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Colour rendering of indoor lighting with CIE illuminants and white LEDs for normal and colour deficient observers

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Abstract

The goal of this work was to evaluate the colour rendering of indoor lighting with CIE illuminants and white LEDs by estimating the chromatic diversity produced for normal and colour deficient observers. Reflectance spectra of a collection of scenes made of objects typically found indoors were obtained with hyperspectral imaging. Chromatic diversity was computed for 55 CIE illuminants and five LED light sources by estimating the number of different colours perceived in the scenes analysed. A considerable variation in chromatic diversity was found across illuminants, with the best producing about 50% more colours than the worst. For normal observers, the best illuminant was CIE FL3.8 which produced about 8% more colours than CIE illuminant A and D_{65}; for colour deficient observers, the best illuminants varied with the type of deficiency. When the number of colours produced with a specific illuminant was compared against its colour rendering index (CRI) and gamut area index (GAI), weak correlations were obtained. Together, these results suggest that normal and colour deficient observers may benefit from a careful choice of the illuminant, and this choice may not necessarily be based only on the CRI or GAI.

Keywords: colour deficiencies, colour gamut, colour rendering, colour vision, illumination

Introduction

The visual perception of a scene is critically influenced by the spectral composition of the illumination (Davis and Ginthner, 1990; Fotios, 2001; Scuello *et al*., 2004a,b; Fotios and Gado, 2005; Pinto *et al*., 2008; Mahler *et al*., 2009) and, from a practical point of view, the evaluation of the visual effects of light sources is an important aspect of colour science (Schanda, 2007).

Chromatic effects of the light sources are quantified by colour rendering indices (for a review of indices see Guo and Houser (2004)). One aspect typically quantified is the effect of an illuminant on the colour appearance of objects by comparison with their colour under a reference illuminant. This property, quantified by the Colour Rendering Index (CRI)(CIE, 1995), has, however, a number of limitations (Xu, 1993; CIE, 1995; van Trigt, 1999) and other quality measures have been considered (Pointer, 1986; Xu, 1997; Davis and Ohno, 2005; Li, 2008). In particular, the gamut area index (GAI) (Rea and Freyssinier-Nova, 2008) which provides instead an estimation of the extension of the chromatic gamut produced by the specific light source and, indirectly, measures the resulting chromatic diversity; or the colour rendering index based on colour volume which estimates the volume of 684 reflectance spectra from the boundary of the gamut of the real surface colours under the test illuminant and a reference illuminant (Li, 2008).

One limitation of these indices is that they rely on the effects of the light sources on a small set of predefined standard colour samples, and the general effects on complex scenes and with LED lighting may be difficult to infer (Davis and Ohno, 2005; Vienot *et al*., 2008). Such a limitation can be overcome by considering entire scenes (Linhares *et al*., 2009) or the boundaries of the object-colour space (Perales *et al*., 2006;

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Martinez-Verdu *et al*., 2007; Li, 2008). Another limitation is that the indices are defined for colour normal observers and the effects on colour deficient observers are generally not considered.

In this work we assess the quality of 55 CIE illuminants and 5 LEDs by estimating the number of discernible colours they produce for normal and colour deficient observers for scenes composed of objects typically found indoors. This is a methodology akin to that applied by Xu (1993) who computed the colour volume of the theoretical limits defined by the optimal colours (MacAdam, 1935a,b) in L*u*v* colour space.

Methods

Figure 1 shows pictures of the scenes analysed. The three pictures represented on the right column are from publicly available hyperspectral image data (Brainard, 1997) and the other 12 scenes were digitized in our laboratory. Brainard's data were acquired from 400 to 700 nm in 10 nm steps using narrowband interference filters and a monochromatic CCD camera with a spatial resolution of 2000 × 2000 pixels and 12-bit output (Vora *et al*., 2001). Our images were acquired over the range 400–720 nm at 10 nm intervals using a fast-tunable liquid-crystal filter and a low-noise Peltier-cooled digital camera with a spatial resolution of 1344 × 1024 pixels and 12-bit output (for more details on the hyperspectral system see Foster *et al*., 2006).

The scenes contained objects typically found indoors, like books, coloured fabrics, toys, stationery items and fruits, among others. In Brainard's images the spectral reflectance of each pixel was obtained by dividing the raw data by the illuminant spectrum of the scene obtained at a given reference location. For the data obtained in our laboratory, illuminant and optical spatial non-uniformities were minimized by dividing the data obtained with a grey uniform reference imaged in the same place as the scene and under the same illuminant conditions (Pinto *et al*., 2008; Linhares *et al*., 2009). The spectral reflectance of each pixel of the scene was estimated from a gray reference surface present near the scene at the time of digitization.

The radiance spectrum reflected by each pixel of each scene was estimated by multiplying each spectrum of a set of 60 illuminants by the spectral reflectance estimated for that pixel. Illuminant spectra were considered from 400 to 720 nm for our data and from 400 to 700 nm for Brainard's data. Both sets of spectral reflectance data points were interpolated to 5 nm steps. The illuminants were tabulated CIE illuminants (CIE, 2004) and white LEDs. The CIE illuminants were: CIE illuminant A, C, 21 D illuminants including D55 and D65 (Correlated Colour Temperature (CCT) in the range 25,000 K to 3,600 K in steps of 1190.3 K), 27 FL illuminants (FL1, FL2, FL3, FL4, FL5, FL6, FL7, FL8, FL9, FL10, FL11*, FL12, FL3.1, FL3.2, FL3.3, FL3.4, FL3.5, FL3.6, FL3.7, FL3.8, FL3.9, FL3.10, FL3.11, FL3.12, FL3.13, FL3.14, and FL3.15) and 5 HP illuminants (HP1, HP2, HP3, HP4 and HP5). The white LEDs were: LXHL-BW02, LXHL-BW03, LXML-PWC1-0100, LXML-PWN1-0100 and LXML-PWW1-0060 (Luxeon; Philips Lumileds Lighting Company, San Jose, CA, USA). These LEDs were chosen because they are widely used and are commercialized by one of the main illumination companies. *Figure 2* represents their

Figure 1. Pictures of the scenes analysed. The three pictures represented in the right column are from publicly available hyperspectral image data (Brainard, 1997) and the other 12 scenes were digitized in our laboratory.

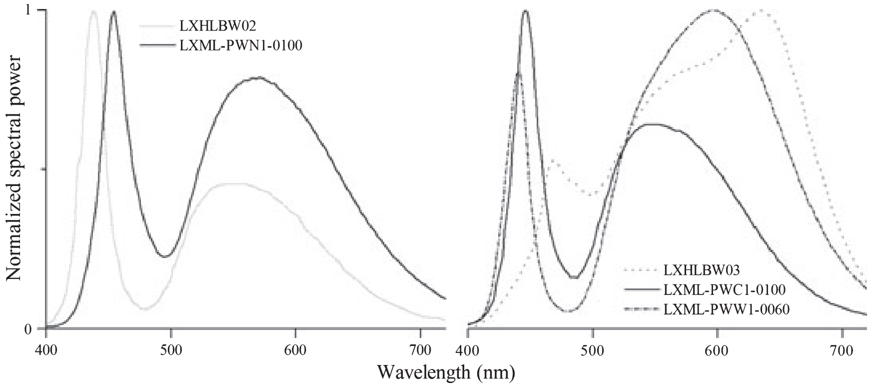


Figure 2. Normalized spectral power distribution of the five white LEDs used (Luxeo; Philips Lumileds Lighting Company, San Jose, CA, USA). Graphs prepared from data available from the manufacturer website (http://www.philipslumileds.com/pdfs/DS25.pdf and http://www.philipslumileds.com/pdfs/DS64.pdf).

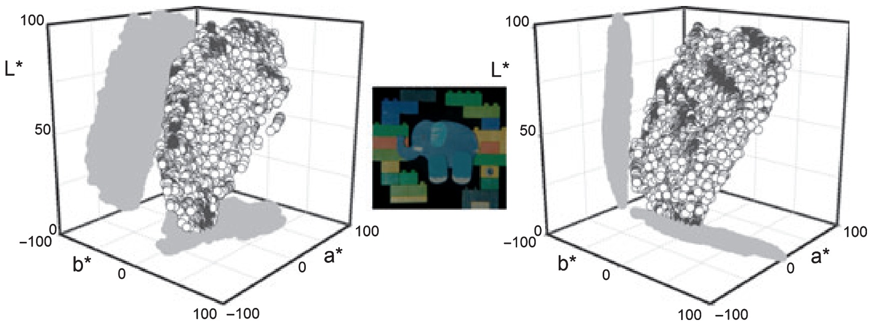
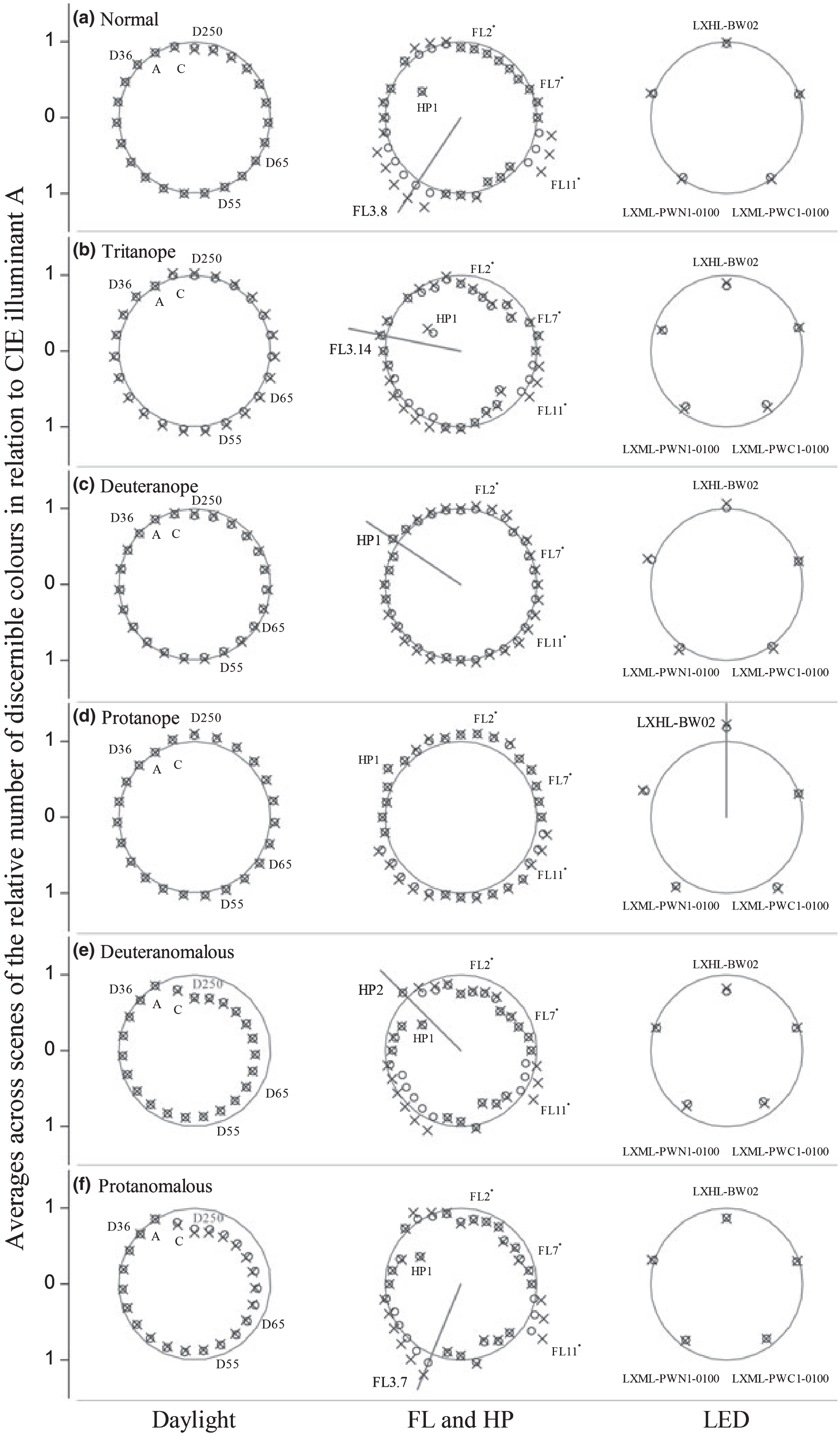


Figure 3. Illustration of the chromatic effects of the illuminant spectral distribution on the colours of a scene for a normal observer. On the left is represented the CIELAB colour volume produced by CIE FL3.8 and on the right the CIELAB colour volume produced by CIE HP1 for the scene shown.

normalized spectral power. The other illuminants were selected because they represent a wide range of chromaticities, CRI and CCT, including fluorescent and high pressure lamps (for tabulated data see CIE, 2004).

For normal trichromats, the CIELAB colour volume assumed rendered under each illuminant was computed for each scene using the CIE 1931 2° standard observer (CIE, 2004). The number of discernible colours in each case was estimated by segmenting the CIELAB colour volume into unitary cubes and by counting the number of non-empty unitary cubes. This simplified approach to compute the number of discernible colours encloses the assumptions that all the colours inside the same cube are not discernible and that the CIELAB space can be used to represent colour stimuli within complex scenes rendered with any of the illuminants used. The methodology gives an approximate but reasonable estimate (Pointer and Attridge, 1998; Linhares *et al*., 2008). For dichromats, the CIELAB colour volumes were computed from the dichromatic tristimulus values estimated using a computational algorithm which simulates the dichromatic colour perception to a normal trichromatic observer (Brettel *et al*., 1997; Linhares *et al*., 2009). The number of discernible colours was estimated in the same way as for normal trichromats. For anomalous trichromats, the CIELAB colour volumes were computed from the anomalous tristimulus values obtained using anomalous cone spectral sensitivities estimated by shifting the normal M cone spectral sensitivity 10 nm towards long wavelengths to obtain the protanomalous sensitivity curve and the normal L cone 6 nm towards shorter wavelengths to obtain the deuteranomalous sensitivity

Figure 4. Averages across scenes of the relative number of discernible colours obtained by computing the ratio between the number of discernible colours for each illuminant, and that obtained with CIE illuminant A. The grey circular line represents the locus for CIE illuminant A (unitary circle), circular symbols represent data for the scenes obtained in our laboratory and crosses represent data for the other three scenes. Left column refers to CIE D, A and C illuminants, centre column to CIE FL and HP illuminants and right column to LEDs. Results for (a) normal trichromats, (b) tritanopes, (c) deuteranopes, (d) protanopes, (e) deuteranomalous, and (f) protanomalous, are represented on different lines. In each case the best illuminant is signalled by a grey straight line.


(a) Normal
(b) Tritanope
(c) Deuteranope
(d) Protanope
(e) Deuteranomalous
(f) Protanomalous
D250
D36
A
C
D65
D55
FL2*
FL7*
FL11*
HP1
HP2
FL3.8
FL3.14
FL3.7
LXHL-BW02
LXML-PWN1-0100
LXML-PWC1-0100
Averages across scenes of the relative number of discernible colours in relation to CIE illuminant A
Daylight
FL and HP
LED

curve (DeMarco *et al*., 1992) instead of the CIE 1931 2° standard observer. The number of discernible colours was then estimated in the same way as for normal trichromats. The underlying assumption in the computations of colour appearance for the anomalous trichromats is that same trio of cone excitations produce the same perception for anomalous trichromats as for normal trichromats.

All computations of the number of discernible colours for the different illuminants were compared with the estimates obtained for the CIE standard illuminant A. This illuminant was used for comparison because it is still used in households in spite of the increasing popularity of compact fluorescent lamps.

The CRI was estimated by computing the General Colour Rendering Index R_a (CIE, 1995) using the spectral data of the eight coloured samples recommended by CIE. The same methodology was used to compute an equivalent index R_b but using the extended set of 14 coloured samples also recommended by the CIE. The GAI (Rea and Freyssinier-Nova, 2008) was computed as the area of the polygon defined by the chromaticity coordinates of the same eight Munsell coloured samples recommended by CIE for the calculation of the CRI rendered under the test illuminant in the CIE 1964 colour space (CIE, 2004).

Results

As illustration of the chromatic effects of the illuminant spectrum on the colours of a scene for normal observers, *Figure 3* represents on the left the CIELAB colour volume produced by CIE FL3.8 and on the right the CIELAB colour volume produced by CIE HP1 for the scene shown. These illuminants produced the highest and the lowest number of colours for that scene, respectively, corresponding to a variation of about a factor of 2.

Figure 4 represents averages across scenes of the relative number of discernible colours obtained by computing the ratio between the number of discernible colours for each illuminant and those obtained with CIE illuminant A. Daylight illuminants have similar effects across the CCT range analysed, except for deuteranomalous and protanomalous where chromatic diversity decreases with increasing CCT. For FL and HP illuminants chromatic diversity is more variable with the illuminant and type of observer. For example, for normal observers the CIE HP1 illuminant reduces the number of discernible colours by about 40% whereas it is the best illuminant for deuteranopic observers with an enhancement of about 8%. The best illuminants were FL3.8, FL3.14, HP1, LXHL-BW02, HP2 and FL3.7, with enhancements of about 7.5% (±2.5), 6% (±4), 8% (±2), 18% (±6), 7.5% (±2.5) and 12% (±2.3) for normal, tritanopes, deuteranopes, protanopes, deuteranomalous and protanomalous observers, respectively (numbers in parentheses represent standard error). These results are similar for both sets of hyperspectral data.

To investigate the relationship between chromatic diversity evaluated by the number of discernible colours, and more conventional colour rendering indices, CRI and GAI were computed for all illuminants and compared against the average number of discernible colours. *Figure 5* represents the ratio between GAI for each illuminant and GAI for illuminant A as a function of the ratio between the number of discernible colours for each illuminant and the number of discernible colours for illuminant A. *Table 1* represents the proportion of variance R^2 accounted for in the regression for each case, and also for a similar analysis with R_a and R_b. A low degree of correlation was found for all cases, including considering R_a and $R_{b,}$ except for GAI calculated in CIELAB space where the correlation is higher.

Discussion

In this work hyperspectral data of indoor scenes were used to estimate the number of discernible colours for a collection of illuminants for normal and colour deficient observers. A large variation in chromatic diversity was found across illuminants with the best illuminant producing about 50% more colours than the worst for a particular image of an indoor scene.

The results obtained with hyperspectral data from two different origins were very similar. If the number of discernible colours was plotted for the two datasets for each illuminant a good correlation between the two databases was found with the proportion of variance R^2 accounted, of about 0.75, 0.93, 0.89, 0.94, 0.74 and 0.93 for normal, tritanopes, deuteranopes, protanopes, deuteranomalous and protanomalous observers, respectively. This level of correlation between the two datasets suggests adequate sampling.

Comparing the results presented here with those for artistic paintings (Linhares *et al*., 2009) it was found that the illuminant producing the maximum number of discernible colours is not the same for the two types of scene. The best illuminants found were FL11*, FL3.14 and HP2 for normal, tritanopes and deuteranomalous observers respectively, and HP4 for deuteranopes, protanopes and protanomalous observers. However, the best illuminants for indoor scenes corresponded to relative maxima for art paintings, suggesting that the same illuminant may be used for both conditions.

The low correlation between the number of discernible colours and the CRI was expected as they refer to different properties. For the GAI, the correlation was higher, in particular when the CIELAB space was used, which indicates that the two quantities have common features.

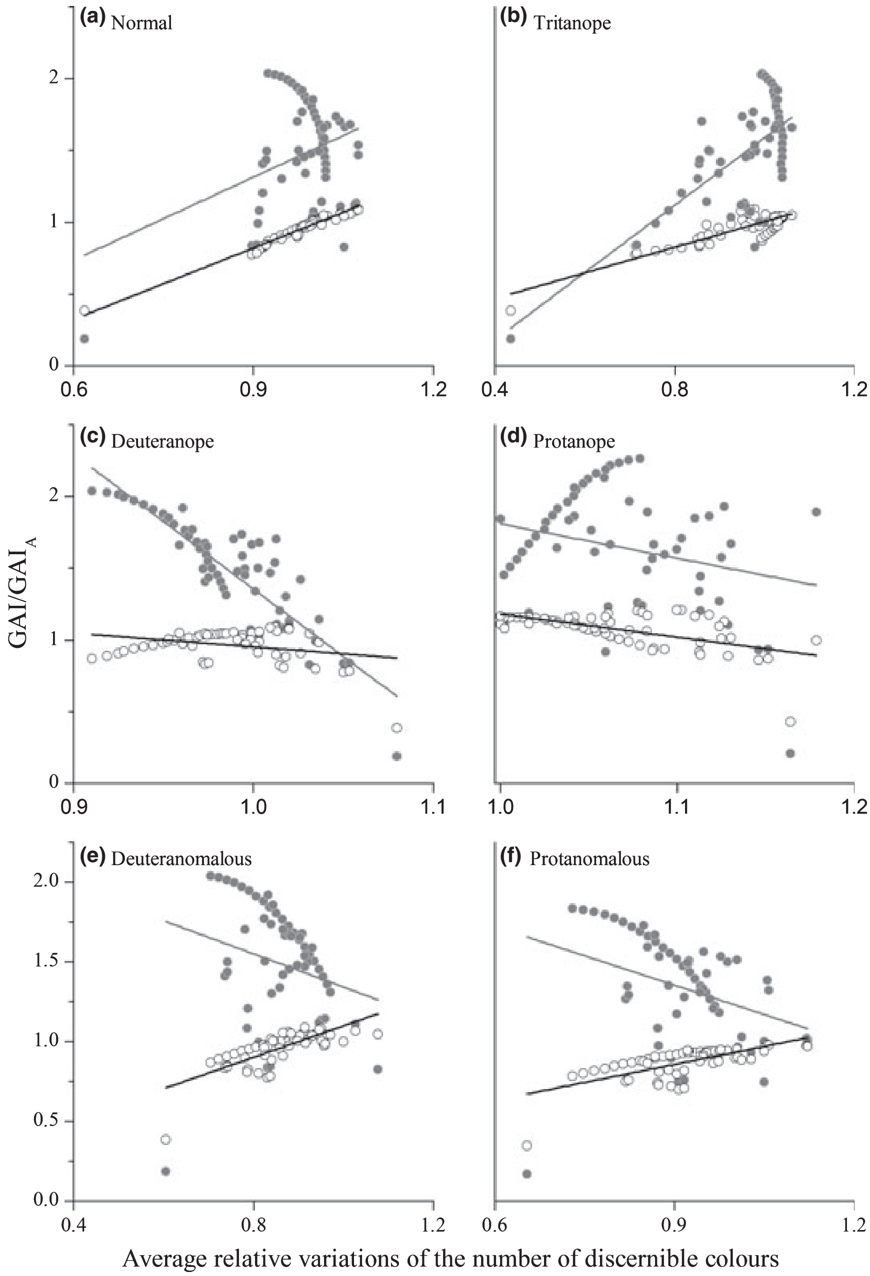


Figure 5. Ratio between GAI for each illuminant and GAI for illuminant A as a function of the ratio between the number of discernible colours for each illuminant and the number of discernible colours for illuminant A. Grey solid circles represent GAI ratios computed in the CIE 1960 UCS; black open circles GAI ratios computed in the CIE (a*,b*) colour space. Straight lines represent unweighted linear regressions to each data set. The proportion of variance R^2 accounted for are indicated in *Table 1*.

The results presented here were based on models of colour deficient observers that are known to be incomplete. Several limitations to the dichromatic colour perception model (Capilla *et al*., 2004) and the non-uniformity of the colour space used (in particular, in blue and gray areas (Fairchild, 2005; Luo *et al*., 2001)) are known. The use of cubic segmentation is also a limitation because it assumes that all the colours that are inside the same cube could not be discernible, when in fact some pairs have colour differences higher than the unit. The use of a spherical packing could eventually overcome this limitation, but former studies (Linhares *et al*., 2008) suggest that the use of relative estimations to compute the number of discernible colours is robust.

The quality of a light source depends on factors other than its chromatic effects, such as the perceived brightness (Fotios *et al*., 2008; Fotios and Houser,

Observer	GAI/GAI_A	$GAI^{(a^*,b^*)}/GAI_A^{(a^*,b^*)}$	R_a/R_{aA}	R_b/R_{bA}
	R^2			
Normal	0.11	0.96	0.21	0.14
Tritanope	0.48	0.74	0.86	0.84
Deuteranope	0.77	0.07	0.58	0.66
Protanope	0.06	0.33	0.46	0.55
Deuteranomalous	0.05	0.55	0.06	0.04
Protanomalous	0.11	0.44	0.00	0.00

Table 1. Proportion of variance R^2 accounted for in the regressions of GAI/GAI_A, $GAI^{(a^*, b^*)}/GAI_A^{(a^*, b^*)}$, R_a/R_{aA} and R_b/R_{bA} as a function of the average relative variations of the number of discernible colours. The subscript capital A refers to data computed for the CIE illuminant A

2009). However, the number of discernible colours may be useful to quantify how much a light source separates apart the colours of a scene and hence contributes to colour discrimination of its elements. Thus, the use of the number of discernible colours as a complement to GAI and CRI indices may benefit normal and colour deficient observers in the selection of the best light source to use in indoor environments.

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