Checking Recent Colour-Difference Formulas with a Dataset of Metallic Samples and Just Noticeable Colour-Difference Assessments

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Abstract

Several colour-difference formulas have been proposed since the last recommendation of CIEDE2000 by the 'Commission Internationale de L'Eclairage' (CIE) in 2001. Some of them have been tested using the same dataset used to fit them. Thus, it is of great interest to check the performance of these formulas with new experimental datasets. On the other hand, some previous studies show that many colour-difference formulas perform quite badly in the very small colour difference range of 0 to 1 CIELAB units. This paper pursues these two goals. The colour-difference formulas DIN99d, OSA-GP, OSA-GP Euclidean (OSA-GPE), CAM02-SCD and CAM02-UCS are tested with a new experimental dataset, which has been carried out in the Laboratoire Hubert Curien of Saint Etienne (France) in two different modes, physical metallic samples and virtual samples displayed in a LCD monitor. This new dataset is composed by 390 colour pairs arranged around 16 colour centres with colour differences in the range 0.14 to 2.14 CIELAB units, with an average value of 0.80. In this work only just noticeable differences have been considered from this dataset. The results show a bad performance of all studied colour-difference formulas for just noticeable colour differences, in agreement with previous studies. Further research must be conducted to fit colour-difference formulae to this important range of colour differences.

Introduction

Since the recommendation of the last colour-difference equation by the International Commission of Illumination (CIE), CIEDE2000 [1] in 2001, some new colour-differences equations have been proposed by different authors. Some of these equations are being tested by members of the CIE Technical Committee 1-55 "Uniform Color Space for Industrial Colour Difference Evaluation". Besides CIEDE2000, the formulas CAM02-SCD and CAM02-UCS [2], OSA-GP [3], OSA_GPE [4], and DIN99d [5] are considered. In addition, CIELAB, CIE94 [6] and CMC [7] are also tested here as important historical colour-difference formulas.

Some of the former recent formulas have been tested and developed using the same experimental dataset, which consists of 4 reliable different sets, each one from a different laboratory, called BFD-P, Leeds, RIT-DuPont and Witt. A combined dataset designed as COMData was employed at CIEDE2000 development [8]. In this context, new experimental data are very useful to check the performance of any new colour-difference formula and, although new experimental data have been required by CIE TC1-55 [9], the number of currently available data is quite limited.

Another CIE Technical Committee, CIE TC 1-63, "Validity of the Range of CIEDE2000", is in charge of study the validity of CIEDE2000 in different ranges. At first CIEDE2000 and the former formula recommended by the CIE, CIE94, were recommended in the range 0 to 5 CIELAB units. A previous study [10] indicates that most formulas perform quite badly in the very small colour-difference range of about 1 CIELAB units. In addition, a study of the colour pairs in the COMData indicates that the small colour differences are overestimated [11]. Therefore, it seems convenient to study the performance of colour-difference formulas especially for small colour differences, which are of great interest in many applications.

In this work the performance of the above mentioned colour-difference formulas is tested using a new experimental dataset obtained in the Laboratoire Hubert Curien of Saint Etienne (France). This dataset is formed by very small colour differences, in the range 0.14 to 2.14 CIELAB units, with an average value of 0.80. The weighted normalized *STRESS* (standardized residual sum of squares) index [12] has been employed to check the performance of the formulas in this small colour difference range.

Method

The analyzed dataset was obtained in two experiments carried out in the Laboratoire Hubert Curien of Saint Etienne (France), called experiment R and V. In experiment R real surface metallic samples were observed in a VeriVide light booth provided with D65 light source [13,14] (see Figure 1). The illuminating/viewing conditions were close to the ''reference conditions'' suggested by the ISO standard 3668:2003 [15] for visual comparison of the color of paints and varnishes but note that they are quite different of the reference conditions recommended for CIEDE2000. The viewing conditions were illumination in a light booth (mixing direct light at 45º and also diffuse light) and observation at 0º, i.e. observers were perpendicularly to the surface specimens to avoid glosses. The two samples were compared side by side (at about 500 mm from the eyes), separated by a black area of 1mm wide.

In experiment V virtual samples were displayed in a LCD monitor (Eizo ColorEdge CG241 TFT monitor) in dark viewing conditions [13,14]. The size of colour patches displayed on the LCD screen was identical to the size of surface specimens. The LCD was first calibrated using a GretagMacbeth *i1Pro* colorimeter to match the colour values of LCD colour patches to surface specimen. The colour patches displayed on the LCD screen were then measured by a Minolta CS1000 tele-spectroradiometer (TSR), from which all the results reported here are based. The average uncertainty was estimated around 0.46 CIELAB units. That means that, because of the usual limitations in calibrations of displays such as the well known quantisation error, the colour of colour patches displayed on the LCD screen were not exactly identical to those of surface specimens. Additionally, the accuracy of pairs of colour patches displayed on the LCD screen was also measured by the TSR. In this case the average uncertainty was estimated to lower than 0.2 CIELAB units. That means that for each pair of colour patches displayed on the LCD screen the colour difference was close to those of pair of surface specimens. So we can consider that the relative accuracy of the LCD screen did affect neither the observer judgment nor its absolute accuracy.

Figure 1. *Pair of surface specimens viewed in the light booth.*

The luminance of the reference white in the light booth and of the screen patches was 120 cd/m^2. To achieve it the illuminance of the light booth was decreased below 1000 lux, which is the value stated in the reference conditions recommended for CIEDE2000. Surface and virtual samples were independently observed against a neutral background with L*=77, a*=-0.77, b*=0.55 (see Figure 2). Then, to use the extended uniform colour spaces based on CIECAM02 colour appearance model, the following parameters were set: c=0.69, N_c=1 and F=1 for experiment R; c=0.525, N_c=0.8 and F=0.8 for experiment V. In both experiments the value of L_A was 24 cd/m^2. The CIE 1964 Supplementary Standard Observer was used according to the samples size and observers' position.

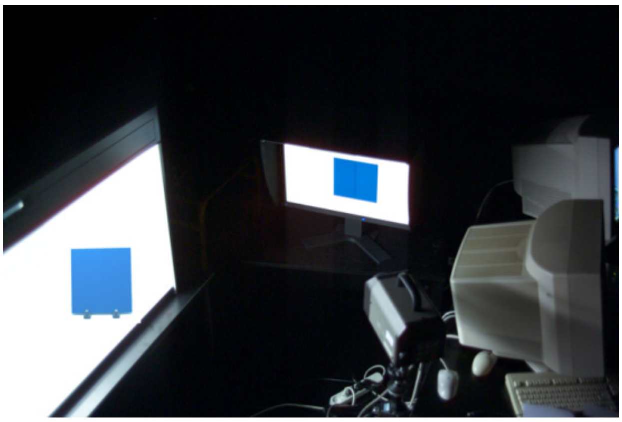

Figure 2. *Pair of surface specimens viewed in the light booth (left) and pair of virtual samples, with nearly same L*a*b* values, displayed in the LCD monitor (right).*

In Experiment R five colour centres were employed, while in Experiment V were used the same five plus eleven additional ones. Table 1 shows the CIELAB coordinates of the centres in columns 2 to 4 (hue angle in degrees). The name of the colour centres comes from the RAL colour chart [16] (except the reference 0000 which corresponds to none RAL reference). Note that some centres have the same names but are designated with '(a)' or '(b)'. As can be observed in the table, these centres have close colour coordinates but not exactly the same. Note that the centres in bold letters were used in both experiments, R and V.

Table 1. CIELAB coordinates, number of pairs and number of observers for each centre. Bold indicates shared centres in experiments R and V. The numbers of pairs after slash correspond to experiment R. Numbers of used pairs are in bracket.

Centre	L^*	C^*_{ab}	h_{ab}	N. of pairs virtual/real	N. of observers
0000	58.00	14.47	33.95	26 (25)	14
1015(a)	85.36	15.46	83.20	20/10 (12/8)	23
1015(b)	89.60	5.83	129.43	26 (16)	14
3000(a)	36.28	65.35	38.18	10/10	26
3000(b)	33.50	54.68	35.97	26 (25)	14
5010(a)	30.25	35.82	259.73	10/10	26
5010(b)	32.00	46.86	230.19	26	14
6300(a)	28.96	24.57	171.32	10	26
6300(b)	32.00	21.50	158.45	26 (25)	14
8004(a)	37.24	41.32	46.57	20/10	23
8004(b)	40.00	32.89	56.82	26	14
8717	23.00	9.64	72.75	26 (22)	14
9005	8.64	2.66	82.70	26 (10)	14
9006	75.00	1.50	180.00	26 (20)	14
9106(a)	84.94	2.25	146.59	10/10	26
9106(b)	86.00	14.98	104.50	26 (24)	14

The centres, which are represented in Figure 3, have CIELAB coordinates in the range 8.64 to 89.6 for L*, 1.5 to 65.4 for C^*_{ab} and 33.9 to 259.7 deg. for h_{ab}.

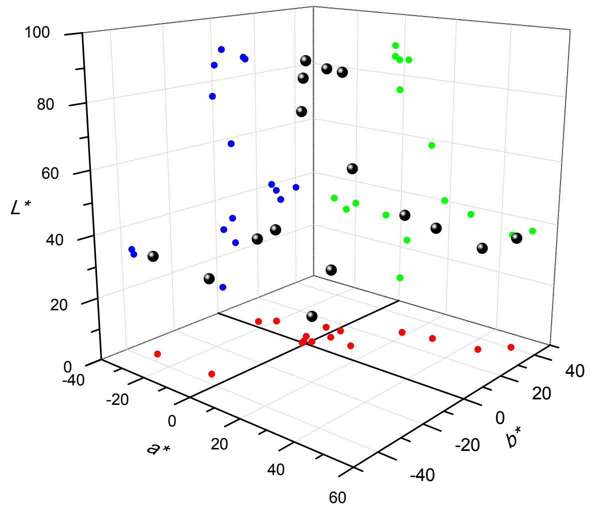

Figure 3. *CIELAB coordinates of the 16 centres. Red, green and blue colours correspond respectively to the projections in a*b*, L*a* and L*b* planes.*

Different samples were considered in each centre, differing from it in lightness, chroma, hue, or combination of them. The colour differences of all pairs ranged from 0.14 to 2.14 CIELAB units in Experiment R and from 0.20 to 2.12 CIELAB units in Experiment V. Table 1 shows in column 5 the numbers of pairs in each centre and experiment. The values after slash correspond to Experiment R. Combining the two experiments, the dataset consists of 390 colour pairs, arranged around 16 colour centres.

The surface specimens (i.e. coil coating metallic paints) and the virtual samples (i.e. colour patches displayed on the LCD screen) were measured by the same TSR with the same angle of measurement as for visual assessments. The surfaces were visually flat without roughness. Their coarseness, the graininess and the sparkle of metallic surfaces were measured by the TSR and a multi-angle colorimeter (Byk-mac). No visual effect, except a colour effect, may affect the observer judgment. The repeatability and the uniformity of measurements of metallic surfaces were lower than 0.2 CIELAB units. The repeatability and the uniformity of measurements of virtual samples were respectively lower than 0.4 CIELAB units and 0.2 CIELAB units.

A total of 26 observers participate in Experiment R of test involving 10 pairs of samples per colour centre and a total of 14 observers participate in Experiment V of test involving 26 pairs of samples per colour centre (see Table 1), 7% women and 93% men, aged from 24 to 45, all with normal colour vision, checked with the Ishihara pseudo-iso-chromatic plates and the Farnsworth-Munsell 100 Hue Test. In total 7524 estimations were performed.

The observers were instructed to compare pairs of samples in the light booth and to compare pairs of samples on the LCD monitor in independent sessions. They were also instructed to face directly the samples in the cabinet or the monitor so that the observational angle with all stimuli was normal, to avoid the change of colour with viewing angle, typical for LCD monitors. The task of the observers was to estimate and score the global colour difference in each pair as not noticeable (score 0), just noticeable (score 1) or noticeable (score 2). Identical instructions were given to the observers in Experiments R and V.

The performance of the colour difference formulas could be checked by different measures, but lately the *STRESS* index [12] is increasingly employed because it allows statistical inferences on the significance of the difference between two colour-difference formulas for a given set of visual data through the *F*-test. *STRESS* ranges between 0 and 100 in such a way that greater values mean worse agreement between visual and computed color differences. Specifically for this study the weighted normalized *STRESS* is employed, which is defined as follows:

$$WSTRESS = \left(\frac{\sum w_i \left(\Delta E_i - F_1 \Delta V_i \right)^2}{\sum w_i \left(F_1 \Delta V_i \right)^2} \right)^{1/2} x100 \qquad (1)$$

where:

ΔV is the visual difference estimated by the observers, in this work taken equal to 1 because for all cases it is the just noticeable colour difference and STRESS is invariant to multiplying ΔV or ΔE by a factor.

$$F_1 = \frac{\sum \Delta E_i^2}{\sum \Delta E_i \Delta V_i} \qquad (2)$$

The weighting factor, w_i, for each colour difference pair *i*, is obtained as:

$$w_i = \frac{S1}{TNS} \qquad (3)$$

where *S1* is the number of estimations with score 1 (just-noticeable differences) and *TNS* is the total number of estimations for pair *i*.

Checking the performance of colour-difference formulas, by means of the above procedure the variability between observers is taken into account through the weighting factors, contrary to the usual procedure followed with many datasets, where only the average or another statistical figure obtained from the visual differences is considered. To work out the W*STRESS* we used all colour pairs, except the ones with a weighting factor of 0, which means that not any observer has estimated the colour difference as just noticeable, or, equivalently, that all observes agree that the colour difference is either not noticeable (score 0) or more than just noticeable (score 2). With the method explained above these color differences were not considered as this work focuses in just noticeable colour differences. Table 1 fifth column shows in bracket the numbers of pairs after removing the pairs with weighting factor equal to 0.

Table 2 shows in columns 1 and 2 the average CIELAB colour differences and corresponding standard deviations for the pairs in each centre. In this computation the pairs with weighting factor equal to 0 have been removed. However the rest of the pairs have different weights according to the observers' estimations, which just the average does not take into account. A 'weighted mean' can be computed as:

$$WMean = \frac{\sum w_i \Delta E_{ab,i}^*}{\sum w_i} \qquad (4)$$

Table 2 shows in the third column the computed values of the 'weighted mean'. Note in the last row the average values for all centres.

Table 2. Means, standard deviations and weighted means in CIELAB units for all centres and average. Values after slash correspond to Experiment R.

Centre	Mean	STDV	WMean
0000	0.58	0.09	0.57
1015(a)	0.98/1.16	0.51/0.62	0.72/1.12
1015(b)	0.87	0.16	0.84
3000(a)	1.01/1.01	0.03/0.03	1.01/1.02
3000(b)	0.90	0.19	0.91
5010(a)	0.60/0.60	0.26/0.26	0.54/0.58
5010(b)	0.87	0.13	0.88
6300(a)	0.66	0.25	0.67
6300(b)	0.80	0.13	0.79
8004(a)	0.85/0.71	0.13/0.22	0.84/0.73
8004(b)	0.62	0.09	0.63
8717	0.67	0.08	0.67
9005	1.07	0.11	1.06
9006	0.59	0.10	0.59
9106(a)	0.55/0.55	0.31/0.31	0.47/0.43
9106(b)	0.69	0.10	0.70
Average	0.77/0.79	0.23/0.39	0.76/0.75

For most of the centres there are small differences between the average (removing pairs with weighting factor 0) and weighted average. These values in Table 2 are the average of only colour differences which have been estimated as just noticeable by at least one of the observers. Thus, they could be considered as the just noticeable difference (JND) in CIELAB unit for different centres. It can be noted that almost all values are below 1 CIELAB unit, which has been considered approximately as the just perceptible colour difference [17]. Can also be noted similar values in the results of Experiment R and V, i.e. real and virtual samples.

To analyze 'a posteriori' the properness of the design of the experiments, i.e. the good election of the samples around each pair, the histograms of the weighting factors for each centre are shown in Figures 4, 5 and 6. The optimal design would correspond to weighting factors varying from 0 to 1, with most cases around 0.5, which corresponds to 50% of observers estimating the colour difference as just noticeable (score 1). More cases close to 0 than to 1 are expected because weighting factor 0 groups the extreme two types of colour differences: not noticeable difference (score 0) for all observers and noticeable difference (score 2) for all observers. On the other hand, weighting factor 1 corresponds to a just noticeable difference (score 1) for all observers, which is very difficult to reach.

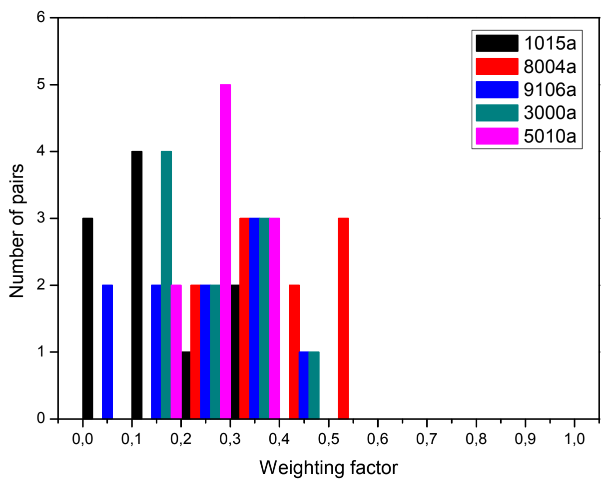

Figure 4. *Histogram of weighting factors for centres in Experiment R.*

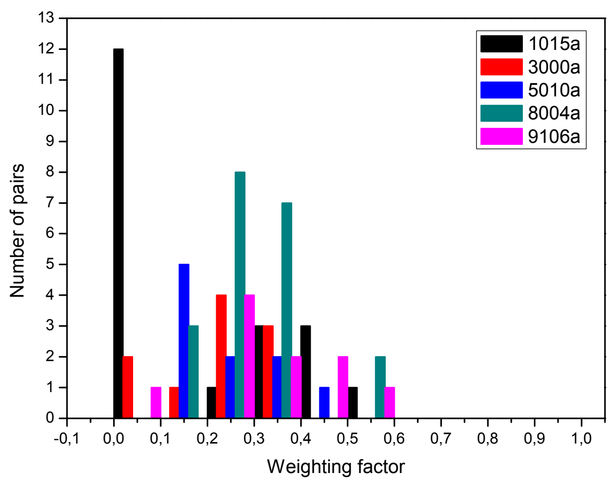

Figure 5. *Histogram of weighting factors for the centres in Experiment V shared with Experiment R.*

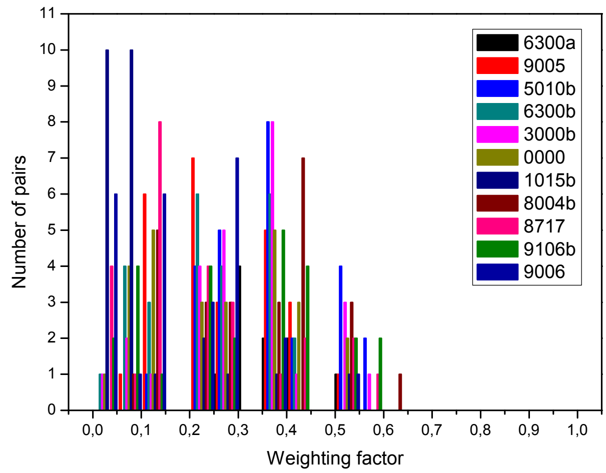

Figure 6. *Histogram of weighting factors for the the centres 6300(a), 9005, 5010(b), 6300(b), 3000(b), 0000, 1015(b), 8004(b), 8717, 9106(b) and 9006 in Experiment V.*

From Figures 4 and 5 it would be concluded a poor choice of samples for centre 1015a, which would be considered in future measurements in this centre. Besides, few colour centres have colour differences with weighting factor higher than 0.6, which means high variability between the observers estimating the just noticeable differences.

Results and Discussions

Table 3 shows the weighted *STRESS* values obtained in Experiment R, V and global. For comparison purposes *STRESS* values for the formulas in the COMData [4,18], which was used to develop CIEDE2000 formula, are shown in column 5. The second row shows the total number of pairs in each dataset and in bracket the number of pairs after removing the pairs with weighting factor equal to 0.

Table 3. *WSTRESS* values for 9 colour-difference formulas in Experiments R, V, Global, COMData and Reduced Experiment V.

	Exp. R	Exp. V	Global	COM Data	Red. Exp. V
N. of pairs	50 (48)	340 (307)	390 (355)	11273	70 (62)
CIELAB	44.89	28.48	31.35	43.93	43.55
CIEDE2000	56.16	41.05	43.32	27.49	53.91
OSA-GP	55.65	38.74	41.35	29.70	54.09
OSA-GPE	54.69	40.85	42.86	29.48	53.48
DIN99d	52.03	40.51	42.12	29.24	49.59
CAMO2-SCD	50.18	37.30	39.12	28.46	42.54
CAM02-UCS	48.98	34.60	36.72	29.08	41.38
CIE94	52.73	34.99	37.71	32.07	50.34
CMC	49.93	43.94	44.76	30.64	48.66

It can be noted that all formulas performed considerably better in Experiment V than R. The different number of both centres and pairs (see Table 1) between Experiment R and V could be the reason. A small number of pairs would lead to a deficient evaluation of the statistical index *STRESS*. For a more meaningful comparison between Experiments R and V a reduced set of Experiment V has been considered, containing only the same centres of Experiment R, but different number of pairs. The STRESS values computed in this subset, shown in column 6 of Table 3, are now very close to the values for Experiment R. For the global set, the values are close to Experiment V, with much higher number of pairs than Experiment R.

Table 3 also shows that all formulas, except CIELAB, perform worse in both Experiments R and V than in COMData. However, considering the range 0-1 CIELAB unit in the COMData, similar values of *STRESS* have been reported [10]. Therefore, the range of colour differences is a critical question in the performance of colour-difference formulas. Thus, additional research would be desirable to adjust the colour difference formulas in this small colour differences range.

Table 4 shows the study of statistical significance from values of *STRESS* shown in Table 3 for Experiments R (rows 1 to 10) and V (rows 15 to 24). Surprisingly, CIELAB is either better or significantly better than any other formula for this data. Among the others, CAM02-UCS performs quite better than the rest, and also CIE94 only in Experiment V. CIEDE2000 is the formula performing worst in general, except in Experiment V where CMC is the worst.

Table 4. Statistical significance of the differences between any two colour-difference formulas for Experiment R (*N*=48, F_C=0.561, 1/F_C=1.784) and Experiment V (*N*=307, F_C=0.799, 1/F_C=1.252)

Experiment R	CIELAB	CIEDE2000	OSA-GP	OSA-GPE	DIN99d	CAMO2-SCD	CAM02-UCS	CIE94	CMC
CIELAB	1.000	0.639	0.650	0.674	0.744	0.800	0.840	0.725	0.808
CIEDE2000	1.566	1.000	1.018	1.055	1.165	1.253	1.315	1.134	1.266
OSA-GP	1.537	0.982	1.000	1.035	1.144	1.230	1.291	1.114	1.243
OSA-GPE	1.485	0.948	0.966	1.000	1.105	1.188	1.247	1.076	1.200
DIN99d	1.343	0.858	0.874	0.905	1.000	1.075	1.128	0.973	1.086
CAMO2-SCD	1.250	0.798	0.813	0.842	0.930	1.000	1.049	0.905	1.010
CAM02-UCS	1.191	0.761	0.775	0.802	0.886	0.953	1.000	0.863	0.962
CIE94	1.380	0.882	0.898	0.930	1.027	1.104	1.159	1.000	1.116
CMC	1.237	0.790	0.805	0.833	0.921	0.990	1.039	0.896	1.000
	Formula shown in the row is significantly better than the one given in the column.								
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	Formula shown in the row is significantly worse than the one given in the column.								
Experiment V	CIELAB	CIEDE2000	OSA-GP	OSA-GPE	DIN99d	CAMO2-SCD	CAM02-UCS	CIE94	CMC
CIELAB	1.000	0.481	0.541	0.486	0.494	0.583	0.678	0.663	0.420
CIEDE2000	2.077	1.000	1.123	1.010	1.027	1.211	1.408	1.376	0.873
OSA-GP	1.850	0.890	1.000	0.899	0.914	1.079	1.254	1.226	0.777
OSA-GPE	2.057	0.990	1.112	1.000	1.017	1.199	1.394	1.363	0.864
DIN99d	2.023	0.974	1.094	0.984	1.000	1.180	1.371	1.340	0.850
CAMO2-SCD	1.715	0.826	0.927	0.834	0.848	1.000	1.162	1.136	0.721
CAM02-UCS	1.475	0.710	0.798	0.717	0.729	0.860	1.000	0.977	0.620
CIE94	1.509	0.727	0.816	0.734	0.746	0.880	1.023	1.000	0.634
CMC	2.379	1.145	1.286	1.157	1.176	1.387	1.613	1.576	1.000

Conclusions

The performance of recent colour-difference formulas has been checked in the specific region of just noticeable colour differences. For this goal, a new experimental dataset, formed by very small colour differences, and the weighted *STRESS* index have been employed, assigning different weight to each colour difference based on the answers of the observers. The dataset combines data from two different experiments, one with surface specimen observed in a light booth and the other with virtual samples displayed in a LCD monitor.

All the analyzed colour-difference formulas perform quite badly in this region, agreeing with former studies realized in the context of CIE TC1-63. It seems that the most recent colour-difference formulas, which outperform CIELAB in most of the data sets, are not well fitted to this particular colour difference magnitude. These results encourage the research about the validity of colour difference formulas in the range 0 to 1 CIELAB unit, and the subsequence fit of the formulas in this region.

Aknowlegments

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Author Biography

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