Performance of Recent Color Difference Equations around a CIE Blue Color Center

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Abstract

In 2004, an ISO committee found that insufficient data were available to make a decision on whether to recommend CIEDE2000 in place of DE_{CMC}. However, a provisional work item was initiated [1] to test independently the performance of the major color difference formulae specifically in the blue and near neutral regions. Accordingly, the objective of this work was to develop a new, comprehensive visual dataset around one blue color center, and to compare the performance of all the major formulae against the new dataset.

A total of 5148 assessments using 66 textile sample pairs with small color differences (DE<5) were obtained. Each pair was visually assessed by 26 color normal observers in three separate sittings using a gray scale method. A third-degree polynomial equation was used to convert gray scale ratings to visual differences (DV). The performance of major formulae was evaluated based on a correlation coefficient (r) and the PF/3 measure at two lightness weights (K_L or l) of 1 and 2. Correlation coefficients of 0.91, 0.92 were obtained for CIEDE2000 at K_L of 1 and 2, which were the highest amongst the color difference equations examined although at K_L (or l)=2, CIEDE2000 and BFD performed comparably. Using the PF/3 metric the BFD equation gave the best results at both lightness scales (37.46, and 42.46 respectively), however, at K_L or l =2, all major equations gave approximately the same performance.

Introduction

The ultimate goal of color management is to develop an accurate and precise integrated color control system that can be easily implemented throughout the industrial manufacturing complex. 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 (e.g. dyed textile samples) 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 [2-4]. These formulae have as a primary goal the generation of a single number color difference value, DE, 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.

The CMC formula was developed by the Society of Dyers and Colourists [5] in 1984 and is currently recommended by the ISO [6] and other organizations that oversee standards, such as the AATCC [7], ASTM [8] and SAE [9]. However, other formulae have been developed in an attempt to obtain the best performing color difference model that has general applicability in industrial color technology.

In 1987, Luo and Rigg introduced BDF(l:c) [10], a modification to the DE_{CMC} structure. In 1994 Berns et al [11-12] proposed a formula with a similar structure to that of CMC(l:c) which became known as CIE94 [13]. More recently, Luo, Cui, and Rigg [14] developed the newest formula, which in 2001 was adopted by the CIE as a general formula for color differences [15], known as CIEDE2000. The formula was optimized against five independent sets of perceptual color difference data with a primary objective to improve the correlation with visual assessment for blues, dark colors and near neutral colors.

Visual Assessment Methodology

A total of 67 blue samples including one with attributes corresponding to a CIE recommended blue color center (L*=36, a*=5, b*= -31) were produced on 100% knitted polyester fabrics using commercial disperse dyes stable to light and weathering, and 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. Dyed samples were distributed around the CIE recommended blue color center within 3.00 DE CMC(2:1) or 5.00 DE CIELAB units. Most of the samples, however, were distributed within 2.00 DE CMC(2:1) units from the color center. Samples were prepared such that the differences were mostly due to hue alone, chroma alone or lightness alone. Additional samples with variations due to a combination of hue, chroma and lightness were also obtained.

A custom made sample stand, based on a 45/0 illumination viewing geometry, was painted in neutral gray (Munsell N7.25) to house the standard and test samples as well as a gray scale pair immediately below the dyed samples. The gray scale and the viewing illumination geometry are shown in Figure 1.

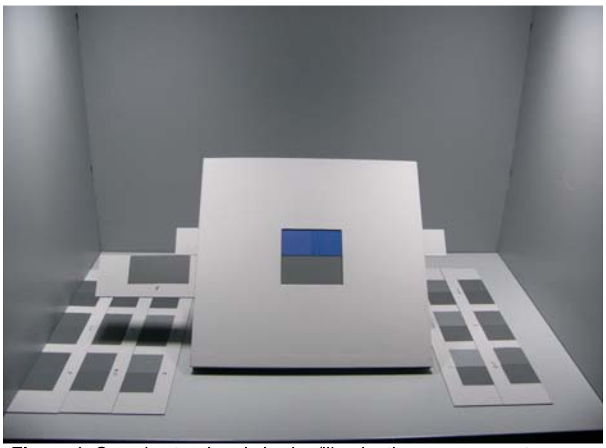

Figure 1. *Sample stand and viewing/illumination arrangements.*

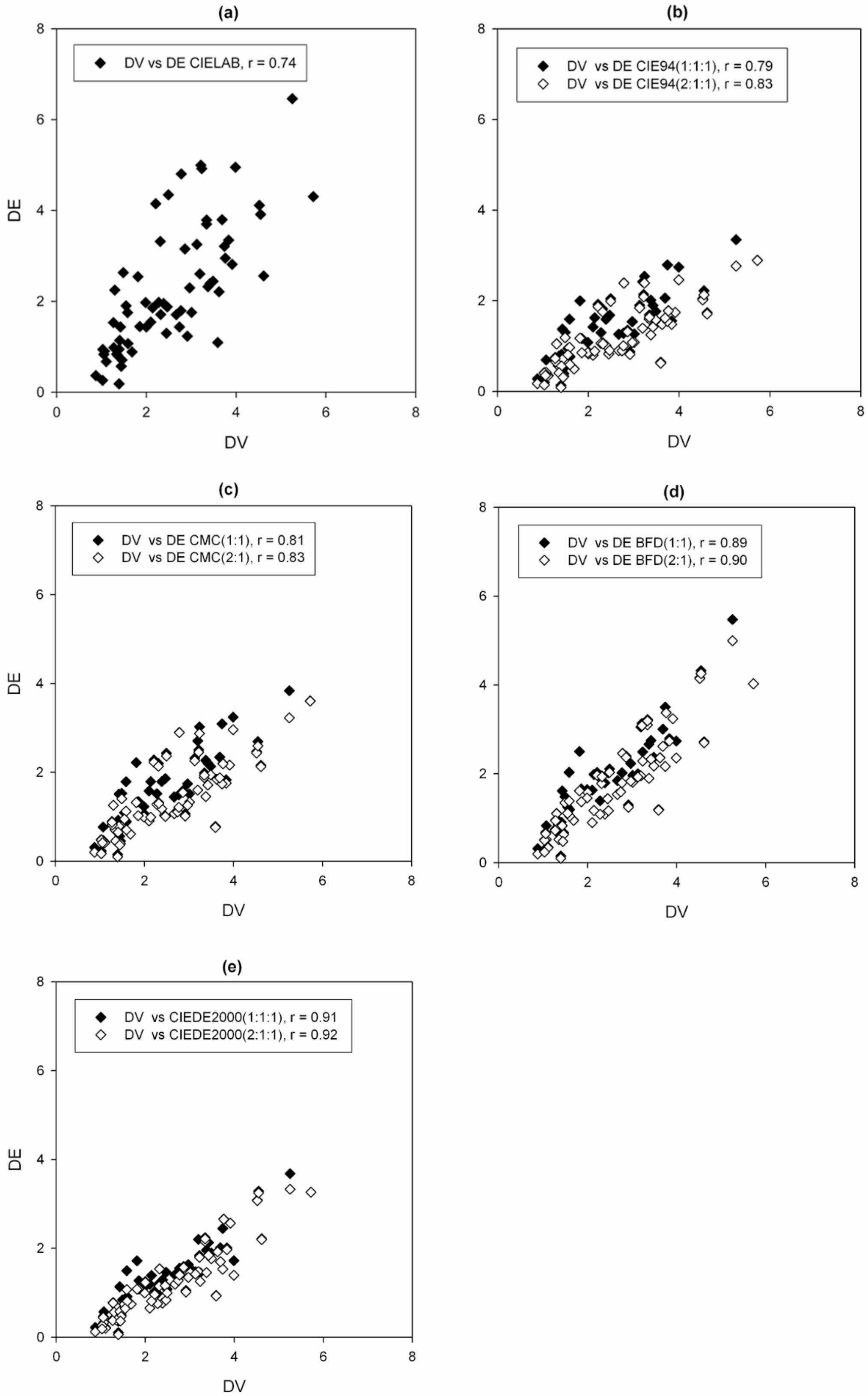

Figure 2. *Correlations between CIELab, CIE94, CMC(l:c) BFD(l:c) CIEDE2000 and ΔV at l or K_L values of 1 and 2.*

CIE illuminant D65 and CIE 10° supplemental standard observer were used for all colorimetric calculations. A Datacolor SF600X spectrophotometer with a large area view aperture was used, 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.

Reported here are results of visual assessments that were conducted using 26 observers (16M, 10F) under well controlled viewing and illumination conditions (using a calibrated filtered incandescent daylight simulator). All extraneous light sources were excluded during the assessment. All observers were tested for normal color vision using the Ishihara confusion plates [16]. Each trial consisted of 66 sample pairs divided into 2 groups with 33 random sample pairs each to avoid observer fatigue. The interval between repeat sessions was at least one week. A total of 5148 visual assessments were conducted. Standard gray scale papers, supplied by X-Rite, were used to develop an in-house gray scale for visual assessments.

Formulae Assessment Metrics

Correlation coefficient, *r*, shown in equation 1 has been used to evaluate the performance of color difference formulae [17]. The PF/3 measure, shown in equation 2, introduced by Luo and Rigg [10], has also been widely used as a performance metric. These metrics were used to assess the performance of color difference equations based on the dataset developed in this study.

$$r = \frac{N\Sigma\left(X_i Y_i\right) - \Sigma X_i \Sigma Y_i}{\sqrt{\left[N\Sigma X_i^{\,2} - \left(\Sigma X_i\right)^2\right]\left[N\Sigma Y_i^{\,2} - \left(\Sigma Y_i\right)^2\right]}} \qquad (1)$$

where X_i is the instrumental value, DE, for sample i, Y_i is the visual value, DV, for sample i, and N is the number of pairs of samples. A correlation coefficient of 1 corresponds to perfect agreement between the visual and instrumental data.

$$PF/3 = 100\left[(\gamma - 1) + V_{AB} + CV/100)\right]/3 \qquad (2)$$

CV and γ are statistical models introduced by Alder, et al [18], and V_{AB} is a model introduced by Schultz [19]. PF/3 is commonly used as a measurement of fit for testing color difference formulae. In the case of perfect agreement between visual data and instrumental data CV = 0, V_{AB} = 0, γ = 1.

Results and Discussion

Figure 2 shows graphs of correlation between DV and all color difference formulas tested for the new NCSU-Blue (NCSUB1) dataset. Visually, the largest spread in points is observed for CIELAB, while graphs of DV versus BFD and CIEDE2000 both show relatively well correlated data. This is confirmed via calculation of both r and PF/3. A summary of results of corresponding *r* and PF/3 values is shown in Table 1. Using the correlation coefficient as a metric at K_L or *l* = 1, BFD and CIEDE2000 gave the best performance, and CIELAB the worst, as shown in Table 1. The BFD equation marginally gives the best performance at K_L or *l* = 2, although, apart from CIELAB, all other equations examined in this study give approximately similar results for this K_L or *l* setting.

TABLE 1. Summary of the PF/3 results and correlation between DE using various color difference formulae and DV for the NCSU-Blue dataset.

Metric	(K_L or *l* = 1)		(K_L or *l* = 2)	
	r	PF/3	*r*	PF/3
CIELAB	0.74	50.01	N/A	N/A
CIE94	0.79	43.13	0.83	43.67
CMC	0.81	41.93	0.83	44.13
BFD	0.89	37.46	0.90	42.46
CIEDE2000	0.91	37.96	0.92	44.44

The PF/3 performance of the five color difference formulas were compared for the NCSUBlue1 visual data and also four other visual datasets, as shown in Figure 3. Using PF/3 for the models studied, at K_L or *l* = 1, CIEDE2000 performs best for three of the five datasets, namely RIT-DuPont, Witt, and Leeds, while BFD performs best for BFD-P and the NCSU-Blue dataset, as shown in Figure 3. Considering the NCSU blue data, the only dataset focused on one blue center using textile samples, BFD and CIEDE2000 perform similarly at K_L or *l* = 1 using both r and PF3. Also, both formulas perform better than CMC.

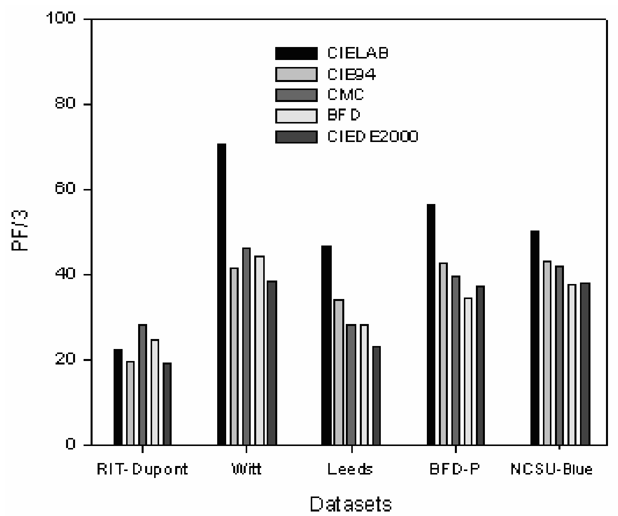

Figure 3. PF/3 results for five visual datasets based on various color difference formulae for K_L and *l* = 1.

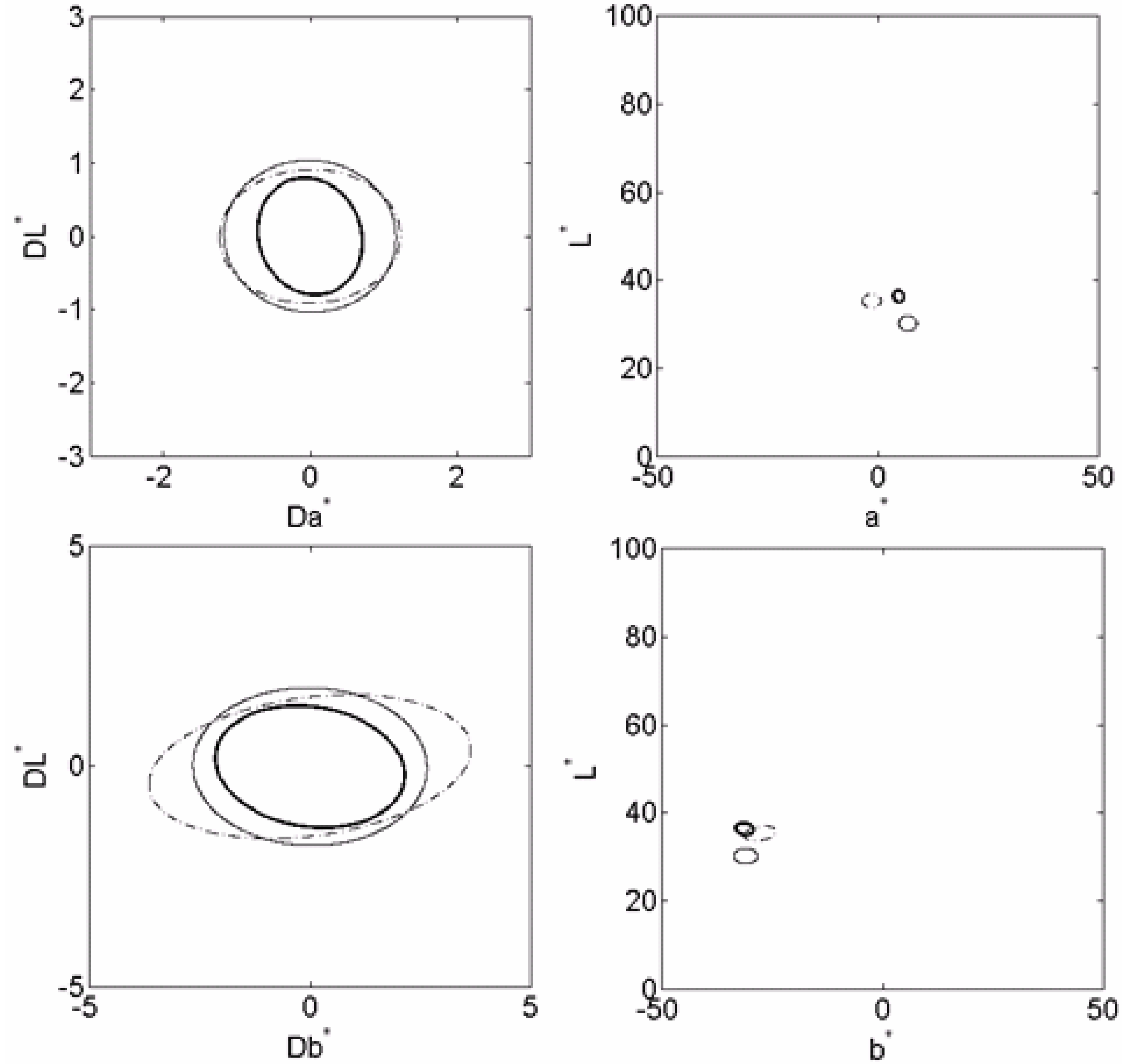

Figure 4. *Ellipses in CIE L*a* & L*b* planes, from RIT-DuPont (Moderate Blue -·- Dark Blue -), and NCSU (CIE Blue, -) datasets.*

The unit difference ellipses for the blue datasets are depicted in Figure 4. The NCSU-Blue (NCSUB1) dataset [20] was compared with four previous datasets (RIT-DuPont [12], Witt [21], Leeds [22], and BFD-P [23]) using the PF/3 metric at K_L or l = 1.

The differences in shape, orientation of the ellipses, together with the differences in correlation between formulas and the various DV sets point to the effects of key variables such as observer set and size, as well as experimental methodology and parameters used in the development of the visual datasets, including light source, sample size, texture, illuminant/observer angles, juxtaposition of samples, background lightness, hue and chroma, among others. All the major datasets varied from each other in each of these key experimental variables [20].

Conclusions:

For the blue visual dataset developed, assessments based on correlation coefficient (r) and PF/3 showed that when K_L or l is set at 1 or 2, the CIEDE2000 and BFD formula correlate comparably with DV, and perform better than CMC, CIE94 and finally CIELAB. When K_L or l is set at 2, the most common setting for the evaluation of textile samples, the BFD equation provides marginally the best performance, although all equations give PF/3 responses in a close range.

Published results obtained from other studies comparing various datasets (RIT-DuPont, Witt, Leeds, and BFD-P) also indicate that CIEDE2000 and BFD provide the best performance when the K_L or l is set at 1. However, differences between these models and CMC, for instance, are not large. And considering that recent independent testing of CIDE2000 and CMC in practical assessment methods have not shown significant differences in performance between these two models further work is required before a final decision on the whether CIEDE2000 should be established as a new standard over CMC, the current standard equation, in most standard methods, for instance in ISO, AATCC, and ASTM standards.

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Author Biography

Renzo Shamey received his BSc in 1989 and following three years of work in industry obtained his MSc(1993) and PhD (1997) from the Colour Chemistry Dept at Leeds University in England. He joined Heriot-Watt University in Edinburgh, Scotland as Lecturer in 1998. In 2003 he joined North Carolina State University (NCSU) where he is currently an Associate Professor in color science. Seung Geol Lee completed a Masters' program at NCSU in 2007. He is currently a PhD candidate at Georgia Institute of Technology, USA. David Hinks is a Leeds University Colour Chemistry graduate (Bsc 1989, PhD 1992) and an Associate Professor and PCC program director at NCSU. Warren Jasper is a Professor of Textile Engineering at NCSU.