07	0.2204	0.1625	4.92
14	0.3017	0.4855	23.73	0.3663	0.5016	22.68
15	0.5432	0.3191	11.79	0.5504	0.3494	11.06
16	0.4459	0.4774	59.93	0.4723	0.4857	64.65
17	0.3670	0.2406	19.27	0.4062	0.2792	18.08
18	0.1943	0.2625	18.68	0.2461	0.2991	15.08

5.3 Computation of appearance data

The colorimetric data were transformed to appearance data: these data are given, for the reference and test charts, in Table 2.

Table 2. Appearance data for the reference and test illuminants.

	Reference chart			Test chart		
	Hue	Chroma	Lightness	Hue	Chroma	Lightness
1	30.3	19.1	29.6	49.2	17.7	29.9
2	31.1	20.9	57.8	44.8	20.3	57.8
3	305.0	32.0	39.7	311.2	30.1	38.3
4	157.9	25.5	32.5	154.2	25.9	32.4
5	321.7	30.5	45.5	324.0	30.0	44.6
6	228.3	36.6	61.4	222.8	27.7	59.8
7	49.4	56.0	54.2	67.4	54.2	56.6
8	313.4	49.7	30.7	316.8	48.7	29.8
9	395.2	51.6	43.0	399.4	42.3	42.2
10	341.7	31.9	23.6	337.5	30.9	23.0
11	145.2	56.6	63.9	142.3	58.7	64.4
12	76.9	56.1	63.9	92.6	59.3	67.1
13	312.5	54.9	20.7	316.1	53.8	19.8
14	176.3	48.9	44.2	168.6	44.5	43.1
15	1.7	66.3	33.5	6.7	50.8	31.1
16	106.7	65.5	76.3	115.4	70.3	78.0
17	366.7	53.0	42.7	361.6	45.5	40.9
18	280.2	50.6	38.1	295.9	43.9	35.0

An immediate impression of some of the differences between the reference and test charts can be obtained by plotting the appearance parameters in a diagram similar to Figure 5 which shows the hue and chroma data for the 18 test colours. The figure shows that the test illuminant, the fluorescent lamp (CIE F2), slightly reduces the chroma of the coloured samples, relative to their appearance under the reference illuminant (CIE D65). In particular, colours in the blue/red to red and yellow to green parts of the hue circle are reduced. There are also some moderate hue differences, especially in the red/yellow to yellow, and blue, region.

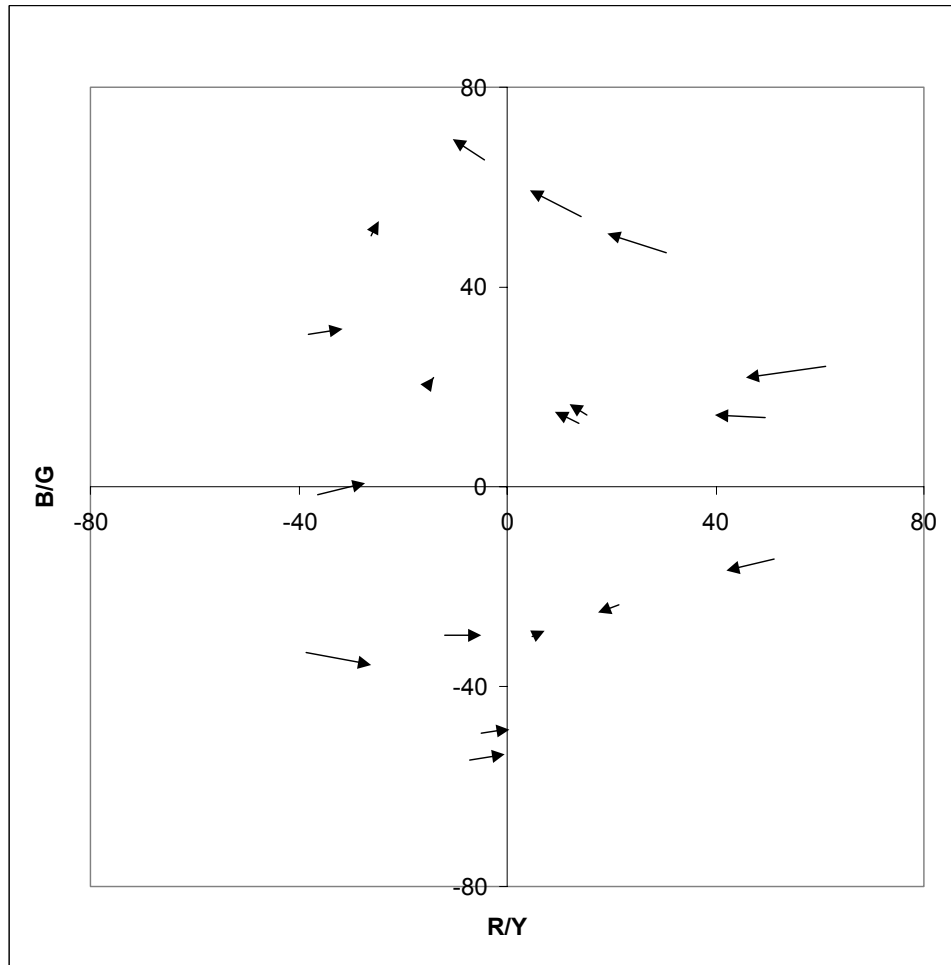


Figure 5. The hue and chroma values of the 18 colours on the ColorChecker Chart, plotted on a redness/greenness, yellowness/blueness diagram. The colours using the reference illuminant (tail of arrow) are shown together with the respective colour using the test illuminant (tip of arrow).

5.4 Computation of weights

The reference chart is the ColorChecker Chart comprising the original scene. Thus, the weights are equal to the amounts of the four unique hues present in each of the coloured samples. These data can be derived straight from Table 2 and are shown listed in Table 3. From this table it can be seen that, for example, Sample 18, which is greenish-blue, has zero weight for red and yellow because it has no red or yellow content, and has weights of 20 for green and 80 for blue because its hue is calculated as 80% blue and 20% green. It can also be seen from Table 4 that 12 coloured samples will contribute to the red indices, 9 to the yellow, 6 to the green, and 9 to the blue. This imbalance between the numbers of samples contributing to each index may be considered a weakness in the theory. However, the numbers are a function of the test chart, or charts, being used and it is conceivable that a different chart may give a better balance between the colours and result in the calculation of a better index. This matter will be considered again later in this report.

Table 3. Weights used in calculating the mean values.

	Weight			
	Red	Yellow	Green	Blue
1	70	30		
2	69	31		
3	5			95
4		42	58	
5	22			78
6			72	28
7	51	49		
8	13			87
9	95			5
10	42			58
11		55	45	
12	23	77		
13	13			87
14		24	76	
15	98	2		
16		93	7	
17	67			33
18			20	80

5.5 Computation of hue indices

The weighted mean absolute hue differences, H_{Aj} , are calculated by the formula:

$$H_{Aj} = 100 - \left(\frac{\sum |\Delta H_i| W_i}{\sum W_i} \right)$$

where $j = r, y, g, b$ (red, yellow, green, or blue), ΔH_i is the hue difference of sample i , equal to [hue (test) – hue (reference)], W_i is the weight of sample i . (The modulus sign implies the absolute value.) The results of these computations are shown in Table 4. The four numbers in the column headed H_{Aj} are the unscaled hue indices.

The weighted mean relative hue difference, H_{Rj} , is calculated using the formula:

$$H_{Rj} = \frac{\sum \Delta H_i W_i}{\sum W_i}$$

where the symbols have the meanings given above.

The results of these computations are also shown in Table 4. The four numbers in the column H_{Rj} are used to decide the direction of the hue indices. Thus, for example, if H_{Rj} , for red, is positive the mean trend is for red colours in the reference chart to appear yellower in the test chart. Conversely, if H_{Rj} is negative the mean trend is for red colours in the reference chart to

appear bluer in the test chart. These directions, and those associated with the other colours are tabulated in Table 5.

Table 4. Calculation of mean differences and indices.

Absolute differences					Relative differences				
Hue					Hue				
	$\Sigma(W_i)$	$\Sigma \left \frac{(\Delta H_i)}{W_i} \right $	H_{Aj}			$\Sigma(W_i)$	$\Sigma(\Delta H_i).W_i$	H_{Rj}	
Red	566.85	4247.60	7.49	92.51	Red	566.85	2881.56	5.08	R→Y
Yellow	403.23	2931.29	7.27	92.73	Yellow	403.23	2162.16	5.36	Y→G
Green	277.69	1312.20	4.73	95.27	Green	277.69	-725.65	-2.61	G→Y
Blue	552.24	4359.40	7.89	92.11	Blue	552.24	2995.51	5.42	B→R
Lightness					Lightness				
	$\Sigma(W_i)$	$\Sigma \left \frac{(\Delta L_i)}{W_i} \right $	L_{Aj}			$\Sigma(W_i)$	$\Sigma(\Delta L_i).W_i$	L_{Rj}	
Red	566.85	727.53	1.28	98.72	Red	566.85	-290.48	-0.51	Drk
Yellow	403.23	605.29	1.50	98.50	Yellow	403.23	532.51	1.32	Lit
Green	277.69	303.79	1.09	98.91	Green	277.69	-227.54	-0.82	Drk
Blue	552.24	752.69	1.36	98.64	Blue	552.24	-752.69	-1.36	Drk
Chroma					Chroma				
	$\Sigma(W_i)$	$\Sigma \left \frac{(\Delta C_i)}{W_i} \right $	C_{Aj}			$\Sigma(W_i)$	$\Sigma(\Delta C_i).W_i$	C_{Rj}	
Red	566.85	3309.03	5.84	94.16	Red	566.85	-3164.35	-5.58	Dec
Yellow	403.23	1108.69	2.75	97.25	Yellow	403.23	533.05	1.32	Inc
Green	277.69	1265.90	4.56	95.44	Green	277.69	-963.48	-3.47	Dec
Blue	552.24	1550.43	2.81	97.19	Blue	552.24	-1550.43	-2.81	Dec

5.6 Computation of lightness indices

The computation of the lightness indices L_{Aj} and L_{Rj} , follows the same pattern as that of the hue indices out- lined above. The results of those calculations are shown in the centre of Table 4. The four numbers in the column headed L_{Rj} , are used to decide on the direction of the lightness shift. A positive value of L_{Rj} indicates an increase in lightness between the test and reference charts, while a negative value indicates a decrease in lightness. These directions are also given in Table 5.

Table 5. Mean directions of the differences.

H_{Rj}	Hue direction	L_{Rj}	Lightness direction	C_{Rj}	Chroma direction
Red positive	R to Y	Positive	Lighter	Positive	Increase
Red negative	R to B	Negative	Darker	Negative	Decrease
Yellow positive	Y to G				
Yellow negative	Y to R				
Green positive	G to B				
Green negative	G to Y				
Blue positive	B to R				
Blue negative	B to G				

5.7 Computation of chroma indices

The computation of the chroma indices C_{Aj} and C_{Rj} , follows the same pattern as that of the hue indices out-lined above. The results of those calculations are shown at the bottom of Table 4. The four numbers in the column headed C_{Rj} , are used to decide on the direction of the chroma shift. A positive value of C_{Rj} , indicates an increase in chroma between the reference and test charts, while a negative value indicates a decrease in chroma. These directions are also given in Table 5.

5.8 Scaling and combination of indices

The separate hue, lightness and chroma indices can now be scaled by subtracting their values from 100; see Table 6.

Table 6. Final colour rendering indices.

Hue			
Red	$H_{Ar} =$	92.51	$R \rightarrow Y$
Yellow	$H_{Ay} =$	92.73	$Y \rightarrow G$
Green	$H_{Ag} =$	95.27	$G \rightarrow Y$
Blue	$H_{Ab} =$	92.11	$B \rightarrow R$
Lightness			
Red	$L_{Ar} =$	98.72	Drk
Yellow	$L_{Ay} =$	98.50	Lit
Green	$L_{Ag} =$	98.91	Drk
Blue	$L_{Ab} =$	98.64	Drk
Chroma			
Red	$C_{Ar} =$	94.16	Dec
Yellow	$C_{Ay} =$	97.25	Inc
Green	$C_{Ag} =$	95.44	Dec
Blue	$C_{Ab} =$	97.19	Dec
Combined			
Hue	$H_A =$	93.07	
Lightness	$L_A =$	98.69	
Chroma	$C_A =$	95.98	
Overall Index $A =$		95.91	

The mean hue index H_A is given by:

$$H_A = 100 - \left(\frac{(100 - H_{AR})W_R + (100 - H_{AY})W_Y + (100 - H_{AG})W_G + (100 - H_{AB})W_B}{W_R + W_Y + W_G + W_B} \right)$$

where H_{AR} , H_{AY} , H_{AG} , H_{AB} , are the red, yellow, green and blue indices, W_R , W_Y , W_G , W_B , are the numbers of samples contributing to each index respectively. In the example $W_R = 12$, $W_Y = 9$, $W_G = 6$, $W_B = 9$. Similar equations are used to average the separate lightness and chroma indices.

The three mean indices are scaled by subtracting their values from 100.

The overall index, A , can be calculated from the mean hue, lightness, and chroma indices using the formula:

$$A = \frac{k_H H_A + k_C C_A + k_L L_A}{k_H + k_C + k_L}$$

where H_A is the mean hue index, L_A is the mean lightness index, C_A is the mean chroma index and k is a weighting constant.

The final overall results are shown in Table 6.

This completes the calculation of the primary indices. The results would be interpreted by saying that, on average, red colours are rendered 8 units yellow, yellow colours 6 units green, green colours 4 units yellow, and blue colours 8 units red. The test illuminant renders colours with on average a 3% lower chroma as compared with the reference illuminant, and with little difference in lightness. The overall index is 96.0 with k_H , k_C and k_L all set equal to unity. The CIE General Colour Rendering Index for this lamp is 64 but no comparison can be made between these two numbers because the CRI is scaled such that a warm white fluorescent lamp would have a value of 50. If a similar scaling were to be applied to the appearance-based index then it would have a value lower than 96.

6. DISCUSSION

This report outlines a procedure which provides a measure of the colour differences between the samples in a set of test colours viewed first in a reference and then in a test situation. It uses measures relating directly to the appearances of the colours as seen using the specified illuminants for both situations.

This represents an advance on traditional colorimetry, which is unable to give numbers relating to the absolute appearance of colours.

The several indices calculated should be useful to different people. The lamp technologist should find the separate colour indices, with their associated direction vector, of use in specifying, for example the differences between two lamps which differ only in phosphor recipe.

The combined indices should give someone interested in comparing different lighting systems an overall view of the general differences; the separate indices will, of course, give more information.

There is no reason why a separate index should not be defined for any specific test colour sample, e.g. the patch in the GretagMacbeth ColorChecker Chart that is metameric to Caucasian skin, Table 7.

Table 7. The special rendering indices for the 18 test colours.

1	Negroid	95.41	10	Purple	96.35
2	Caucasian	96.39	11	Lime	96.99
3	Sky blue	92.97	12	Light orange	89.00
4	Green grass	98.68	13	Blue	93.60
5	Flower	97.59	14	Green	92.96
6	Light cyan	90.68	15	Red	83.82
7	Orange	87.86	16	Yellow	92.36
8	Blue	94.46	17	Magenta	90.61
9	Moderate red	90.09	18	Cyan	86.90

This would be especially useful in comparing the colour appearance under light sources with very different correlated colour temperatures.

There is some sense in always using the same reference lamp when calculating the indices. This would enable the indices to be quoted without stating what the reference conditions were; they would be implied.

The validation of the indices can only come by comparing visual observations, especially those made with modern lamps that were not available when the original colour-rendering index was formulated, with calculated values and some such work is mentioned above. Figure 6 shows the values of colour appearance based rendering index plotted as a function of the corresponding CIE Colour Rendering Index for a series of 13 lamps which all have a correlated colour temperature of approximately 4000 K. The correlation coefficient of the least squares trend line is 0.94.

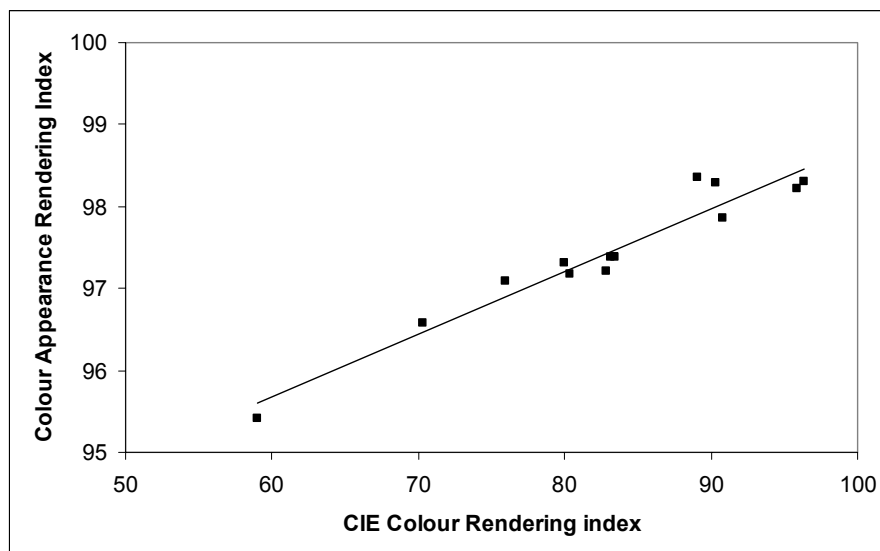


Figure 6. The values of colour appearance based rendering index plotted as a function of the corresponding CIE Colour Rendering Index for a series of 13 lamps which all have a correlated colour temperature of approximately 4000 K, together with a least squares trend line.

The colour-rendering situation can be considered analogous to that found in colour reproduction. Both can involve comparing test charts in specified lighting conditions. The difference however, is that in the rendering situation it is comparison of the light sources that is important while in the reproduction application it is the test charts that would be assessed in the same lighting environment. These charts might represent an original and a reproduction of that original, or perhaps a comparison between two reproductions made using different products of systems. The concept of colour reproduction indices, based on the same principles as the colour rendering indices described above, has been thoroughly tested and found to be of value. Experiments derived to compare the perceptibility and acceptability of differences between two test targets have given results that correlate with indices calculated using the colorimetric data from the respective colour charts^{38, 39, 40, 41, 42, 43, 44}.

7. FURTHER WORK

It has already been mentioned that the distribution of test colours in terms of the number containing red, yellow, green, and blue respectively, is not very uniform in the GretagMacbeth ColorChecker Chart. It is possible that a better chart, or series of charts, could be devised, indeed GretagMacbeth have available at least two other charts containing 237 and 140 coloured samples respectively⁴⁵. Another possibility is to use a series of charts containing samples all with the same nominal hue but differing in chroma and lightness. A second series of charts might contain samples with a constant chroma but varying in hue and lightness. These two series of charts would enable a more rigorous investigation of the colour appearance of a test and reference situation than that offered by the ColorChecker and could easily be constructed from pages of the Munsell Book of Color⁴⁵. This idea has been developed by van Kemenade and van der Burgt^{46, 47} who used a set of 215 test colours to extend the principles of the CIE Colour Rendering Index. Colour rendering vectors for a test source are calculated in CIELAB colour space with respect to a reference source and can be represented as a series of arrows projected on to an a^* , b^* plane. As might be expected, an increase in the size of the average value of the colour rendering vectors correlates with a decrease in the corresponding value of the Colour Rendering Index. Plots of the difference in hue angle, $h_{\text{test}} - h_{\text{reference}}$, and the difference in chroma divided by the value of the chroma, $(C^*_{\text{test}} - C^*_{\text{reference}})/C^*_{\text{reference}}$, both as a function of the hue angle of the reference, further aid an understanding of the colour rendering capabilities of the test lamp.

Another area needing further investigation is the perception of differences in colour appearance terms. There have been some experiments to investigate differences in terms of chromaticity and luminance factor, but these tended to use colorimeters with coloured lights. The results of these experiments may not apply to real surface colours. A knowledge of the size of just-perceptible appearance differences would enable realistic tolerances to be applied to the appearance indices, e.g.: Is 90.2 perceived as being different from 90.3 or are the perceptible differences between values of 90 and 91?

The use of a single number, and index, or a set of indices might not be the best method, and is certainly not the only method, of assessing the rendering capabilities of a light source. In 1967, Pracejus⁴⁸ suggested that the gamut area, the area in the chromaticity diagram enclosed by the points representing the eight CIE test colours, was a possible measure of the acceptability of the colour-rendering properties of a lamp. Thornton⁴⁹ proposed that this concept of gamut area was a function of the discriminating power of a lamp. This idea found some favour but, while it is true that a lamp cannot have good colour rendering without there being good discrimination between colours, the converse is not true and good discrimination

does not necessarily mean good colour rendering. The relationship between rendering and discrimination was investigated by Boyce⁵⁰, and Boyce and Simons⁵¹.

Another aspect of colour rendering is the concept of colour preference. Sanders⁵² devised a method of assessing the colour rendering properties of a light source by determining the shift in chromaticity of a natural object from its preferred colour. Judd⁵³ devised a flattery index based on the preferred colour of the reference colour rather than the calculated chromaticity. Another concept that has found some favour is that of visual clarity, work based on the observation that an interior lit with a 'good' colour rendering lamp appeared brighter than measurements indicated^{54, 55}.

More recent studies include those by Embrechts⁵⁶ who describes a so-called parametric approach based on the lamp spectral power distribution. Three parameters are calculated, the proportion of 'blue, green and red radiation with respect to yellow'. Schanda⁵⁷ describes a combined preference and rendering index for complexion colours. Seim⁵⁸ investigated improvements to the present CIE method by changing the coloured samples, the chromatic adaptation formula, the colour space and the associated colour difference formula. van Trigt⁵⁹ discusses the philosophy behind the concept of colour rendering, as does Worthey⁶⁰, who goes on to suggest a new method for calculating the colour rendering based on the premise that 'lights vary in their ability to render object spectral reflectances into colour contrasts.' Worthey⁶¹ derives a 3×3 'rendering' matrix the middle element of which, element (2, 2), quantifies the loss or gain in redness-greenness which he claims is a major contributor to the rendering ability of the lamp.

Many of these various indices require colorimetric data for their input and it is possible that, if they were reformulated in terms of colour appearance variables, rather than traditional CIE colorimetric correlates of appearance, then better correlation might be found with experimental data.

Thus, the science of colour rendering is still alive and active. The concept of assessing the ability of a lamp to render the colour of samples 'correctly' still, arguably, forms the basis of the new methods proposed and, while the experiments and discussion continue, the CIE recommendation remains as the method preferred by the lamp manufacturers.

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9. APPENDIX: FORMAL DEFINITIONS OF COLOUR APPEARANCE VARIABLES

The definitions of the absolute subjective attributes that describe the appearance of a colour are:

Brightness

Attribute of a visual perception according to which an area appears to emit, or reflect, more or less light.

Colourfulness

Attribute of a visual perception according to which the perceived colour of an area appears to be more or less chromatic.

The appearance of all colours can be described in terms of hue (see below), brightness and colourfulness. The recognition of coloured objects often depends however, not so much on the absolute attributes but on relative values.

The definitions of the relative attributes are:

Hue

Attribute of a visual perception according to which an area appears to be similar to one of the colours, red, yellow, green, and blue, or to a combination of adjacent pairs of these colours considered in a closed ring.

Lightness

The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Chroma

Colourfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

The term saturation also describes an important aspect of colour appearance, although it is not used in the derivation of the appearance indices:

Saturation

The colourfulness of an area judged in proportion to its brightness.

The difference between chroma and saturation can be illustrated by considering a series of colours of constant chromaticity but decreasing lightness, viewed under constant conditions. The saturation of such a series is constant because their colourfulness is judged in proportion to their reduced lightness. Their chroma however, decreases because of the reduced colourfulness judged in proportion to the constant average brightness of the surroundings.

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