Evaluation of Performance of Twelve Color-Difference Formulae Using Two NCSU Experimental Datasets

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Abstract

We previously reported the performance of four color difference equations around the CIE 1978 blue color center (NCSU-B1) using various statistical measures [1,2]. In this study we employed the standardized residual sum of squares (STRESS) [3] index to test the performance of twelve color-difference formulae using two experimental NCSU datasets. The first dataset (NCSU-B1) included 66 sample pairs around the CIE 1978 blue color center and the second dataset (NCSU-2) contained 69 sample pairs around 13 color centers [4]. In the first dataset 26 observers made a total of 5148 assessments of sample pairs with small color differences ($\Delta E^*_{ab}<5$) while the second dataset involved 20,700 assessments by 100 observers from four different geographical regions of the world (25 in each region). Each pair in both sets was assessed by each color normal observer in three separate sittings on separate days and the average of assessments was calculated. For the samples in the first dataset a custom AATCC standard gray scale was employed to assess the magnitude of difference between colored samples. A third-degree polynomial equation was used to convert gray scale ratings to visual differences (ΔV). In the second study a novel perceptually linear gray scale was developed and a linear function was used to obtain visual differences. Based on the analysis of STRESS index results the DIN99d equation gave the best results for both datasets, and the CIELAB equation the worst.

Keywords: CIE TC1-55, color difference, visual dataset, gray scale, CIEDE2000, statistical significance, performance

Introduction

An objective color difference formula that accurately represents average perceptual assessments of subjects is a desirable tool for color quality control of various materials, and is critical for effective electronic communication of colorimetric data. Existing formulae are based on several different sets of perceptual data that have been established under various experimental conditions, using a diverse range of assessors and substrates. One of the most important aspects of successful industrial colorimetry is the development of an accurate relationship between visual assessment of the perceived differences between two color stimuli and a model designed to predict the average perceived magnitude of such differences. During the last several decades, more than 40 color difference formulae have been developed [5-11]. These formulae have as a primary goal the generation of a single number color difference value (ΔE) representing the overall magnitude of perceived color difference between two stimuli, and are generally obtained from visual pass/fail (accept/reject) decisions, or from just noticeable perceptibility experiments. Formulae have also been developed in an attempt to obtain the best performing color difference model that has general applicability in industrial color technology.

Recently, Luo, Cui, and Rigg [12] reported the development of a formula, which in 2001 was adopted by the CIE as a general formula for color differences [13], known as CIEDE2000. The formula was optimized against four independent sets of perceptual color difference data [10-12, 14-16] with a primary objective to improve the correlation with visual assessment for blues, dark colors and near neutral colors. The CIEDE2000 model also revised correction factors for the chroma, hue, and chroma hue-angle positions. It is highly desirable to test color-difference formulae using experimental datasets that are different to those employed at their developments. Accordingly, new reliable experimental datasets on color differences have been requested by CIE Technical Committee 1-55 [17], to pave the way for the development of a uniform color space for industrial color-difference evaluation.

As a part of a larger study conducted at North Carolina State University, two experimental visual datasets were developed to analyze the performance of various color difference equations and contribute to the development of a uniform color space for industrial color difference evaluations.

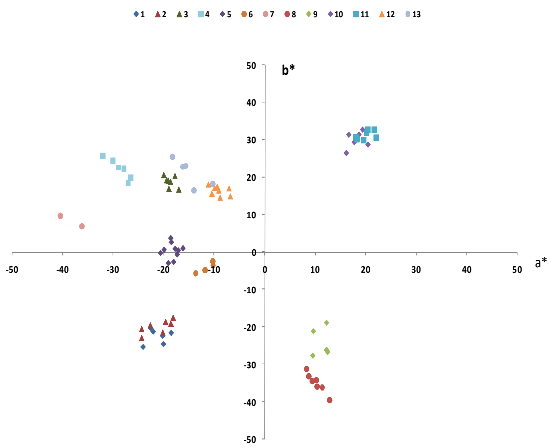

***Figure 1.** Location of samples representing the NCSU-2 dataset in the CIE a*b* plane.*

The positions of samples in NCSU-2 dataset are shown in Figure 1. This paper reports the results of that endeavor.

Visual Assessment Methodology

For the development of the NCSU-B1 dataset 26 observers (16M, 10F) were employed [1,2]. In the development of NCSU-2 dataset a total of 100 observers (37M, 63F) from four different regions of the world, as shown below, participated in the visual assessments [4]:

South America: Twenty-five observers from Colombia (mostly students of LaSalle College in Bogotá: 6M, 19F) with an average age of 21 ranging from 16 to 44. All the participants were native Colombians.

Europe: Twenty-five observers from the Czech Republic (mostly students of Technical University of Liberec, Liberec: 4M, 21F) with an average age of 28 ranging from 11 to 64. All the participants were native Czechs and some of the observers had prior experience in assessing color.

North America: Twenty-five observers participated from the USA (mostly students, faculty and staff of the Rochester Institute of Technology (RIT), Rochester, New York: 15M, 10F) with an average age of 34 ranging from 22 to 67. The participants in this panel, however, were from different cultural, ethnic and geographical backgrounds. In addition, some of the observers in this panel also had prior experience in assessing color differences.

Asia: Twenty-five native Chinese observers in the USA (students and staff at North Carolina State University: 12M, 13F) with an average age of 30 ranging from 22 to 50 also participated in the study.

For the methodology described, each subject wore a mid-gray laboratory coat and a pair of gloves to minimize color variability of the surround during the course of the experiment and to prevent damaging the samples. The samples were placed by the experimenter who also wore a mid-gray laboratory coat. At the beginning of the experiment, the subject viewed the empty illuminated viewing booth for 2 minutes to adapt to the light source; during which time the experiment was explained.

Each observer assessed NCSU-2 samples three times with at least 24 hours between assessments. There was a 2" gap between the pair of colored samples and the gray scale beneath them. The visual assessments were conducted under well controlled viewing and illumination conditions using a SpectraLight III (X-Rite) viewing booth with calibrated filtered incandescent daylight simulator. All extraneous light sources were excluded during the assessments. A novel perceptually linear gray scale was developed and used for visual assessments [4, 18]. The viewing/illumination geometry, including the gray scale used is shown in Figure 2.

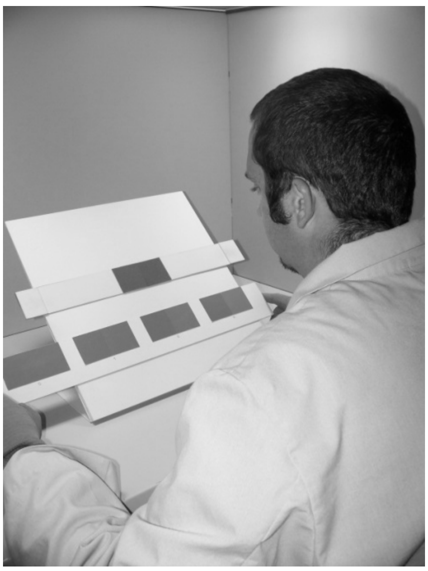

Figure 2. *Sample stand, viewing and illumination arrangements used in the NCSU-2 dataset employing a perceptually linear gray scale.*

All observers were tested for normal color vision using the Ishihara confusion plates (NCSU-B1) [19] or the Neitz test (NCSU-2) [20].

Description and Measurement of Samples

All color samples were produced on 100% knitted polyester fabrics using commercial disperse dyes stable to light and weathering, and a conventional dyeing method. Fabrics were precision cut into 2 × 2 inch dimensions for visual assessment after dyeing. The knit structure was oriented during the preparation of the samples to ensure maximum visual uniformity of all mounted samples. CIE illuminant D65 and CIE 1964 Supplementary Standard Observer were used for all colorimetric calculations. The reflectance of all samples was measured using a Datacolor SF600X spectrophotometer with a large area view aperture, UV light was excluded and specular light was included. Each sample was folded into 4 layers to ensure opacity and was measured a total of 8 times and averaged. Samples were rotated 90° and repositioned after each reading to reduce measurement variability due to fabric construction, directionality of yarns, and non-uniformity in dyeings. The 69 sample pairs used in the NCSU-2 dataset had an average ΔE^*_{ab} of 3.37, with a range of 0.56-7.57. Details of the NCSU-B1 dataset have been previously reported [1, 2, 21]. Figure 3 shows the histogram of all samples representing the NCSU-B1 and NCSU-2 datasets.

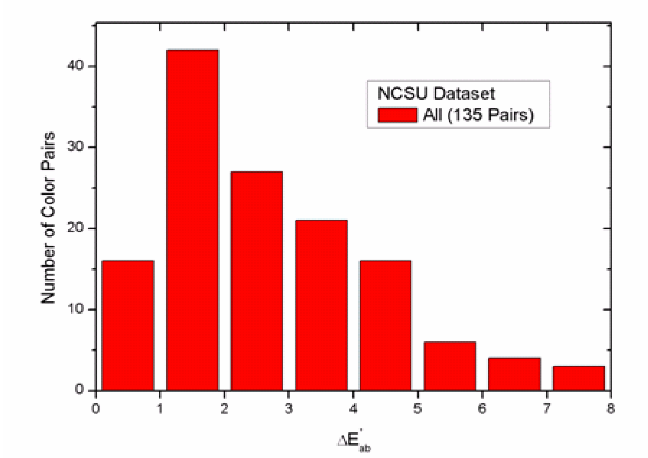

Figure 3. *Histogram of combined samples from two NCSU-B1 and NCSU-2 datasets as a function of CIELAB color differences.*

Conversion of Gray Scale Evaluations to Visual Difference

Visual differences for the NCSU-B1 dataset were obtained using a custom AATCC standard gray scale for color change [22] and a third degree polynomial equation that converted gray scale ratings to visual differences (ΔV) [21]. For the NCSU-2 dataset a linear gray scale developed at NC State and verified by a panel of 25 observers in three independent trials was used [18]. In this perceptually linear gray scale the difference in contrast between gray pairs increases in a perceptually linear manner as shown in Figure 4. A prototype example of the scale in smaller size for comparison with the AATCC gray scale for color change is shown in Figure 5. In the visual assessment each sample of the gray scale pair was cut to 2 × 2 inch dimensions to generate a similar image size to that of the colored samples as shown in Figure 2.

In the gray scale used samples exhibit a color difference (ΔE^*_{ab}) against standard in 9 steps from 0 to 7.50 as shown in Figure 4. For the analysis, the raw data in grade units, G, were transformed to visual difference, ΔV, for each pair using Equation 1.

$$\Delta V = 0.8302G + 0.1122 \qquad (1)$$

The equation was obtained by fitting a linear regression between measured ΔE^*_{ab} and the perceptually linear gray scale grades. The average visual response from all observers in each location was calculated for each sample pair.

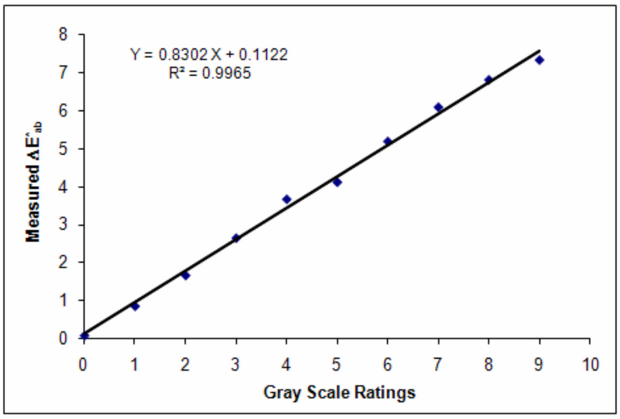

***Figure 4.** Linear transformation of gray scale ratings to visual color differences.*

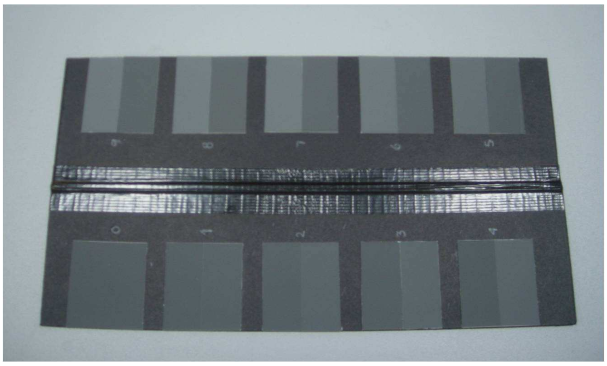

***Figure 5.** Prototype perceptually linear gray scale constructed for comparison against the AATCC gray scale for color change.*

Results and Discussion

Twelve color-difference formulae are examined in the work reported here. First, CIELAB, CMC and CIE94 color difference formulae [23] as well as OSA equation [24] as established models prior to the recommendation of CIEDE2000; second, CIEDE2000 as the currently recommended CIE formula [13]; and third a group of formulae including the DIN99d formula [25], the CIECAM02 color appearance model [26] which in this case is a Euclidean distance in J, aM, bM space proposed by CIECAM02, (though it is also possible to define a Euclidean distance in J, aC, bC space in CIECAM02), the CAM02's models, i.e. CAM02-SCD, CAM02-LCD and CAM02-UCS [27], the OSA-GP's formulae, i.e. OSA-GP [28] and finally OSA-GP-Euclidean formula [29], which have all been developed since CIEDE2000. The parameters used in the CAM02´s formulae were selected according to the experimental conditions employed in NCSU experiments, i.e. L_A =89.1cd/m^2; Y_b =44.4; c =0.69; N_c =1.0; and F=1.0.

Optimization of k_L

The optimized k_L values for each formula are shown in Table I. The STRESS values were thus calculated for the two datasets at k_L = 1 as well as at optimized k_L for each formula. Results are shown in Table II.

TABLE I. Optimized k_L values for 12 color difference formulae using NCSU-B1 and NCSU-2 datasets.

	NCSU-B1	NCSU-2	Combined
CIELAB	0.7	0.7	0.7
CMC	1.3	1.2	1.3
CIE94	1.4	1.3	1.5
CIEDE2000	1.1	1.0	1.1
DIN99d	1.2	1.0	1.2
CIECAM02	0.6	0.8	0.9
CAMSCD	1.2	1.0	1.2
CAMLCD	1.2	1.1	1.2
CAMUCS	1.2	1.1	1.2
OSA	1.1	1.2	1.3
OSA-GP-Eu	1.1	1.0	1.1
OSA-GP	1.2	1.1	1.2

TABLE II. Summary of STRESS results at k_L =1 and Optimized k_L for 12 color difference formulae using NCSU-B1 and NCSU-2 datasets.

	k_L = 1			**k_L = Opt.**		
STRESS	NCSU-B1	NCSU-2	All	NCSU-B1	NCSU-2	All
CIELAB	35.0	25.5	33.8	33.8	23.0	32.8
CMC	27.4	16.5	26.7	26.3	15.8	25.8
CIE94	28.9	18.4	30.4	26.9	15.8	28.0
CIEDE2000	21.2	16.1	24.5	21.1	16.1	24.3
DIN99d	**19.1**	**15.6**	**21.8**	**18.7**	**15.5**	**21.3**
CIECAM02	24.9	22.2	26.9	23.2	21.0	26.7
CAM02-SCD	20.4	17.7	24.9	19.9	17.7	24.5
CAM02-LCD	22.8	18.1	25.1	22.4	17.8	24.3
CAM02-UCS	21.3	17.7	25.1	20.6	17.4	24.2
OSA	28.4	24.2	30.2	28.4	23.3	28.9
OSA-GP-Eu	21.0	19.2	24.3	20.9	19.2	24.3
OSA-GP	20.1	19.9	25.0	19.8	19.8	24.3

Results in these tables include 12 sample pairs with 8>ΔE^*_{ab}>5. The combined dataset included 135 sample pairs in total. The STRESS values were also separately calculated for each dataset as well as for data excluding samples that had ΔE^*_{ab}> 5 color differences. Table II shows that the STRESS values for NCSU-B1 dataset are considerably larger than those for the NCSU-2 dataset under both k_L values. Results shown in Table II indicate that the performance of CIEDE2000 is improved in comparison to CIELAB and also CIE94 in most cases. It can also be seen that the optimization of k_L slightly reduces STRESS values, as expected. In addition, we found that results improve when sample pairs exhibiting ΔE^*_{ab}>5 are excluded. The performance of DIN99d color-difference formula, as determined by STRESS index in almost all cases, shown in bold in Table II, is better than other formulae.

In addition, STRESS values were calculated for CIEDE2000 and five CIEDE2000-reduced models. In each of the reduced models one of the correction factors introduced to CIELAB equation was removed which is expected to result in an increase in STRESS values. In other words the performance of the reduced models in comparison to the CIEDE2000 formula would be expected to become worse. Results are shown in Table III.

TABLE III. Computation of STRESS values for data from NCSU-B1 and NCSU-2 datasets for CIEDE2000 and five reduced CIEDE2000 models.

STRESS	Combined	NCSU-B1	NCSU-2	Excluding $\Delta E^*_{ab}>5$
CIEDE2000 Full Model	**24.5**	21.2	16.1	23.4
CIEDE2000-Lightness	26.0	22.6	16.8	25.8
CIEDE2000-Chroma	36.5	35.1	30.8	33.3
CIEDE2000-Hue	26.3	19.0	19.6	26.9
CIEDE2000-Rot.Term	25.4	25.4	15.2	25.1
CIEDE2000-Gray	24.9	21.5	16.6	23.9

Based on the results reported in Table III it can be concluded that:

1. The performance of CIEDE2000 for the combined NCSU-B1 and NCSU-2 datasets shown in bold (24.5) is similar to those reported previously [30].
2. Also in agreement with previous results, is the fact that the most important correction to CIELAB is the chroma correction: STRESS increases at least 10 units in the 4 previous datasets when this correction is suppressed. The remaining 4 corrections to CIELAB are also efficient in that STRESS generally increases when they are removed.
3. For NCSU-B1 dataset suppressing the hue correction term and for NCSU-2 dataset suppressing the rotation correction term reduces the performance of CIEDE2000 model, however, the difference in performance with the full model is not statistically significant. For the combined dataset containing samples with $\Delta E^*_{ab} < 5$, however, both of these correction terms improve the performance of the CIEDE2000 model.
4. After chroma correction, for the NCSU-B1 dataset, the rotation term is the most important correction and STRESS increases 4.2 units in the reduced model which shows the inclusion of rotation term for blue samples improves the performance of the model.
5. When sample pairs exhibiting color differences greater than 5.0 CIELAB units are removed, the performance of all the formulae slightly improves in comparison to the combined dataset including these samples. This supports the recommendation that CIEDE2000 is most suitable for use when color differences are smaller than or equal to 5.0 CIELAB units.
6. STRESS values calculated for CIEDE2000 using the NCSU-2 dataset are considerably lower than those for the NCSU-B1 dataset. It seems that predictions in the blue region of the CIELAB space are still challenging for most color-difference formulae, including CIEDE2000.

Assessment of Statistical Significance of Differences amongst Tested Formulae

A key question in relation to the performance of color difference equations is whether a new formula is statistically significantly better than another. F-tests using STRESS values [3] can be employed to determine the significance of variation between two formulae.

Previously we reported a comparison of the performance of CIEDE2000 against CIELAB, CMC, CIE94 and BFD formulae using NCSU-B1 dataset [21]. In addition, we examined NCSU-B1 dataset against four established datasets namely, BFD-P [14], Leeds [15], RIT-Dupont [11] and Witt [16]. In this study the performance of twelve color difference formulae was compared against each other using the F test to determine the statistical significance of any improvement in performance of any given equation against another. Results of this assessment are shown in Table IV for the combined set of samples used in NCSU-B1 and NCSU-2 datasets. Table V shows the results for the combined dataset with samples containing $\Delta E^*_{ab} < 5$ CIELAB units as a comparison. A 95% confidence level has been assumed in both tables. In both Tables IV and V optimized k_L values were employed.

TABLE IV. Significance test using combined NCSU-B1 and NCSU-2 datasets (N=135, F_C=0.712, $1/F_C$=1.405).

	CIELAB	CMC	CIE94	CIEDE2000	DIN99d	CIECAM02	CAMSCD	CAMLCD	CAMUCS	OSA	OSA-GP-Eu	OSA-GP
CIELAB	1.000	***0.618***	0.730	***0.549***	***0.423***	***0.661***	***0.557***	***0.548***	***0.544***	0.777	***0.547***	***0.550***
CMC	***1.618***	1.000	1.181	0.888	***0.684***	1.070	0.901	0.888	0.880	1.258	0.885	0.891
CIE94	1.370	0.847	1.000	0.752	***0.579***	0.906	0.763	0.752	0.745	1.065	0.750	0.754
CIEDE2000	***1.822***	1.126	1.329	1.000	0.770	1.205	1.015	0.999	0.991	***1.416***	0.997	1.003
DIN99d	***2.366***	***1.462***	***1.726***	1.299	1.000	***1.564***	1.317	1.298	1.287	***1.839***	1.294	1.302
CIECAM02	***1.512***	0.934	1.104	0.830	***0.639***	1.000	0.842	0.829	0.822	1.176	0.827	0.832
CAMSCD	***1.796***	1.110	1.310	0.986	0.759	1.187	1.000	0.985	0.977	1.396	0.982	0.988
CAMLCD	***1.823***	1.127	1.330	1.001	0.771	1.206	1.015	1.000	0.992	***1.417***	0.997	1.003
CAMUCS	***1.839***	1.136	1.342	1.009	0.777	1.216	1.024	1.008	1.000	***1.429***	1.006	1.012
OSA	1.287	0.795	0.939	***0.706***	***0.544***	0.851	0.716	***0.706***	***0.700***	1.000	***0.704***	***0.708***
OSA-GP-Eu.	***1.828***	1.130	1.334	1.003	0.773	1.209	1.018	1.003	0.994	***1.421***	1.000	1.006
OSA-GP	***1.817***	1.123	1.326	0.997	0.768	1.202	1.012	0.997	0.988	***1.412***	0.994	1.000

TABLE V. Significance test using NCSU-B1 and NCSU-2 datasets excluding samples with ΔE^*_{ab} >5 (N=122, F_C=0.699, $1/F_C$=1.431).

	CIELAB	CMC	CIE94	CIEDE2000	DIN99d	CIECAM02	CAMSCD	CAMLCD	CAMUCS	OSA	OSA-GP-Eu	OSA-GP
CIELAB	1.000	0.709	0.834	***0.520***	***0.393***	***0.583***	***0.494***	***0.481***	***0.473***	0.794	***0.556***	***0.586***
CMC	1.410	1.000	1.176	0.733	***0.555***	0.823	***0.697***	***0.678***	***0.667***	1.119	0.784	0.826
CIE94	1.199	0.850	1.000	***0.623***	***0.472***	0.700	***0.592***	***0.576***	***0.567***	0.952	***0.667***	0.703
CIEDE2000	***1.925***	1.365	***1.605***	1.000	0.757	1.123	0.951	0.925	0.910	***1.527***	1.070	1.128
DIN99d	***2.543***	***1.803***	***2.121***	1.321	1.000	***1.483***	1.256	1.222	1.202	***2.018***	1.414	***1.490***
CIECAM02	***1.715***	1.216	1.429	0.891	***0.674***	1.000	0.847	0.824	0.810	1.361	0.953	1.005
CAMSCD	***2.025***	***1.436***	***1.688***	1.052	0.796	1.181	1.000	0.973	0.957	***1.607***	1.125	1.186
CAMLCD	***2.081***	***1.475***	***1.735***	1.081	0.818	1.214	1.028	1.000	0.983	***1.651***	1.157	1.219
CAMUCS	***2.116***	***1.500***	***1.764***	1.099	0.832	1.234	1.045	1.017	1.000	***1.679***	1.176	1.240
OSA	1.260	0.894	1.051	***0.655***	***0.495***	0.735	***0.622***	***0.606***	***0.596***	1.000	0.700	0.738
OSA-GP-Eu.	***1.799***	1.276	***1.500***	0.935	0.707	1.049	0.889	0.865	0.850	1.428	1.000	1.054
OSA-GP	***1.707***	1.210	1.423	0.887	***0.671***	0.995	0.843	0.820	0.807	1.354	0.949	1.000

In Tables IV and V, light red cells indicate that the formula shown in the row is significantly better than the one given in the column and the dark cells denote improvement in performance is insignificant between the models tested. In addition light olive cells indicate that the performance of the formula shown in the row is significantly worse than the one given in the column. Again dark olive cells signify the deterioration in performance is insignificant.

Results shown in Tables V and VI indicate that DIN99d color difference formula has superior performance compared to all the other equations examined for the combined NCSU-B1 and NCSU-2 datasets. Results based on CAM02-UCS are also very similar. In addition, it can be seen that OSA-UCS and OSA-GP perform relatively well, although their performance is not better than DIN99d or CAMSCD. As expected CIEDE2000 performs significantly better than CIELAB and CIE94 for the dataset excluding samples with ΔE^*_{ab} >5, however, the performance of CIEDE2000 in comparison to more recent formulae in almost all cases is worse, although the difference is not always statistically significant.

Conclusions

For the NCSU-B1 blue dataset as well as NCSU-2 general dataset, assessments based on the standardized residual sum of squares (STRESS) index show that at both k_L =1 and optimized k_L, the DIN99d equation outperforms all the other equations tested in this study. In the case of CIEDE2000 formula, suppression of any of the five correction factors introduced to CIELAB formula considerably lowers the performance of the model with the most important factor being that of chroma correction. In the case of NCSU-B1, the rotational correction is also important; however, in general the STRESS values for NCSU-B1 dataset are relatively high, indicating that an accurate prediction of color in the blue region is still a challenge.

There is a statistically significant improvement in the performance of CIEDE2000 against those of CIELAB and CIE94 models for the complete dataset containing color pairs exhibiting ΔE^*_{ab} < 5 units. For the combined dataset the performance of DIN99d against any other model is improved, however, while this improvement is statistically significant against CIELAB, CMC, CIE94, CIECAM02 and OSA models, it is statistically insignificant against CIEDE2000, CAM02-SCD, CAM02-LCD, CAM02-UCS, OSA-GP-Euclidean and OSA-GP color-difference equations. The main findings are valid when sample pairs exhibiting color differences of ΔE^*_{ab} > 5 are removed from the dataset. The main difference in results when samples with larger color differences are excluded is that the improved performance of DIN99d against OSA-GP also becomes statistically significant.

Acknowledgments

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References

[1]. Shamey R., S.G. Lee, D Hinks, W Jasper "Performance of Recent Color Difference Equations around a CIE Blue Color Center" 4th European Conference on Colour in Graphics, Imaging, and Vision, 10th International Symposium on Multispectral Colour Science, 7-11 June (2008) Terrassa, Spain.

[2]. S.G. Lee, "Assessment of Metrics in Color Spaces". Master Thesis (North Carolina State University, 2007).

[3]. P. A. García, R. Huertas, M. Melgosa, and G. Cui, "Measurement of the relationship between perceived and computed color differences," J. Opt. Soc. Am. A. 24, 1823-1829 (2007).

[4]. L.M. Cardenas, "Evaluation of Variability in Visual Assessment of Small Color Differences" PhD Dissertation (North Carolina State University, 2009).

[5]. Commission Internationale de l'Eclairage. Colorimetry, 2nd edition; CIE Publication No. 15.2; CIE: Vienna, Austria, (1986).

[6]. M. R. Luo "Development of colour-difference formulae." Rev. Prog. Coloration, 32, 28, (2002).

[7]. Rolf G. Kuehni, Color Space and Its Divisions: Color Order from Antiquity to the Present; John Wiley & Sons. Inc: New York, NY, (2003); pp 204-270.

[8]. F. J. J. Clarke; McDonald, R.; Rigg, B. “Modification to JPC79 colour-difference formula.” J. Soc. Dyers Col. 100, 128, (1984).
[9]. M. R. Luo; Rigg, B. “BFD (l:c) colour difference formula, Part I- Development of the formula”. J. Soc. Dyers Col. 103, 86, (1987).
[10]. D.H. Alman; Berns, R. S.; Snyder, G. D.; Larsen, W. A. Performance Testing of Color Difference Matrices Using a Color Tolerance Dataset, Color Res. Appl., 14, 139, (1989).
[11]. R. S. Berns; Alman, D. H.; Reniff, L.; Snyder, G. D.; Balonon-Rosen, M. R. Visual Determination of Supra Threshold Color-Difference Tolerances Using Probit Analysis, Color Res. Appl., 16, 297-315, (1991).
[12] M. M. R. Luo, G. Cui, and B. Rigg, “The development of the CIE colour-difference formula: CIEDE2000,” Color Res. Appl., 26, 340-350 (2001).
[13] CIE, Improvement to Industrial Colour-Difference Evaluation, CIE Publ. 142 (CIE Central Bureau 2001).
[14] M. R. Luo and B. Rigg, “Chromaticity-discrimination ellipses for surface colors,” Color Res. Appl. 11, 25-42 (1986).
[15] D. H. Kim and J. H. Nobbs, New weighting functions for the weighted CIELAB colour difference formula, Proc. AIC Colour 97, Vol. 1, pp. 446-449 (1997).
[16] K. Witt, “Geometric relations between scales of small colour differences,” Color Res. Appl. 24, 78-92, (1999).
[17] M. Melgosa, “Request for existing experimental datasets on color differences,” Color Res. Appl. 32, 159 (2007).
[18] L M Cardenas, R Shamey (advisor), and D Hinks (advisor), 'Development of a Novel Linear Gray Scale for Visual Assessment of Small Color Differences', AATCC Review, 9 (8) 2009, 42-47.
[19]. American Optical Company, Pseudo-Isochromatic Plates for Testing Color Perception, Beck Engraving Company, Inc.: New York, PA.
[20] J. Neitz, Manual: Neitz Test of Color Vision (Western Psychological Services, 2001).
[21] S.G. Lee, R. Shamey, D. Hinks, and W. Jasper. “Development of a comprehensive visual dataset based on a CIE blue color center: assessment of color difference formulae using various statistical methods,” Color Research and Application, published online Nov 10, 2009, DOI: 10.1002/col.20549.
[22] AATCC, Evaluation Procedure 9-2002, “Visual assessment of color difference of textiles,” in AATCC Technical Manual 82, (AATCC, 2007). pp. 394-396.
[23] CIE 15:2004, 3rd Edition (CIE Central Bureau 2004).
[24] D.L. MacAdam "Uniform Color Spaces" JOSA 64, 1691-1702 (1974)
[25] G. Cui, M. R. Luo, B. Rigg, G. Roesler, and K. Witt, “Uniform colour spaces based on the DIN99 colour-difference formula,” Color Res. Appl. 27, 282-290 (2002).
[26] CIE Publication 159:2004, 3rd Edition (CIE Central Bureau 2004).
[27] M. R. Luo, G. Cui, and C. Li, “Uniform colour spaces based on CIECAM02 colour appearance model,” Color Res. Appl. 31, 320-330 (2006).
[28] R. Huertas, M. Melgosa, and C. Oleari, “Performance of a color-difference formula based on OSA-UCS space using small-medium color differences,” J. Opt. Soc. Am. A 23, 2077-2084 (2006).
[29] Oleari, M. Melgosa, and R. Huertas, “Euclidean color-difference formula for small-medium color differences in log-compressed OSA-UCS space,” J. Opt. Soc. Am. A 26, 121-134 (2009).
[30] M. Melgosa, R. Huertas, R.S. Berns, “Performance of recent advanced color-difference formulas using the standardized residual sum of square,” J. Opt. Soc. Am. A 25, 1828-1834, 2008).

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