

Quality of the light sources and colour constancy

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Different strategies are suggested to update the Colour Rendering Index (CRI). Two experiments have been conducted to analyse the effect of different lights on the appearance of colours, with the assumption that the extent of relevant colour differences depends on the different hues. The first experiment starts from the concept of unique hues and analyses the constancy or variations of unique hues under different real light sources. The second experiment deals with colour difference and allows to evaluate local distortions of the colour space. Analysed sources include incandescent lamp, a simple realisation of D65 and three white LEDs. The samples used in the experiments are three dimensional to reproduce more realistic viewing conditions. The results show that the methods used in this research are effective in highlighting the colour variations induced by the different light sources without the need of direct comparisons by the same observer, and avoid the bias due to memory processes typical of other methodologies. They could be the basis for the improvement of the CRI.

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Introduction

The Colour Rendering Index (CRI) [1] is the parameter commonly used to quantify the ability of a light source when colour appearance is considered. Even if it is currently used to characterise lamps and it is suggested to define the effect of a light in defining the perception of colours, there was an open debate on its efficacy, in particular when the new LED sources are considered [2-6]. CIE itself suggests the development of new colorimetric indices to be put beside CRI [7]. To confirm its ability in characterising light sources, it should be supported by visual experiments.

In order to reach a better description of the colour rendering properties of a light, two approaches can be followed: improving the CRI starting from its definition and developing visual experiments as bases of novel colorimetric indices.

The use of the $W^*U^*V^*$ colour space, non uniform with respect to the visual perception, the small number of the colour samples and their medium-saturation, the use of an average value as the only one parameter to describe the appearance variations of many colour samples in different directions, the comparison of the colour rendering with a reference source at the same colour temperature are critical aspects of CRI.

More uniform colour spaces, either like CIELAB or CIECAM02, should allow a better evaluation of the colour differences; most of the researchers agree with this choice. This way, an improvement of CRI definition is presented by Davis and Ohno [8]; furthermore, in the same work, more than fourteen CIE samples are used, which show higher saturation. To highlight large variations of colour appearance under different light sources, a root mean square value is used, in the place of the simple average of CRI. Furthermore, CRI imposes penalty on every non zero variation, this new approach suggests to admit any increase of the chroma, which is looked for in some applications.

According to some research groups a modification of CRI is not enough, in fact, they highlighted by visual experiments the difficulty of CRI in describing the effect of different lights on the colour quality. To overcome these problems they propose different new indices. Undertaken experiments can be subdivided in two main categories: the first is based on the reproduction of the light and the colours on a monitor [8], others use visual chambers to compare the effect of different lights on samples with different spectral reflection coefficients [9-11].

To overcome the problem of the choice of the reference illuminant, the reference could be found in the chromaticity of an ideal object: the judge on the appearance of the object is done against the idea the observer has of the object itself in his/her memory [12,13]. Nine “familiar” objects are considered; they are characterised by a reflection coefficient corresponding to not particularly high saturated colours. Real objects were presented to observers, lit by one hundred different light sources, in front of a self luminous back panel at 5600 K, used for the chromatic adaptation. From these observations weighting functions are deduced to evaluate the colour appearance under an arbitrary light source, the source under test, only on the base of its spectral emission, which could be instrumentally measured. The authors themselves highlight the problem of the possible dependence of the preference and memory colour from the culture, leaving the question open. Furthermore an implicit mention to a reference illuminant is done when the white of the back panel is selected.

Leaving the idea on which is based CRI, the evaluation of the difference of the colour of one sample under the tested source and under the reference source, and starting from visual experiments, the Harmony Rendering Index [11] considers the distances between every pairs of very chromatic samples under each light source and then takes into account their variations.

A way to define a colour rendering index takes advantage of the categorical naming of colours. In the study by Yaguchi *et al.* [9] the evaluation of the light quality considers the eleven categories defined by Berlin and Kay [14] and observes the categorical changes of 292 samples under different sources. This innovative method can be easily implemented by instrumental measurements, but it could be affected by different observers’ ideas of colours during visual tests. This difficulty is present also in the tuning of colorimetric index unless the category number is reduced, but this last choice decreases the resolution of the method.

The colour discrimination of desaturated samples could be difficult under some sources; this property is used to set another visual experiment and its related index [10]. This method requires observers to put in order the proposed samples under the tested source; the length of the path from

the first to the last sample depends on the colour distortion introduced by the tested source, with respect to the reference one.

Following the suggestion of the technical report CIE 177 2007 and the experience of expert research groups, also the Photometric Laboratory in Padova decided to approach the issue of quantifying the colour rendering basing its activity on visual experiments. It was chosen to set up a new vision chamber to test CRI and the new proposed indexes under different kind of light sources by observing directly the effect of the light on physical sample. In comparison with colour reproductions on a monitor there is the limit that only real and existing light sources can be tested, but it should have the advantage of taking account of many side effects, automatically, reducing the risk of the neglect or a bad approximation of important phenomena connected to the colour vision.

Rationality of the experiment

This research directly deals with the colour rendering property of the light sources, and only secondly with the subjective aspect of colour harmony. The main goal is to see what kind of colour shift objects show when observed under different illuminations. The problem is whether all colours undergo a common change, all becoming more or less light, warm, chromatic at the same extent, or the variations are different for different colours. Colour fidelity can be broken at different levels: by irrelevant vs relevant changes first, and if the latter case occurs, changes can be coordinated and follow some rule or on the contrary are disordered. Colour harmony, in the sense of specific relationships among colours, is preserved if the relationships among colours remain almost unaltered when some or most colours change. Therefore it is important to study how colours and their relationships, difference and similarity well above threshold, vary in different parts of the colour space. As consequence the colorimetric colour space changes its mapping to the subjective perceptual colour space as a function of different light sources. If mutual colour relations are kept unchanged, colour harmony is also preserved. There are a few ways of testing whether the whole colorimetric colour space change its relationships with the subjective structure of colours, and one of these consists in determining the personal unique hues [15] under the different illuminations. Unique hues are most likely the same for all humans (at least normal colour observers) in the sense that all people can state which sample appears to them neither greenish nor reddish, if a suitable number of different yellows exemplars are presented (and they can do the same for a red appearing neither yellowish nor bluish, and so on for blue and green, and for white and black as well). This means that these colours only appear similar to themselves, and for this reason are called unique, while all the other colours appear similar to two different (and adjacent) hues (and/or to white and black) and are called binary hues. Unfortunately since the first time Hering proposed his observations the existence of the unique hues was considered a theoretical problem, only solvable by a reference to physiological mechanisms. Hering himself supported this interpretation by proposing a famous hypothesis which saw in some metabolic mechanisms of the retina the neurophysiological processes underlying colour opponency, strictly, but not substantially, related to the concept of unique hues. Opponency adds to uniqueness the fact that binary colours are similar only to two adjacent unique hues in the colour wheel, and not to others (white and black are excluded, as they do not show opponency in the sense that both can be perceived at the same time in one colour, a grey for instance). His theory seemed confirmed when opponent cells were discovered in the retina [16] and in other parts of the visual pathway [17-19] but very few people realised that the physiological mechanism, verified or not, was not the core of

Hering's observations, as on the contrary was his phenomenological description which remains undisputable independently of the physiological discoveries.

Nowadays researchers [20] think that the characteristics of physiological mechanisms do not correspond to the phenomenological properties of unique and opponent hues, and no physiological structure seems to be isomorphic with the phenomenological appearance. The resulting conclusions are critical as different answers can be given to the problem whether unique hues are relevant colour characteristics or not, depending on the criteria used: if appearance is relevant, then the phenomenological criterion is valid and the unique hues are basic characteristics of human colour vision. On the contrary, if physiology is more important, then the concept of unique and opponent hues should be left apart. The common experience show that all people understand the meaning of unique hues (neither ... nor ...) and can perform the task of choosing which are their subjective unique hues, and this skill is used in colour constancy studies [21].

The choice of the unique hues in this kind of research is particularly efficient as there is no need of comparisons with external standards, as unique hues are in-built in our mind, similarly with the memory colour approach. Furthermore, the problems related to the use of memory and artificial objects, which are partially required also in the memory colour method (e.g. the blue of a smurf®), are here avoided completely, both in the sense of short- and long-term memory of colours and colour memory [15,22]. One common problem in memory colours of familiar objects is that often they are not unambiguous (there is a rather large variety of apple colours, and also many green apple colours). Personal experience is the foundation of memory colours [23], and for this reason a universal use of it is not satisfactory.

Furthermore, the applied method allows the possibility of analysing a wider portion of the colour space, also far from the low saturation portion of the colour space usually considered in many methods, and at different values of lightness.

In the definition of CRI and when using the memory colour approach and other methods, absolute variations of the appearance of the objects are considered in the evaluation of the colour quality of the light under test, even if the chromatic adaptation is taken into account. On the contrary the concept of colour harmony is neglected, with the related significance of relative variations of all the samples together, and the importance of the possible space distortion introduced by the tested source. A second way here applied of studying how the subjective colour space might be modified by different light sources is to compare a pair of colour samples under two illuminations: if the perceived difference remains the same, no deformation is introduced by the different light. On the contrary, if under one light the perceived difference between the two colours appears larger than under the other light, the illumination change introduces a distortion in the colour space. The perceived difference between two colours can be consistently evaluated [24] in different ways: first by a direct estimate in a numerical (or categorical) scale [25], secondly by reproducing a colour difference (along an achromatic scale) between two grey samples which appear of the same difference as the comparison one. The lightness difference between the two greys can be measured in a uni-dimensional scale under all kinds of illuminations and therefore can be a measure of the multidimensional difference between two given colours samples. The choice of the colours in a pair can take into account different angular position in the hue circle, different lightness, different chroma, and therefore distortions in different parts of the colours solid can be tested. If all differences remain constant under two illuminations, one can conclude that the mutual relationships between colours remain the same although uniformly shifted in the colour space, and therefore colour harmony should not change. On the other side, differences in specific places of the colour solid can appear larger than in other parts, and therefore the overall structure of the colour space is distorted and colour harmony can be affected.

The evaluation of the light quality can be made in ecological viewing conditions if real 3D objects are freely observed without time limits. If the complexity of environment is reduced for experimental reasons, one essential condition for a correct perception of surface colours is the presence of a white background. The anchoring theory of lightness perception, although developed to model the perception of the grey scale [26], is well consolidated and stresses the role of the white background considered as an anchor for all other surface colours. In the case of achromatic colours the lightness of a surface is determined by the highest luminance present in the visual field, independently of its reflectance, with some further specifications. One of this is relative to the size of the surface showing the highest luminance: the larger its size, the whiter it appears, and the background is generally perceived as a quite large surface.

Moreover the whole visual field can be segmented in different frames as a function of the different illumination levels, and the local backgrounds are integrated in a general model [27]. The model includes the different roles of increments and decrements as respect to the background, which induce different effects in the perception of surface colours (see for instance many lightness illusions like the traditional contrast and the White illusion [28,29]). For this reason the use of a grey background (as often advised) is not suitable for perceiving a correct grey scale, and therefore the background should generally be lighter than all other surface colours. Dark backgrounds favour the fluoresce appearance of colours [30], and also for this reason should be avoided in the general procedures of the colour rendering evaluation.

Set-up of the visual experiment

Among the approaches based on visual chambers, it was decided that the use of only one chamber should allow to obtain results not affected by the different adaptation of the observer in looking at the two chamber containing the source under test and the reference source, and by the imperfect adaptation due to the continuous change of observed object.

A viewing booth was set up to accommodate the sources under test, its internal dimensions are about 50 cm (length) × 70 cm (width) × 50 cm (height). The walls, the top and the bottom of the chamber are all covered by white paint, with a spectral reflection coefficient of about 90% for wavelength longer than 450 nm. It allows a good uniformity of the illuminance all over the internal surfaces of the chamber (95% on the bottom plane), furthermore a white background is a reference for the adaptation of the observer.

The sources under test

At present the chamber is set up to allows the analysis of different light sources, in this work are shown results for five of them: illuminant A (realised by tungsten halogen lamps powered to bring the correlated colour temperature of 2856 K), D65 (realised by a tungsten halogen lamp filtered to obtain a CCT of about 6500K), and three white LED with CCT of about 6500 K, 4000 K and 2700 K.

Figures 1 and 2 show their spectral power distribution measured using a Minolta CS-1000 spectroradiometer and a certified white sample. Each spectrum is normalised to obtain the same luminance (Y tristimulus value) on a white sample.

The tungsten halogen filtered called “D65” attempts to approximate the spectra of D65 defined by CIE. Actually, it is a simple exercise to obtain a light of about 6500K with a continuous spectra, instead of the fluorescent sources. As can be seen, the emission spectrum is out of line with illuminant CIE D65 for wavelength longer than 700 nm, however it causes a minimal contribution to the white

tristimulus values when the CIE 1931 standard observer colour matching functions are considered. Table 1 shows declared, measured and calculated colorimetric characteristics of the light sources used in the experiments. It is shown also the standard deviations of the special colour rendering indices (R_i), they highlight the differences which are averaged in the general colour rendering index (R_a) calculated using the CIE test method [31].

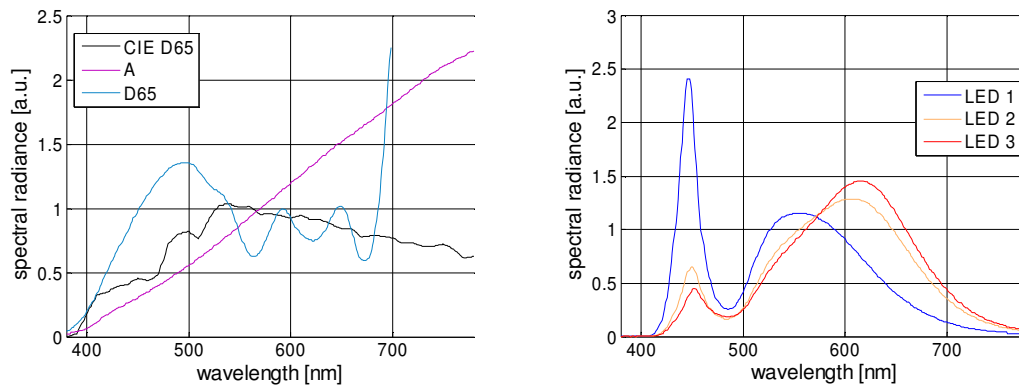


Figure 1 (left): Spectral power distribution of the realised Illuminant A and Illuminant D65.

Figure 2 (right): Spectral power distribution of the three LED considered in the experiments.

Source	CCT declared (K)	Ra declared	CCT meas. (K)	8 CIE samples		14 CIE samples	
				Ra	SD	Ra	SD
D65	6500	-	6569	79	13.0	74	18
A	2856	100	2856	99	0.2	99	0.5
LED 1	6350-7000	75	6831	73	12.0	67	28
LED 2	4000-4300	75	4096	83	4.1	75	18
LED 3	2600-2700	80	2625	82	7.0	75	20

Table 1: Declared, measured and calculated colorimetric characteristics of the light sources used in the experiments.

The procedure

The visual experiments aim at determining the variation of the perception of colours under different light sources. The experiments want to analyse both global and local effects introduced in the colour space by different light: the global changes could be highlighted by the recognition of unique hues, while smaller variation in the three directions of lightness, hue and chroma are studied by quantifying differences between pairs of colour samples evenly distributed in the colour space.

Six observers participated to the experiments, three of them only partially and one performed twice the task. Variations in the colour perception, under the different light sources, are evaluated within the results of each observer, separately. After a normalisation which account for the instrumentally measured differences, the contribution of every observer can be combined to estimate a more significant result. This procedure supposes the repeatability of each observer, but is not affected by different sensitivity of the subjects to colour differences.

Unique hues

The visual experiment asks the observer to identify the unique hue, for red, yellow, green and blue, among eleven proposed colour samples. Results should show how unique hues surfaces are affected by the light of the different tested sources.

For red hue, the observer has to search for a colour that is neither bluish nor yellowish, for the yellow hue, a colour neither reddish nor greenish, for green hue, a colour neither yellowish nor bluish, for the blue hue, a colour neither greenish nor reddish. The choice of the observer can be represented by one of the 11 presented 3D colour samples or by a colour in the middle of two of the presented samples: this improves the hue resolution without increasing the number of samples and a consequent reduction of their total number /amount. The position of the samples within the presented sequence is made random by shifting the beginning and the end of the sequence of one or two steps, so as to reduce a possible bias in the observer choice. Results derived from this task should confirm our expectation that light sources generally induce colour shifts of different extent as a function of the different unique hues, similarly to what happens with the memory colour procedures [12] which show different distributions of colour differences as a function of the familiar objects considered.

Colour differences

In the second experiment, observers have to choose a grey patch from a grey scale so that its perceptual difference from a fixed grey patch equals the perceptual difference between two chromatic 3D samples observed under different illuminations.

Pairs of colours oriented along the three main directions (lightness, hue, chroma) and regularly distributed in the CIECAM02 colour space are studied. A representation of these displacements is sketched in Figure 3.

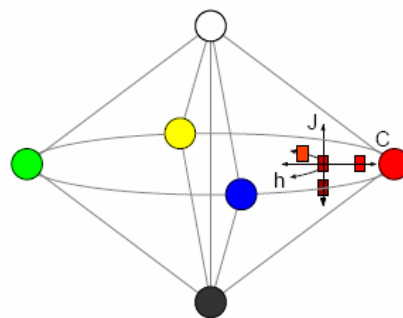


Figure 3: Sketch of the impressed displacements in the NCS colour space, for each colour in a pair.

Results should show whether and how much chromatic relationships between colours in different part of the CIECAM02 colour space vary as a function of the selected light source.

The colour and the grey pairs are placed in fixed position within the visual chamber. We realised that the relative position of the two samples of a pair affects the perception of the difference, therefore a fixed distance (1.5 cm, 0.86 deg) between the samples in a pair was defined; furthermore a large enough distance (10 cm, 5.7 deg) between the pairs (chromatic and achromatic) is required and fixed to obtain repeatable observations.

The colour and reference samples

All the coloured and the grey samples are 3D, patch of printed semi-glossy paper are fixed to cylinders with a diameter of 30 mm and a high of 50 mm. The samples are presented bent backwards

with respect to the horizontal plane, this choice allows to reduce desaturating reflections from the white ground floor.

Unique hues

Three series of samples are used for the choice of the unique hues. One of them presents a high chroma and medium lightness; the other two 'darker' and 'lighter' series are characterised by a reduced chroma and increased blackness and whiteness, respectively.

The chromatic series for the red unique hue choice is presented in Figure 4, as an example. The distributions in the CIECAM02 colour space of the series used for the unique colour choice are presented in Figure 5. For the more chromatic samples, an interruption of the series occurs in the purple region, as samples in this zone are not useful for the unique hues investigation.

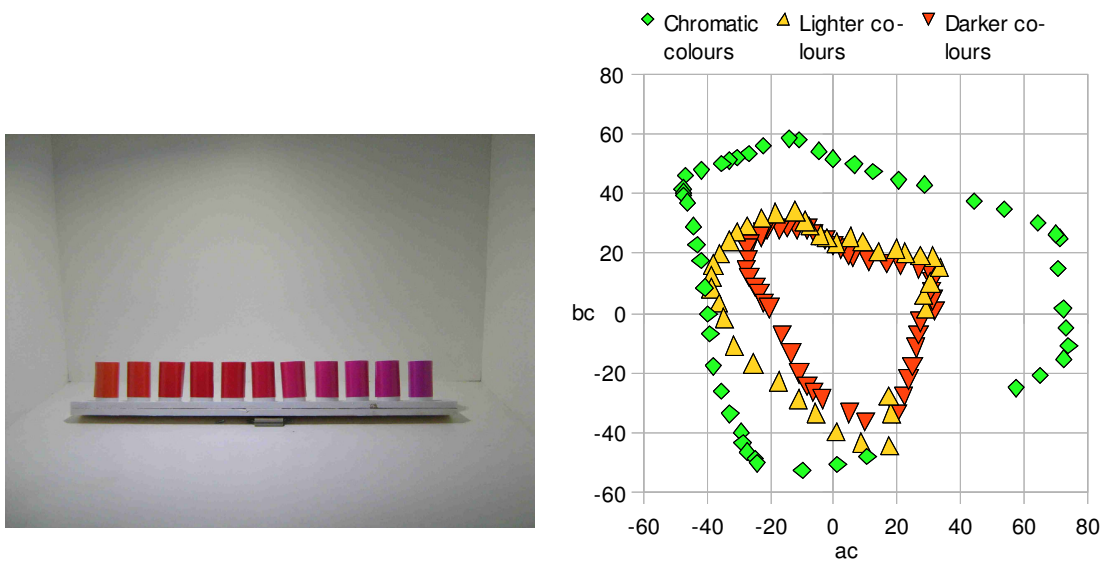


Figure 4 (left): The chromatic series for the choice of the red unique colour.

Figure 5 (right): Distributions in the CIECAM02 colour space of the series used for the unique colour choice. The chromatic coordinates are computed under the illuminant CIE D65. Greens squares: chromatic series; orange triangle: light series; red triangles: dark series.

Colour differences

As for unique hue analysis, also for the study of the colour differences chromatic, darker and lighter series are considered. Within each series, variations along the three direction in the colour space are considered; a number of fifteen chromatic, lighter and darker pairs was analysed by each observer. The positions of the three series (chromatic, lighter and darker) of the more chromatic pairs in the CIECAM02 colour space are presented in Figure 6. The pairs are placed in the red, yellow, green, blue and purple regions to complete the colour wheel.

Relatively small colour differences are presented in the second experiment (a rather large difference for the light pairs, between 11 and 13.6 CIECAM02-UCS $\Delta E'$; between 4.5 and 8.2 $\Delta E'$ for the light pairs; between 5.6 and 7 $\Delta E'$ for the dark pairs): this allows an easier and probably more reliable use of the grey scale to quantify the difference in the pair than in the case of the analysis of larger distances in the colour space: the risk of possible error in the association should be reduced.

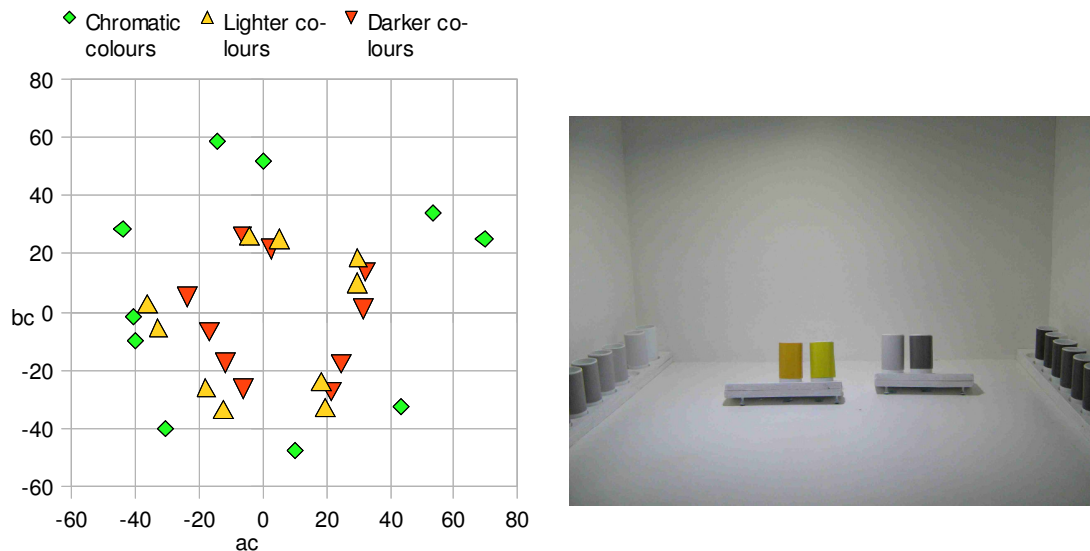


Figure 6 (left): Positions of the three series of the colour pairs in the CIECAM02 colour space. Symbols as in Figure 5.

Figure 7 (right): The yellow pair of the more chromatic series and a possible choice of the correspondent grey pair.

Figure 7 shows the samples of a pair from the more chromatic series in which the hue difference clearly appears. Aside it is placed a possible choice of the grey pair used to quantify the colour difference. On the right and on the left of the chamber all the samples of the grey scale are present to the observer.

Experimental results

Unique hues

The unique hues chosen by the observers under the different sources are represented in the following figures. An analysis of Figure 8, in which the choice of unique hues for the chromatic samples is represented, helps to understand the others.

The red square at right, in a D65 CIECAM02 diagram, presents the sample that under our source D65 appears as unique red, while the yellow square shows its coordinates in its LED1 [CCT 6830K] CIECAM02. As one can see, the same sample keeps the same hue angle under both the light sources, and one can expect that it should be chosen as a unique red also under the source LED1, as it actually occurs. The red triangle (hidden under the yellow square at right) shows the sample chosen as unique red under the LED1 source, and its representation in a D65 diagram (yellow triangle, hidden behind the red square) corresponds to the red square. This result seems to show a very good colour constancy, as the same sample appears as a unique red under both sources; moreover the sample under the LED1 source is also a little more chromatic, due to the non perfect circularity of the hue sequence.

In the case of the unique yellow two statistically different samples have been chosen, represented by the red square and the yellow triangle at the top of the D65 Diagram. The sample corresponding to the square has been chosen under the D65 source (red square at the top of the figure, yellow if its coordinates are computed according to the LED1 spectral distribution), while the sample corresponding to the triangle has been chosen under the LED1 source (red triangle in a D65 diagram,

yellow if its coordinates are computed according to the LED1 spectral distribution). The results show that colour constancy does not occur, as the same sample does not appear as unique yellow under both sources. Anyway the difference between the two samples is very small in terms of hue angle (they are not significantly different) while both appear a little less chromatic under the LED1 source.

Also in the case of the unique green two different samples have been chosen, although statistically their choice does not significantly differ, represented in a D65 diagram by the red square and the yellow triangle at left. The colour corresponding to the triangle has been chosen as a unique green under the LED1 source (red triangle if its coordinates are computed according to the LED1 spectral distribution). The choice of two different samples as unique green has in this case kept the same hue angle, (although their difference is of about 12° , they do not significantly differ), with a negligible variation in chroma. The observers' choice of the unique hue is quite constant, as they keep the same hue angle in the two illuminations for their subjective unique green. In different words, the subjective unique green has the same hue angle in both the D65 and LED1 diagrams. For the unique blue a similar result as for the yellow is obtained, with the difference that not only the samples but also the hue angles are statistically different under the two illuminations.

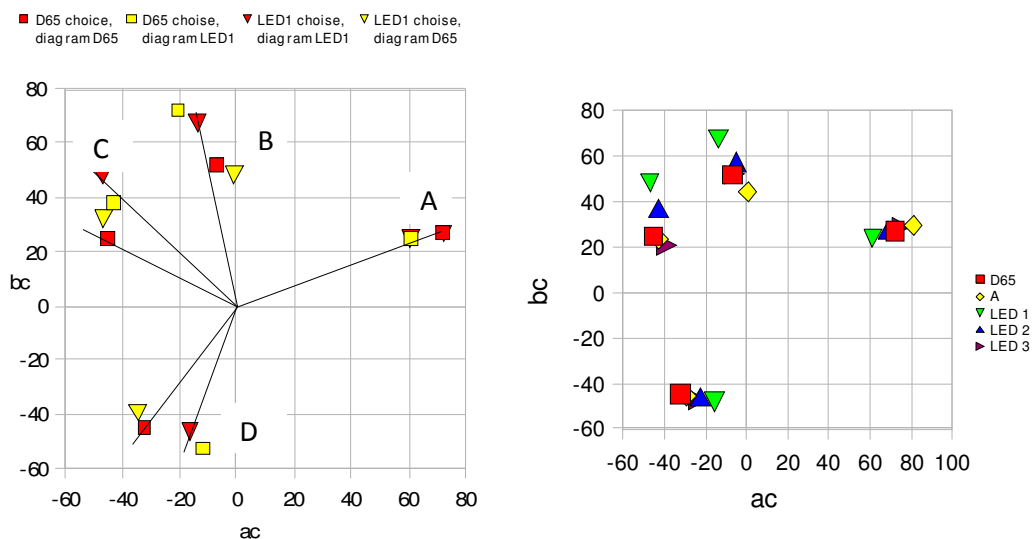


Figure 8 (left): The unique hues of chromatic samples chosen under the D65 and LED1 at 6500 K sources. A B C D: different kinds of constancy.

Figure 9 (right): The unique hues of chromatic samples chosen under all the used sources.

Figure 9 shows the unique hues chosen for all the chromatic colours, and Figure 10 for all colours (chromatic, light, dark), under all the used sources. The coordinates, on the ac, bc plane of the CIECAM02 colour spaces corresponding to our experiment, have been computed on the basis of the source spectra under which the unique hues have been chosen. The hue angle is notably constant for the unique red and the unique yellow, is quite variable for the unique green, and is not linear for the unique blue. The general results show that a given set of colour samples does not appear the same under different light sources because they are not constantly mapped in the subjective colour space based on the unique hues. The changes in the colour appearance introduced by different light sources can be suitably described by analysing how the choice of unique hues is modified. For instance green samples corresponding to the area included by the hatched lines in Figure 10 can show either a yellowish or bluish appearance according to the light source under which they are observed. The

rather large area means that relevant differences are spread along a rather large hue angle. This result does not hold for the red and yellow hues, as in those cases relevant hue differences occupy a much smaller angle. Therefore it seems that our results are similar to those found by Evans [30], according to which apple colours, under different illuminations, occupy a larger area in the IPT space than the lavender or the caucasian hand colours. In both cases the uniformity of the colour spaces is unable to express the relevant colour differences which are relevant in describing the colour variations following different illuminations. Traditional measures of colour difference therefore then do not seem suitable to model a Colour Rendering Index, which might on the contrary take into account variations in the unique hues as relevant characteristics of the light sources.

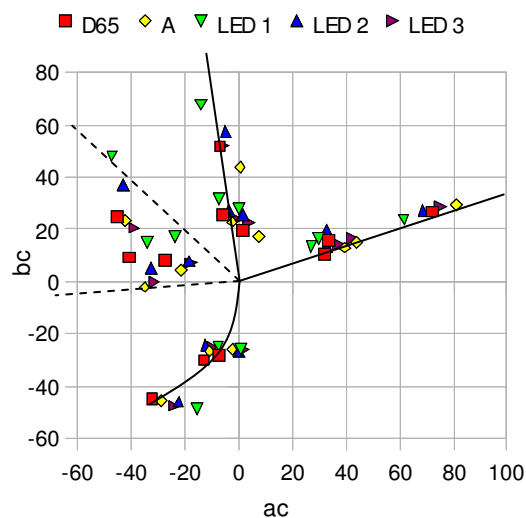


Figure 10: The unique hues of all samples chosen under all the used sources.

One main goal of the research was to find whether and how much a light source modifies (as respect to another source) the perception of coloured objects (colour stimuli). The unique hues have been considered as the anchors of the colour space, under the assumption that general colour deviations are well described by shifts of unique hues. In the whole experiment the chromatic red sample never changed its unique appearance, while the light and dark red samples changed very few times (2 and 1 respectively out of 10 comparisons). The other samples significantly changed their appearance about 11 times out of 30 each (10 pairs \times 3 kinds of colour, chromatic, light, dark).

The source under which the samples maintained their uniqueness is the LED2 - LED3 pair (the same samples were chosen as unique hues, that is $\Delta E'$ does not significantly differ from 0, under both illuminations), followed by the A - LED3 and the A - LED1 pairs (11 out of 12 samples remained unique hue – 4 hues \times 3 kinds of colour); then by the LED1 - LED2 pair (9 out of 12); under the other source pairs about 4 or 5 samples out of 12 changed their unique appearance.

A secondary problem is whether unique hues are represented in an ac, bc CIECAM02 diagram with the same angle when they are computed according to the source spectra under which they have been observed. This problem does not strictly belong to the quality evaluation of a light source but to the characteristics of the colour space, nevertheless is important when comparing the colours seen under different lights.

From the results it appear that the red chromatic, the blue light and the blue dark samples which have been chosen as unique hues are plotted always with the same hue angle under all the examined light sources (the hue angle of the chromatic unique blue deviates significantly under different

illuminations, see Figure 10). For the other red and blue samples which appear unique under the different sources, the angle deviations occur rather seldom (4 and 3 times out of 30 each – 10 pairs \times 3 kinds of colour: chromatic, light, dark). Hue angles deviate more for the yellow and green unique hues (5 and 8 times out of 30 each).

The sources under which the unique hues maintain their hue angle in an ac, bc CIECAM02 diagram are the A – LED1 (with 1 out of 12 exceptions - 4 hues \times 3 kinds of colours), the A - LED4 and the LED2 - LED3 pairs with 2 exception out of 12 each. The other source pairs show from 4 to 6 changes in the hue angle of the subjective unique hues, and the green hue angle is often one of them.

The other source pairs show from 4 to 6 changes in the hue angle of the subjective unique hues, and the green hue angle is often one of them.

Putting together the results relative to the colour samples (whether the same samples are chosen as unique hues under different illuminations) and the hue angle (whether unique hues are represented with the same hue angle in an ac, bc, CIECAM02 diagram) four combinations are possible when comparing the effects of two light sources as regard to unique hues: A) the same samples and the same hue angles (for instance Figure 8, the red unique hue); B) the same samples but different hue angle (Figure 8, the green unique hue); C) different samples but the same hue angle (Figure 8, the yellow unique hue); D) different samples and different hue angles (Figure 8, the blue unique hue). Conditions A and B imply good hue constancy, or in other words good colour rendering properties of the illuminations, while conditions C and D involve bad hue constancy, or a poor CRI. This categorisation ensues from a statistical analysis, hardly present in the traditional colour difference measurement, and might be a suitable procedure for modelling a new colour rendering index.

Colour differences

Figures 11 to 14 show some colour pairs evaluated in the experiment. The coordinates are computed under the relative light sources and plotted in D65 CIECAM02 diagrams.

In this experiment the task required to evaluate the perceptive difference between two coloured samples under different light sources. The result was in term of a pair of grey cylinders which appeared to the observer of the same difference as the comparison colour pair. The lightness of the greys and the colour difference of the comparison pair were computed relatively to the light source under which they were observed. The null hypothesis is that the visual evaluation of the colour difference has to be the same for the same pair under any two light sources, meaning that no distortion is introduced in the colour space passing from one to the other source. To normalise the lightness difference of the individual grey settings, it was divided by the CIECAM02-UCS $\Delta E'$ of the corresponding colour pair relative to the specific light source. Moreover the result was further subdivided in the three colour components (CIECAM02 $\Delta J'$, $\Delta C'$, $\Delta H'$) normalised for $\Delta E'$, to see in which direction the visual colour difference might differ from the expectations. All the subjective differences were compared to see whether the null hypothesis held for all colour pairs and all illuminations, or in which direction some colour difference would show deviations passing from one to another light source. The general finding is that the null hypothesis is verified in the great majority of the cases, and the subjective colour difference relative to a specific colour pair does not change passing from one to another illumination. This kind of colour constancy seem to guarantee that colour harmony, and in general all colour relationships, would be preserved when the same coloured objects are seen under different illuminations. Nevertheless a number of significant deviations from the null hypothesis have been found. The t-Test results were corrected according to the False Discovery Rate method [32] to avoid apparently significant differences as consequence of the great number of comparisons performed. In a first analysis the different kinds of colour pairs (chromatic, light, and

dark) were kept separate, and in a second step fused, while the 15 colour pairs (5 differing mainly in hue, 5 in lightness, and 5 in chroma) relative to the five main hue regions (red, yellow, green blue, and purple) of the colour space have been always kept separate, as the aim was to check whether possible deformations interested one instead the other part of the colour space. The first result is that the *dark* colour pairs almost always maintain their subjective *hue* difference except in 5 cases out of 150 comparisons, while the subjective difference of *light* colour pairs is significantly different under different light sources in 22 cases out of 150, and the *chromatic* colour pairs in 18 cases out of 150; moreover the subjective *chroma* difference of the dark colour pairs is not maintained in 3 cases out of 150, and in 28 cases out of 150 of the light colour pairs, and in 16 cases out of 150 of the chromatic colour pairs.

The colour pairs whose subjective *hue* difference deviates more are those red ones in which either lightness or chroma difference is enhanced (7 and 8 out of 30, respectively), as well as the purplish colour pairs of enhanced lightness difference (6 out of 30) and the yellowish pairs of enhanced chroma difference (9 out of 30). In the whole the subjective hue difference is not maintained in 23 out of 150 colour pairs with enhanced chroma difference, in 16 out of 150 colour pairs with enhanced lightness difference, and only in 6 out of 150 colour pairs with enhanced hue difference.

As regard to the subjective *chroma* difference, this is not maintained in 29 out of 150 colour pairs with enhanced hue difference (specifically, 12 out of 30 yellowish, 4 out of 30 reddish, and 4 out of 30 greenish, bluish, and purplish each), and in 17 out of 150 of colour pairs with enhanced lightness difference. Worth of noticing is that the colour pairs in which the enhanced difference is in chroma, the subjective chroma difference is always kept unchanged (with 1 exception – a yellowish pair - out of 150), although the absolute value of the found differences is quite high.

As regard to the illumination which induces a larger number of *hue* deviations, the A source determines 25 out of 180 deviations from the expectation (null hypothesis) when compared with all the other sources, the LED1 determines 24 out of 180 deviations when compared with all the other sources, and so the D65 also 24 deviations out of 180, the LED3 10 out of 180, the LED2 out of 180.

As regard to the illumination which induces a larger number of *chroma* deviations, the A source determines 30 out of 180 deviations from the expectation (null hypothesis) when compared with all the other sources, the LED1 determines 24 out of 180 deviations when compared with all the other sources, and so the D65 11 deviations out of 180, the LED3 13 out of 180, the LED2 16 out of 180.

Lastly the null hypothesis is valid for all subjective *lightness* differences which remain unchanged in all comparisons, with 4 exceptions out of 450 (2 chromatic bluish and 2 chromatic purplish pairs with enhanced hue difference). This result seems important as it shows that lightness is the most relevant feature which resists to colour changes induced by different light sources.

Conclusions

The two presented experiments and the related methods prove to be effective to highlight the variations on the appearance of colours induced by different light sources. In particular, the methods allow to identify general and local distortions in the colour space; furthermore, they enable the discrimination of the direction of the colour variation (lightness, chroma and hue), reckoned as useful specifications of a colour rendering index. Moreover this last aspect can be useful to recognise desired from unwanted deformation of the colour space.

The approach presented in the work shows very interesting potentialities in the description and the study of crucial aspects of the colour quality under different light sources, and can be a good basis for

developing a new CRI metric. It can ensure the best colour adaptation in the subjective evaluation procedure, as all colour comparisons, both the unique hue recognition and the colour difference evaluation, are performed inside the same illumination and without cultural bias. The suggested procedure is believed to lead to objective results which depend on universal perceptual structures: although there are well known inter-subjective differences in recognising the unique hues, the fundamental functioning similarity among persons allows a good normalisation. As consequence a CRI derived on the described starting point will more closely fit the general demand.

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