Calculation of number of distinguishable colours by real normal observers

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Abstract

The colour-matching functions of standard observers proposed by the CIE represent the normal colour vision for the worldwide population. But there are deviations in the colour-matching functions for real observers with a normal colour vision, so the observer metamerism index was defined by CIE to evaluate the mismatch between them in colour appearance. In this work, we present an alternative form to evaluate the differences between the CIE standard observer and real observers (Stiles-Burch database) according to the number of distinguishable colours in the colour solid associated to each observer. Unlike the metamerism index defined by CIE, we evaluate globally the colour appearance for a real observer taking into account its colour gamut volume. After analyzing the results, we have seen that the gamut volume of the real-observers is lower than to that associated to the CIE standard observer, even to that associated to the CIE modified observer. Therefore, this work and its methodology could be used to know the ability of the CMF's of different observers to get the maximum colour gamut under the same illuminant. Furthermore, this methodology could be applicable to study the gamut volume variability of the real observers regarding to age, race, etc, or even with abnormalities in colour vision (dichromacy, pathologies, etc).

Introduction

The colour-matching functions of standard observers proposed by the CIE (CIE 1931 and CIE 1964) represent the colour vision for the average population. But it is known that there are deviations in the colour-matching functions for real observers with a normal colour vision. For this reason, it was defined the special metamerism index, introduced to describe the mismatch observed among metameric pairs under the CIE standard observer and a standard observer deviated with normal colour vision [1]. A colour appearance model describes the colour perception from the tristimulus values and other parameters relating to the stimulus and the environment. The colour appearance models, for instance, CIELAB and CIECAM02, are based on the descriptors associated to the CIE 1931 standard observer. But an integral model should describe the colour perception for any real observer with normal colour vision.

On the other hand, we know that a colour appearance model, for instance CIECAM02, allow us to define the colour solid where all distinguishable colours by the human visual system are enclosed. The colour stimuli shaping the intermediate frontiers of the colour solid, obviously with the maximum colourfulness, are called optimal colours and they were exhaustively studied by MacAdam in 1935 and it is proved that their spectral reflectance or transmittance can be only zero or one. Due to this, the colour solid borders are also known as MacAdam limits. There are two types of optimal colours: type 1, with "mountain"-like spectral profiles, and, type 2, with "valley"-like spectral profiles. Although these colours are not present in nature, they are very important for Colour Science because they constitute the frontier of the human colour solid. In a recently published work [2], a new algorithm have been developed to calculate the optimal colours associated to different illuminants and light sources taking into account the CIE 1931 standard observer. But we can modify this algorithm to obtain the optimal colours for any lightness value and for any illuminant or light source and for any observer.

Therefore, the main aim of this work is obtain the colour solid under a fixed illuminant, for instance the illuminant D65, but with different real observers with normal colour vision. After this calculation, we evaluate the number of distinguishable colours according to different packing methods [2] to evaluate the deviations found among these observers and the CIE standard observer.

This methodology could be useful to evaluate globally the colour appearance for different observers, that is, this would be an alternative way of evaluating the colour appearance change among observers.

Data and Methods

In this work, we have studied 10 real observers, observers from Stiles-Burch [3] data and the CIE 1931 modified observer, to analyze the differences among these observers and the CIE 1931 standard observer according to the number of distinguishable colours (Figure 1). These real colour-matching functions, joint to those associated to CIE system, were previously normalized by means the G94 system [4, 5].

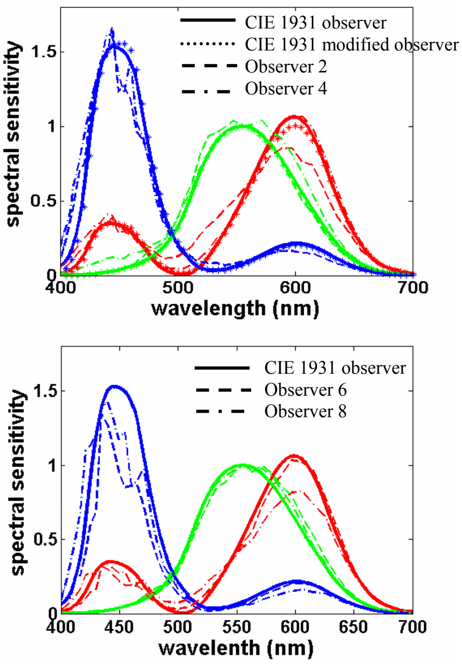


Figure 1. *Colour matching functions for different real observers and the CIE 1931 observer at the G94 system.*

Firstly, we calculated the deviation functions, $\Delta\bar{x}(\lambda), \Delta\bar{y}(\lambda), \Delta\bar{z}(\lambda)$ for all observers to know the real deviation among the different real observers as follows:

$$\Delta\bar{x}_i(\lambda) = \bar{x}_{i,real}(\lambda) - \bar{x}_{i,CIE1931}(\lambda) \quad i = 1,2,3 \tag{1}$$

The obtained results can be seen in the Figure 2 and we checked that the deviation functions for the real observers are bigger than the CIE 1931 modified observer.

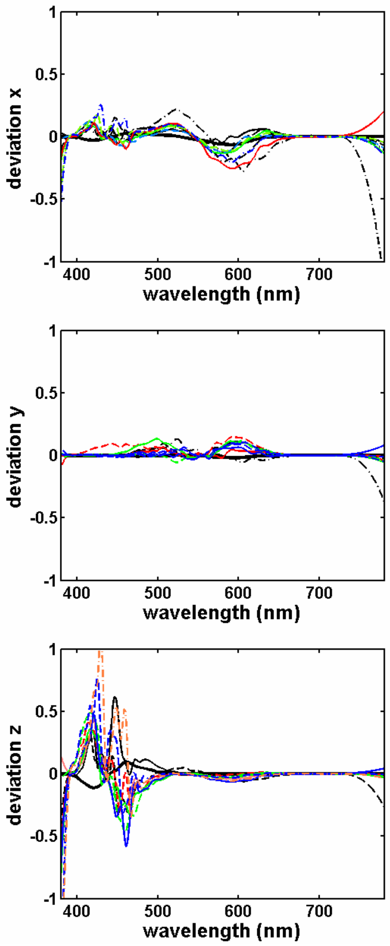


Figure 2. *Deviation functions of the 10 real observers and the first deviation functions defined by the CIE (CIE 80:1989) with the CIE 1931 standard observer (black solid line).*

In spite of the fact all these colour-matching function are not normalised to the same illuminant, we tested if colour-matching functions associated to different real observers fulfil the Luther condition [6]. We found that any colour-matching functions fulfil the Luther condition, even the CIE 1931 modified observer. This preliminary test warns us that there will be observer metamerism, and it is possible that each optimal colour set associated to the real observers may differ from that of the CIE standard observer. Moreover, as the observer metamerism means that color-stimuli encoded equal for the standard colorimetric observer in CIE color space can be encoded different for other real observers, and vice versa, this preliminary result will warranty that we find chromatic regions without perceptual correspondence among observers.

Next, we obtained the colour solid to calculate the number of distinguishable colours. The colour solid is obtained following the methodology described in our published work [2]. We need the following inputs:

- The visible spectrum range, (from 380 to 780 nm).
- The spectral sampling, N, in this case is equal to 0.1 nm.
- The spectral power distribution S(λ) of illuminant D65.
- The lightness value L*, with tolerance ΔL*, to transform it into Y(L*).
- The colour-matching functions associated to the different real observers and the CIE 1931 standard and modified observer.

With these preliminaries, for each fixed Y(L*) value, the routine systematically locates the wavelengths λ_1 and λ_2 where the sudden change of reflectance or transmittance happens (from 0 to 1 or opposite).With each pair of limiting wavelengths, λ_1 and λ_2, and the illuminant D65 S(λ) it is very easy to generate the optimal colour stimuli $C_{optimal}(\lambda)$ as $\rho_{optimal}(\lambda)*S(\lambda)$. Obviously, from here it is almost immediate to compute the XYZ tristimulus values from the colour-matching functions and to encode them into perceptual values in several colour spaces (CIELAB, DIN99d, CIECAM02, etc). Therefore, in this way, changing the colour-matching functions, we can obtain the colour solid associated to different real observer with normal colour vision and the colour solid associated to the CIE 1931 standard observer and the CIE 1931 modified observer.

But the real colour-matching functions were previously normalized by means the G94 system. For this reason, we get XYZ values encoded in the G94 system. After this, we transform the XYZ94 values into XYZ values encoded in the CIE 1931 system [4, 5] to obtain the colour solid in different colour spaces. After getting the complete colour solid for each real observer and the CIE 1931 modified observer, we calculate the number of distinguishable colours with the *convex hull* mathematical technique and the ellipses packing method [2]. In the Figure 3 it can be seen the scheme of the methodology followed in this work:

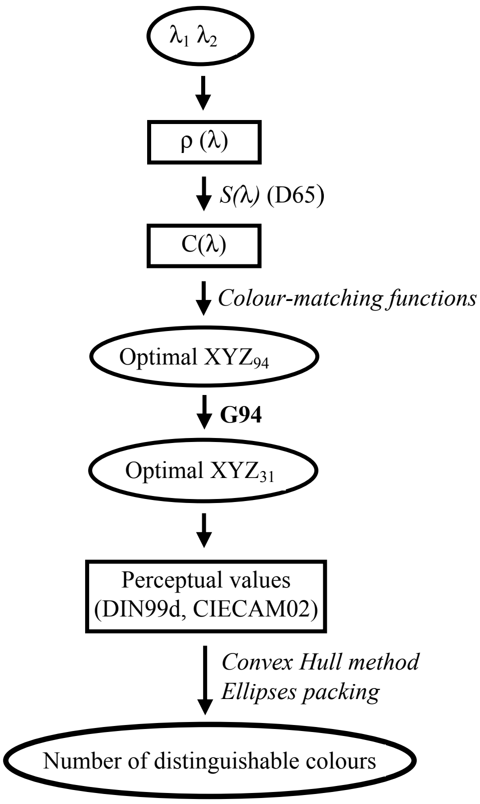


Figure 3. *Scheme of the methodology followed in this work.*

Results and Discussion

After that to be described the methodology of this work, we next show the obtained findings. Firstly, Figures 4 and 5 show the top view of the colour solid in the DIN99d [7] and the CIECAM02 [8] colour spaces associated to different real observers and the CIE 1931 standard and modified observer.

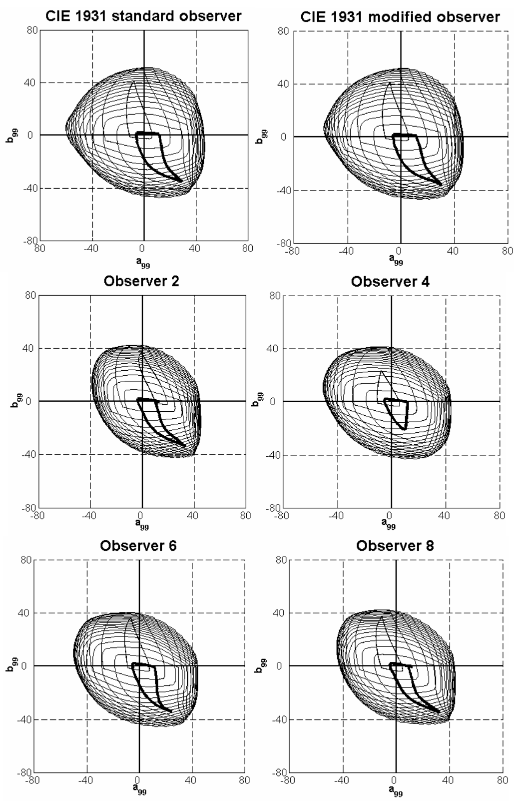


Figure 4. Top view of colour solids associated to different real observers under the illuminant D65 in DIN99d colour space. (The MacAdam locus with the solid curve corresponds to the lowest constant lightness plane).

It can be clearly seen that their shapes are different among them in both colour spaces. In fact, the colour gamut belonging to the CIE 1931 standard observer is greater that the other ones. On the other hand, we can see that the colour gamut volume of the CIE 1931 modified observer is very similar to the CIE 1931 standard observer in DIN99 colour space but it is more different in CIECAM02 colour space, especially for light yellow colours.

However, as it can be seen in Figure 5, the MacAdam limits in constant lightness planes for real observers encoded by CIECAM02 are not smooth in some chromatic regions unlike in DIN99d, in particular for the first and second quadrant. In fact, it is here, in both chromatic quadrants, where we find the most significant differences among real observers. Therefore, although it is obvious CIECAM02 is not currently prepared to run with real observers, it would be interesting to explore in future some new ways to adapt the CIECAM02 model, or any new colour appearance model, for real observers with normal and abnormal colour vision.

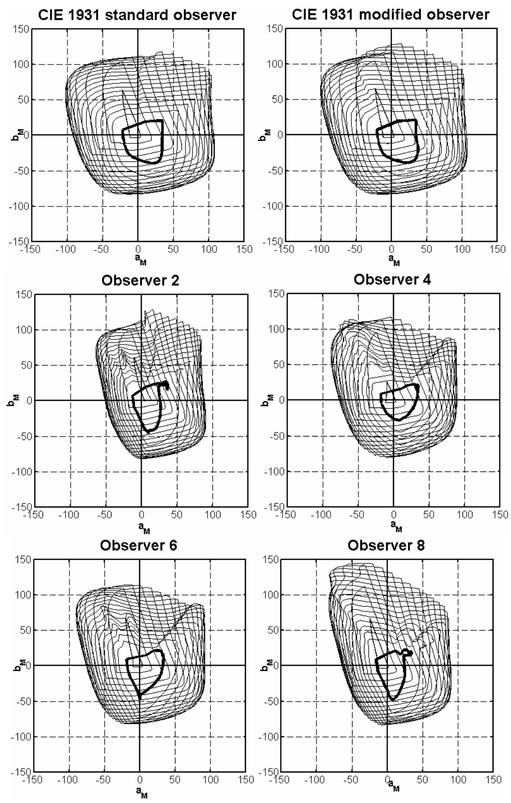
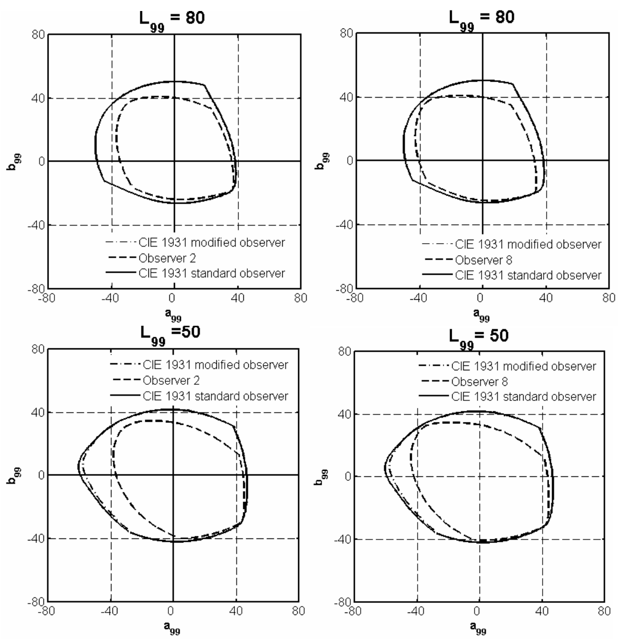


Figure 5. Top view of colour solids associated to different real observers under the illuminant D65 in CIECAM02 colour space. (The MacAdam locus with the solid curve corresponds to the lowest constant lightness plane).

On the other hand, to analyze better the differences among different observers, we compare the MacAdam limits in some constant lightness planes belonging to the CIE 1931 standard and modified observer and the Observers 2 and 8 in both colour spaces (Figures 6 and 7).



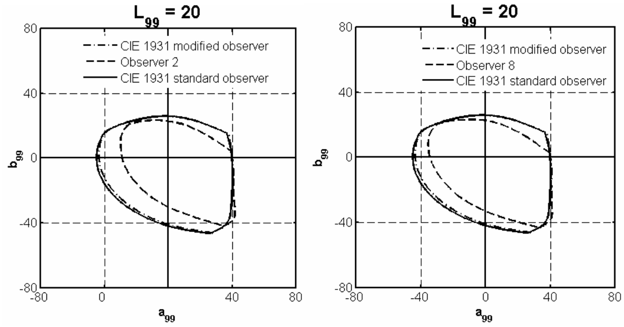


Figure 6. Comparison between the MacAdam limits for constant lightness planes associated to the CIE 1931 standard observer and the Observer 2 (top) and the MacAdam limits for constant lightness planes associated to the CIE 1931 standard observer and the Observer 8 (bottom) in the DIN99d colour space.

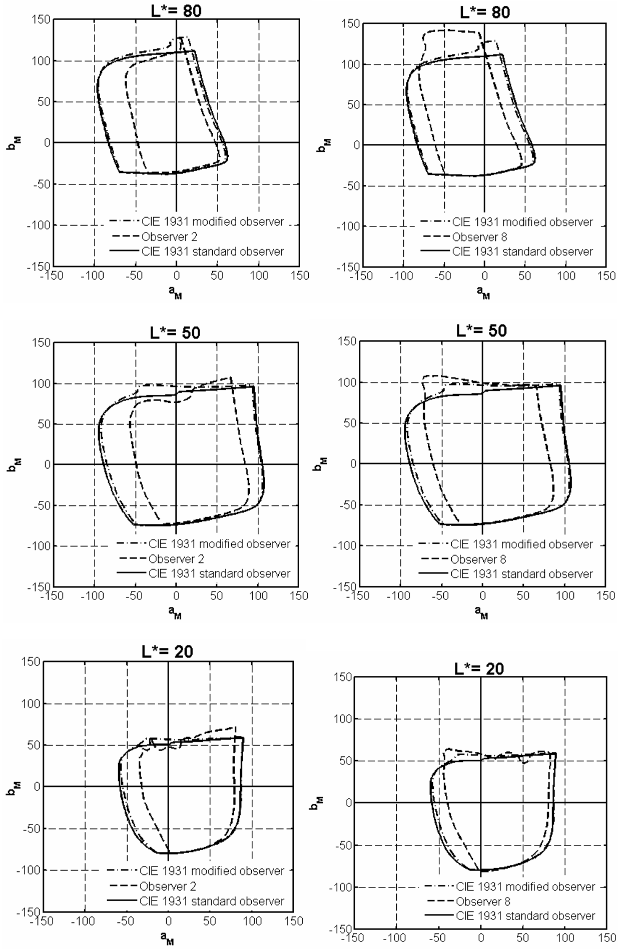


Figure 7. Comparison between the MacAdam limits for constant lightness planes associated to the CIE 1931 standard observer and the Observer 2 (top) and the MacAdam limits for constant lightness planes associated to the CIE 1931 standard observer and the Observer 8 (bottom) in the CIECAM02 colour space.

In these figures we can see better that the colour gamut associated to the CIE 1931 standard observer is greater than the other ones, both low and high constant lightness profiles. For instance, there are more green colours for all the lightness profiles for the CIE 1931 standard observer. Although it must be emphasized that all real observers and the CIE 1931 modified and standard have a similar blue and purple gamut. Therefore, assuming the same chromatic discrimination mechanism as for real observers as for CIE 1931 observer, the colour gamut estimation by gamut volume, in contrast with the CIE metamerism index, is a logical method to evaluate integral differences in colour appearance and distinguishable colours among different real observers.

After checking the differences among the colour solids, we calculate the gamut volume of the colour solids. The first algorithm we use is the convex hull mathematical technique [2]. This method to calculate the volume is an approximation by excess because if it is possible that the colour solid does not define a convex shape. For this reason we also use the ellipses packing method [2], an approximation by defect, to compare the results obtained with the both methods (Tables I and II). With this packing method, we obtain the number of distinguishable colour in the colour solids. Therefore, we also follow the current trends regarding to the similarities and differences between the gamut volume and the number discernible colours in imaging devices [9]. Although, in a future work, we try to calculate the number of distinguishable colours with unit diameter spheres in a perceptually uniform colour space in order to obtain more exactly the number of distinguishable colours.

Table I: Colour gamut volume depending on the observer according to convex hull packing method in the DIN99d colour space

Observer	Volume (convex hull)	Deviation (%)	Ranking
CIE 1931	515,850		1
CIE 1931 mod.	509,080	1.31	2
1	401,110	22.24	7
2	360,400	30.13	12
3	397,400	22.96	9
4	399,530	22.55	8
5	412,660	20.00	3
6	408,530	20.80	5
7	410,480	20.43	4
8	386,690	25.04	11
9	406,340	21.23	6
10	391,310	24.14	10

Table II: Colour gamut volume depending on the observer according to convex hull packing method in the CIECAM02 colour space

Observer	Volume (convex hull)	Deviation (%)	Ranking
CIE 1931	1,917,400		2
CIE 1931 mod	1,945,800	1.48	1
1	1,795,900	6.34	5
2	1,374,100	28.34	12
3	1,488,50	22.37	10
4	1,597,600	16.68	9
5	1,466,500	23.52	11
6	1,639,200	14.51	7
7	1,663,300	13.25	6
8	1,612,300	15.91	8
9	1,854,100	3.30	3
10	1,811,000	5.55	4

As it can be seen, in spite of the fact that we have different colour spaces, the worst result in both tables is for the real observer no. 2, with a percent deviation equals approximately to 30 % with respect to the CIE 1931 standard observer. Other curiosity is the alternation in the first position between the CIE observers, the standard one and its modified version. In contrast, as it can be seen in Table III, applying the ellipse packing method for estimating the total number of discernible colours, the percent deviations are different. Still, again we have the total number of distinguishable colours for real observers is lower than the CIE 1931 standard observers.

Table III: Total number of distinguishable colours depending on the observer according to the ellipse packing method.

Observer	Volume (ellipses)	Deviation (%)	Ranking
CIE 1931	30,736		1
CIE 1931 mod.	30,207	1.72	2
1	29,638	3.57	5
2	26,804	12.79	11
3	28,098	8.58	8
4	24,747	19.49	12
5	27,612	10.16	3
6	27,612	10.16	9
7	28,610	6.92	7
8	26,737	13.01	10
9	28,989	5.68	6
10	28,968	5.75	4

However, as it can be seen in previous Figures, and although the calculations done in Table III are not based on these colour spaces but in a modified MacLeod-Boynton colour space, perhaps it is possible that there are distinguishable colours associated to same real observers without perceptual correspondence under other real observers, even though its gamut volume (or number of discernible colours) was small. For instance, if we compare the real observers 2 and 8 in Figure 6, it can be clearly seen in the middle sub-figures that the sub-gamut of yellow colours is different. This corollary, consequence from the significance of the observer metamerism, should be analysed in depth in near future.

Conclusions

The metamerism index proposed by the CIE evaluates the degree of colour mismatch for a metameric pair when an actual observer with normal colour vision is substituted for the standard colorimetric observer. But in this work, we propose a procedure for evaluating the colour appearance for different real observers in a globally way evaluating the colour solid associated to each observer and calculating the colour gamut volume and/or number of distinguishable colours in the colour solid. Therefore, this work is an alternative form to evaluate the integral change in colour appearance for each real observer.

After analyzing the results, we may say that the shape and the volume of each colour solid under the same illuminant are very different among them. In fact, the number of distinguishable colours decreases for real observers, even assuming the same chromatic discrimination mechanisms. Therefore, this confirms the existence of the observer metamerism, previously predicted since the colour-matching functions associated to different real observers do not fulfil the Luther's condition. Therefore, this work and its methodology could be used to know the ability of the colour-matching functions of different real observers to get the maximum colour gamut under the same/different illuminant.

In future works, we will widen the data of real colour-matching functions and illuminants to evaluate if the variability found is very different, even applying other packing methods for discernible colours, as the calculation with spheres of unit diameter. Furthermore, this methodology could be applicable to study the gamut volume variability of the real observers regarding to age, race, etc, or even with abnormalities in colour vision (dichromacy, pathologies, etc).

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Author Biography

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