Analysing observer metamerism in CIECAM02 using real observers

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Abstract

Given a fixed set of viewing conditions, a colour appearance model provides a method for transforming tristimulus values to perceptual attributes correlates, and vice versa. Current colour appearance models, like CIECAM02 [1], have been developed assuming the CIE31 Standard Observer. However a general model must adequately describe the colorimetric behaviour of a large enough set of real observers. In this work we analyse the variability of the different parameters defined by CIECAM02 when different sets of colour-matching functions associated with real observers are considered. All our sets of colour-matching functions are for small-size fields (smaller than 4^o). Our main goal is to evaluate the observer metamerism provided in CIECAM02 for a set of 13 real observers, when the reflectances of the 24 chips of the GretagMacbetch ColorChecker are illuminated under D65 and A illuminants.

Preliminaries

As it is well known, the colorimetric behaviour of an observer α is characterized by its corresponding set of colour-matching functions, $\hat{x}_i^{\alpha}(\lambda)$ (i = 1, 2, 3). In order to check the influence of the inter-observer variability on the perceptual attribute correlates provided by CIECAM02, we have used the following sets of colour-matching functions: CIE1931 Standard Observer (α =1), those associated with the ten observers in Stiles-Burch's

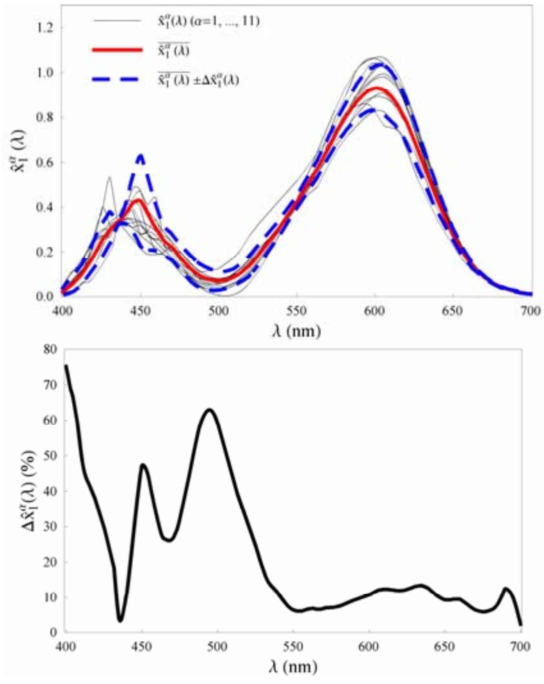

Figure 1: Colour-matching functions $\hat{x}_1^{\alpha}(\lambda)$ (α=1, …,14) used in this work (upper graphic) and the corresponding percent standard deviation (lower graphic)

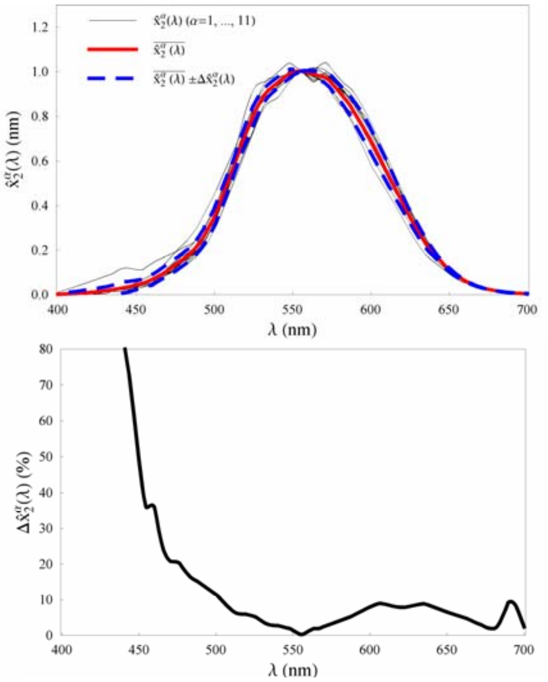

Figure 2: Colour-matching functions $\hat{x}_2^{\alpha}(\lambda)$ (α=1, …,14) used in this work (upper graphic) and the corresponding percent standard deviation (lower graphic)

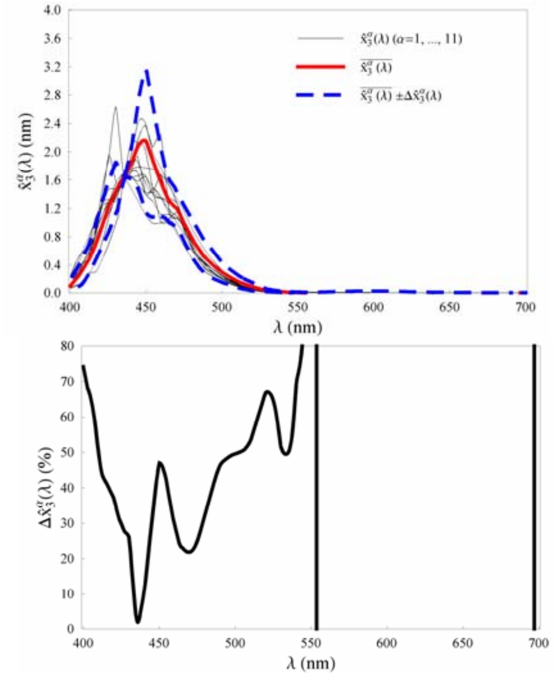

Figure 3: Colour-matching functions $\hat{x}_3^{\alpha}(\lambda)$ (α=1, …,14) used in this work (upper graphic) and the corresponding percent standard deviation (lower graphic)

pilot research (α =2…11) [2], and the CF, JAM, and MM observers (α =12, 13, and 14) [3, 4]. In this way, α runs from 1 to 14. This number is large enough in order to provide significative statistical results. The previous mentioned sets of colour-matching functions are shown in Figures 1 to 3, referred to the CIE31 representation system. In these Figures the thin solid lines in the upper graphics represent the individual $\hat{x}_i^{\alpha}(\lambda)$ colour-matching functions. The red thick solid line shows the average value of these functions and the blue dashed lines represent the average plus/minus the corresponding standard deviation. The lower graphics in these Figures exhibit the percent standard deviation associated with the average for the corresponding functions. The standard deviation in Figure 3 exhibit an anomalous behaviour for the larger wavelengths. This manner of acting has no importance due to the fact that the $\hat{x}_3^{\alpha}(\lambda)$ functions take no significative values in this spectral range. From the previous Figures it becomes obvious that functions $\hat{x}_2^{\alpha}(\lambda)$ show a lower standard deviation (lesser than 20%) in all the spectral range in which they take significative values. For the $\hat{x}_1^{\alpha}(\lambda)$ and $\hat{x}_3^{\alpha}(\lambda)$ colour-matching functions the standard deviations are about 40-60% in the significative spectral regions. These results point out that the inter-observer variability is relevant.

The different colour stimuli used to evaluate the behaviour of the CIECAM02 appearance model have been generated by using the 24 spectral reflectances of the GretagMacbetch ColorChecker. The measurements of these reflectances have been performed from 400 nm to 700 nm in steps of 5 nm. For each observer, the tristimulus values of the different reflectances have been computed by using the CIE standard illuminants D65 an A. These illuminants can be considered as representative of two very different conditions of lighting: outdoor and inside lighting.

The categorical viewing and lighting conditions setting for the CIECAM02 model were those associated with condition named "Surface colour evaluation in a light booth" in Reference [1].

The present work is an extension consequence of a previous one carried out by the authors [5].

Results

Given an observer α (α =1, …, 14), a spectral reflectance l (l=1, …, 24), and an illuminant m (m=D65, A), we have computed the following perceptual attribute correlates: brightness ($Q_l^{\alpha,m}$), lightness ($J_l^{\alpha,m}$), colorfulness ($M_l^{\alpha,m}$), hue angle ($h_l^{\alpha,m}$), and the Cartesian coordinates $(a_m)_l^{\alpha,m}$ and $(b_m)_l^{\alpha,m}$. For each reflectance we have computed the average of the previous quantities over all the observers (it is done for both of the illuminants D65 and A). The corresponding coefficients of variance are also obtained: CVQ_l^m, CVJ_l^m, CVM_l^m, CVh_l^m, $CV(a_m)_l^m$, and $CV(b_m)_l^m$. In the case of the brightness an the illuminant D65, we have

$$CVQ_l^{D65} = \frac{1}{14}\sum_{\alpha=1}^{14} CVQ_l^{\alpha,D65} \quad . \qquad (1)$$

The same procedure has been followed for all the remainder perceptual attribute correlates and illuminant A. The coefficients of variance provide a measure of how much variability there is in the corresponding parameters when a given set of different observers are considered.

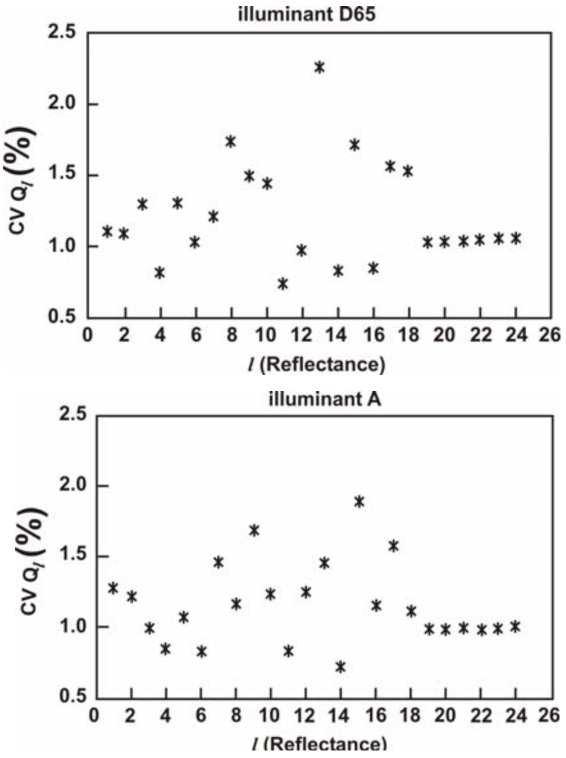

Figure 4: Coefficient of variance CVQ_l^{D65} (upper graphic) and CVQ_l^{A} (lower graphic).

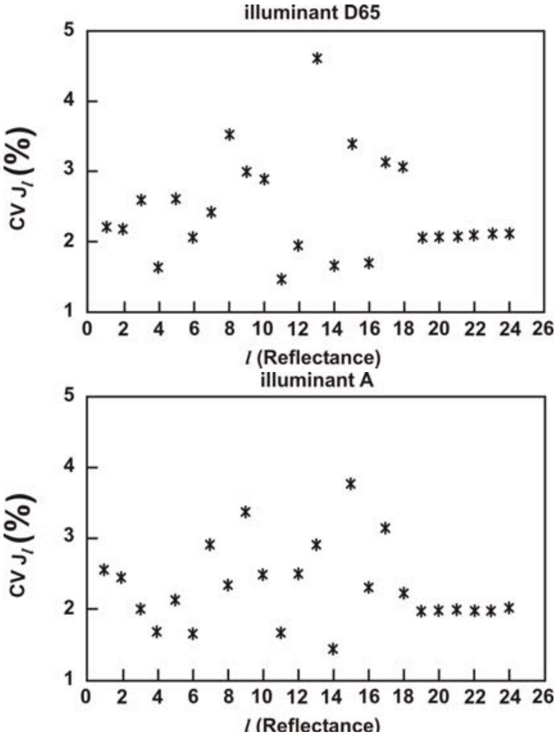

Figure 5: Coefficient of variance CVJ_l^{D65} (upper graphic) and CVJ_l^{A} (lower graphic).

The percent coefficients of variance obtained for each reflectance when averaging to the observers for the CIECAM02

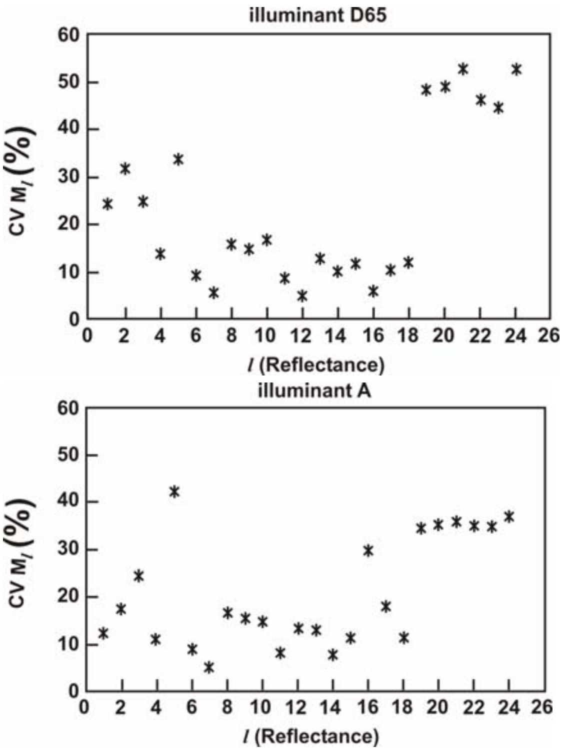

Figure 6: Coefficient of variance CVM_l^{D65} *(upper graphic) and* CVM_l^{A} *(lower graphic).*

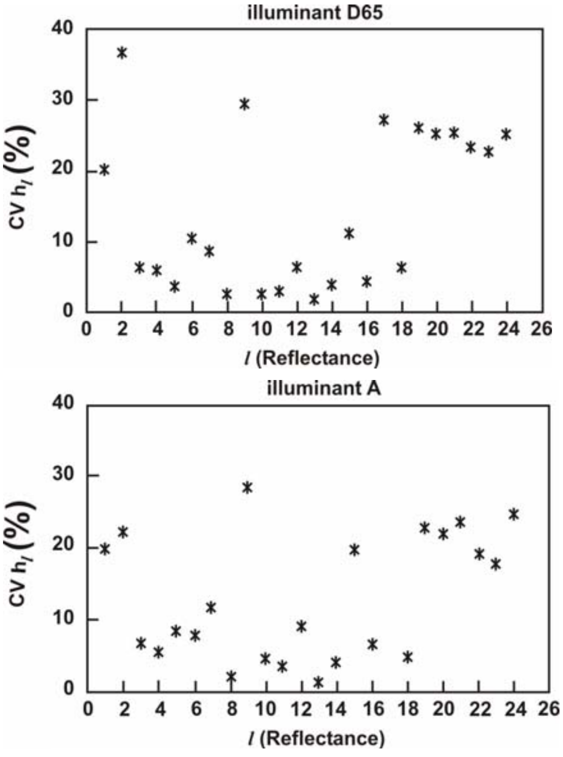

Figure 7: Coefficient of variance CVh_l^{D65} *(upper graphic) and* CVh_l^{A} *(lower graphic).*

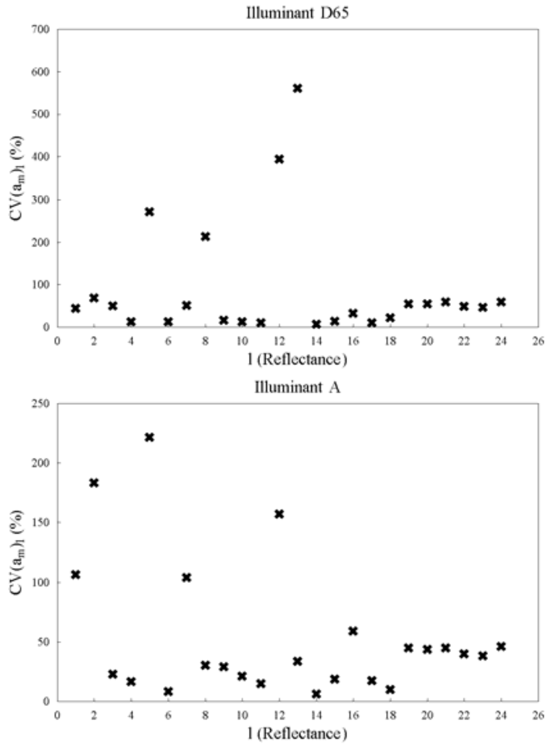

Figure 8: Coefficient of variance $CV(a_m)_l^{D65}$ *(upper graphic) and* $CV(a_m)_l^{A}$ *(lower graphic).*

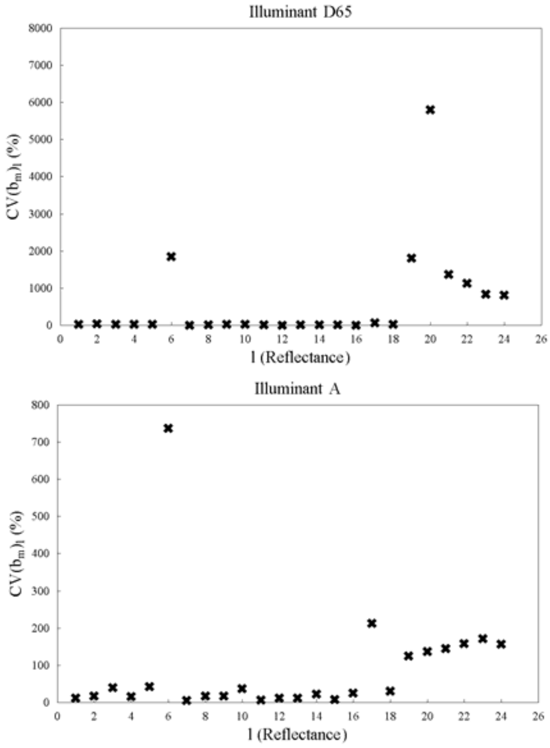

Figure 9: Coefficient of variance $CV(b_m)_l^{D65}$ *(upper graphic) and* $CV(b_m)_l^{A}$ *(lower graphic).*

perceptual attribute correlates considered, are shown in Figures 4 to 9 for illuminants D65 and A. A similar analysis was carried out for the other CIECAM02 correlates, leading to similar results than the current one.

The previous computed averages and variances provide useful information about the individual behaviour and variability of the considered perceptual attribute correlates, but they does not allow us to obtain information about the global colorimetric behaviour. In order to obtain a quantitative global estimation of the influence of the inter-observer variability using CIECAM02, we have computed, for each reflectance l, the colour differences,

Table I: Average colour differences (2) for all the reflectances and Illuminant D65.

D65	$\Delta E_l^{CIE31} \pm std(\Delta E_l^{CIE31})$		
l	LCD	SCD	UCS
1	7 ± 3	6 ± 2	6 ± 3
2	10 ± 4	7 ± 3	8 ± 4
3	8 ± 5	5 ± 4	6 ± 4
4	5 ± 3	3 ± 2	4 ± 2
5	8 ± 5	5 ± 3	6 ± 4
6	9 ± 7	6 ± 5	7 ± 6
7	13 ± 5	8 ± 3	10 ± 4
8	7 ± 4	4 ± 2	5 ± 3
9	12 ± 5	6 ± 3	8 ± 3
10	5 ± 3	4 ± 2	4 ± 3
11	7 ± 3	4 ± 2	5 ± 2
12	12 ± 5	7 ± 3	9 ± 4
13	6 ± 4	4 ± 2	4 ± 3
14	5 ± 3	3 ± 2	3 ± 2
15	11 ± 5	6 ± 3	7 ± 3
16	11 ± 5	6 ± 3	8 ± 3
17	9 ± 5	5 ± 3	6 ± 3
18	9 ± 7	6 ± 5	7 ± 5
19	13 ± 8	11 ± 6	12 ± 6
20	12 ± 7	10 ± 5	10 ± 6
21	11 ± 6	9 ± 5	9 ± 5
22	9 ± 5	7 ± 4	8 ± 5
23	7 ± 4	6 ± 3	6 ± 4
24	5 ± 3	5 ± 3	5 ± 3

$\Delta E_l^{CIE31,\alpha}$, between the CIE31 Standard Observer an each one of the α real observers considered in this work. These differences have been calculated for both illuminants D65 and A using the CAM02-LCD, CAM02-UCS, and CAM02-UCS colour spaces.

For each reflectance, the average values over all the observers

$$\Delta E_l^{CIE31} = \frac{1}{14}\sum_{\alpha=1}^{14} \Delta E_l^{CIE31,\alpha} \qquad (2)$$

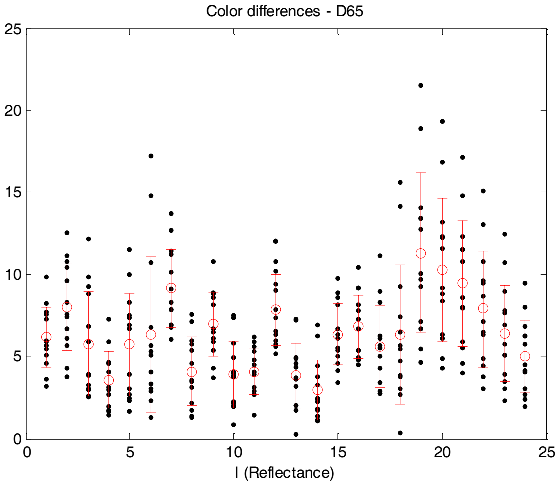

Figure 10: CAM02-SCD colour differences between the CIE31 Standard Observer and all the α observers, for each one of the l reflectances for illuminant D65. The error bars show $\Delta E_l^{CIE31} \pm std(\Delta E_l^{CIE31})$.

Table II: Average colour differences (2) for all the reflectances and Illuminant A.

A	$\Delta E_l^{CIE31} \pm std(\Delta E_l^{CIE31})$		
l	LCD	SCD	UCS
1	12 ± 5	9 ± 4	10 ± 4
2	15 ± 6	12 ± 5	13 ± 5
3	11 ± 5	8 ± 4	9 ± 4
4	8 ± 3	5 ± 2	6 ± 3
5	13 ± 6	10 ± 4	11 ± 5
6	10 ± 5	6 ± 3	7 ± 4
7	19 ± 8	12 ± 5	14 ± 6
8	7 ± 4	4 ± 2	5 ± 2
9	18 ± 8	11 ± 5	13 ± 6
10	8 ± 4	5 ± 3	6 ± 3
11	12 ± 5	6 ± 2	8 ± 3
12	18 ± 9	11 ± 5	13 ± 6
13	5 ± 3	3 ± 2	3 ± 2
14	7 ± 3	4 ± 2	4 ± 2
15	17 ± 8	9 ± 4	11 ± 5
16	20 ± 10	11 ± 6	14 ± 8
17	14 ± 6	7 ± 3	9 ± 4
18	7 ± 5	5 ± 3	5 ± 4
19	19 ± 8	15 ± 6	16 ± 6
20	17 ± 7	14 ± 5	15 ± 6
21	15 ± 6	12 ± 5	13 ± 5
22	13 ± 5	11 ± 4	11 ± 4
23	10 ± 4	9 ± 3	9 ± 4
24	8 ± 3	7 ± 3	7 ± 3

obtained. The results are listed in Tables I and II. From these data

From this Table, it can be checked that, in the current case, the three colour differences CAM02-LCD, CAM02-UCS, and CAM02-UCS are closely linear related and therefore only CAM02-SCD results are plotted in Figures 10 and 11. In these figures, black solid points represent the $\Delta E_l^{CIE31,\alpha}$ values for all the 13 real observers in each reflectance l. The circles indicate

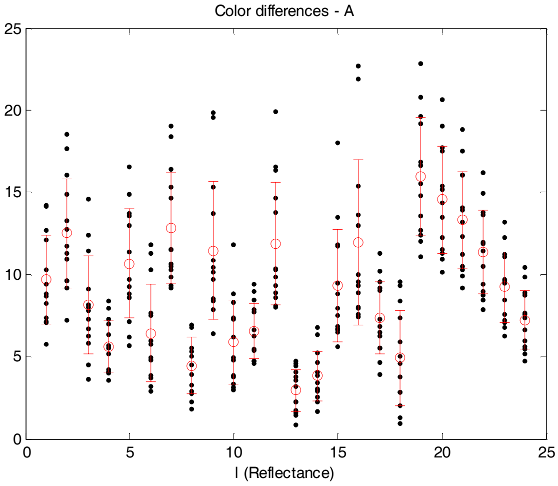

Figure 11: CAM02-SCD colour differences between the CIE31 Standard Observer and all the α observers, for each one of the l reflectances for illuminant A. The error bars show $\Delta E_l^{CIE31} \pm std(\Delta E_l^{CIE31})$.

the corresponding averages ΔE_l^{CIE31} and the associated standard deviations $std(\Delta E_l^{CIE31})$ are represented by error bars. Note that these error bars correspond to the standard deviations which appear in the third column in Tables I and II.

As a last comment in this Section, it should be pointed out that colour-matching functions associated with CF, JAM, and MM observers (α=12, 13, 14) are quite different from those of the Stiles-Burch's pilot research. This is not a surprising result if we take into account that both different sets of colour-matching functions have been measured by using different apparatus, set of primaries, and experimental procedure.

Preliminary conclussions

- The brightness Q and the lightness J correlates exhibit a low interobserver-variability. The values for the coefficient of variance are about 0.5-2.5% for Q and 1-5% for J. In this way, the variability for J correlate is slightly higher than in the case of the Q correlate. It seems that variability does not strongly depend on the reflectance. In particular, for the achromatic reflectances - *l*=19…24 - in Figures 4 and 5, the variability of Q (≈1%) and J (≈2%) is nearly constant. Although the variability for the two correlates seems to be slightly lesser with the illuminant A, in our opinion, it can be concluded that the dependence of the illuminant on the variability of quantities Q and J is not very significative.
- For colorfulness and hue correlates, M and h, the values of the coefficient of variance fluctuate in the ranges 5-50% and 1-40% respectively. These values are clearly larger than those obtained for the previous correlates Q and J. In the case of M and h, the variability of both magnitudes is higher in the case of the D65 iluminant (see Figures 6 and 7). It seems that there is not an evident dependence of the variability for these correlates on the reflectance.
- As it is shown in Figures 8 and 9, the variability for the values of the a_m and b_m coordinates is extremely large, when compared with the variability of the previously considered correlates. The values of the coefficients of variance are so large that the average values of a_m and b_m seem do not provide relevant information. There is no appreciable difference between the results obtained for both illuminants and it seems that the coefficient of variance does not strongly depends on the reflectance (it value is very large for all of them). The variance due to the inter-observer variability is larger for the b_m coordinate than for the a_m. The extremely large values for the variability of correlates a_m and b_m must be deeper analysed. Perhaps the results obtained can be due to the differences between the different sets of colour-matching function, as it has been previously pointed out.
- Concerning to the values obtained for the colour differences $\Delta E_l^{CIE31,\alpha}$, it should be pointed out that they are quite large (see Figures 10 and 11). In the case of the A illuminant the scattering of the data for each reflectance seems to be larger then in the case of the D65 illuminant. The magnitude of the colour differences and the scattering of the data seems to be independent on the reflectance which is considered. The large values of the computed differences are clearly pointed out when the corresponding average over all the observers for each reflectance, ΔE_l^{CIE31}, are considered, as it is shown in Tables I and II. In this Tables are also listed the standard deviation, $std\left(\Delta E_l^{CIE31}\right)$ for the previous average values. The large values of deviations $std\left(\Delta E_l^{CIE31}\right)$ qualitatively confirm us the significative scattering of the data plotted in Figures 10 and 11.
- The values of the colour differences obtained in this work are, in most of cases, clearly larger than threshold differences. This seems to indicate that there are discrepancies in the perceptual evaluation between real observers and the CIE 1931 Standard Observer.

Acknowledgments

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Author Biography

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