Correlation of Visual and Instrumental Color Measurements to Establish Color Tolerance Using Regression Analysis

by

Malathy Jawahar,* Swarna V. Kanth, R. Venba and Narasimhan Kannan Chandra Babu

Council of Scientific and Industrial Research-Central Leather Research Institute,

Adyar, Chennai 600 020, India

Abstract

Color is one of the important parameter considered in the determination of quality for fashion materials like leather. The color variation in each piece of leather sample in a batch should be within the acceptable range. Visual assessment is currently used in leather industry for quality control and color sorting. The current method used is subjective and often leads to disagreement between buyer and seller. Color measurement using reflectance spectrophotometer evaluates color consistently and is an objective assessment system. However, there is always an apprehension that the instrumental color assortment may not agree with the human perception of color difference. Hence, in the present investigation, an attempt was made to screen four color difference formulae, viz., CIELAB76, CMC (2:1), CIE94 and CIE2000 for their suitability in obtaining pass/fail decisions, which would be in conformity with that of the average human observer. Regression analysis was performed to find a correlation between visual and instrumental color assessments and the results indicate that CMC(2:1) formula may be the most suited for the purpose. A detailed analysis of visual and instrumental color values revealed visual non-uniformity towards sensitivity to hue, chroma and lightness. This difference in sensitivity was also taken into consideration in instrumental color sorting and pass/fail tolerance was established that led to closer conformity between visual and instrumental methods.

Introduction

Leather manufacturers produce large consignment of leathers in a particular shade/color with a reasonable degree of accuracy to meet the requirement of a buyer. Color is a vital factor used during quality inspection of finished leathers for different end products. Nevertheless, color variations within a batch of leathers are inevitable even though dyeing/finishing is carried out with best process control systems due to heterogeneity of the substrate. Color variations with perceptible changes in the leathers need to be characterized and the batch can be assorted into acceptable and unacceptable groups to enable corrective measures. The color variations are due to inconsistency in raw material homogeneity and leather processing technology adopted that result in variations in dye diffusion and uptake. Even though hides and skins are processed and finished with organolleptic properties needed for end-use applications; the resultant leathers may be rejected, if the color does not match the buyer's sample/swatch (beyond 5% tolerance limit). Assortment of color into groups of almost similar shades is also done during the manufacture of leather products. The panels of leather product should be of same color as more than one piece of leather is used. Leather manufacturers and leather goods/garment/footwear producers consider shade-sorting as a challenge to bring in color consistency using visual assessment.

Visual evaluation of color tolerance is not consistent when establishing the fine line between acceptable color differences (maximum color difference between the standard and sample) and perceptible color differences (minimum color difference between the standard and sample). Such a highly subjective visual color assessment system[1] generally results in dispute between the buyer and the seller of the leathers. Large errors in judgment are common due to lack of experience and color vision defects of the evaluators. But error occurs even among the experienced evaluators due to ageing and fatigue. There is a growing need to shade-sort leather samples consistently with the increasing stringent demands by quality conscious customers.

Advancements in computer technology have made it possible to replace the visual evaluation with instrumental objective color measurements to obtain reproducible and reliable data that give consistent pass/fail decisions. Acceptable color limits are set as tolerances on color scales or indices such as L*a*b* (ΔL value '+' is lighter and '–' for darker, Δa is '+' for redder and '–' for greener and Δb value is '+' for yellower and '–' for bluer) and LCH (ΔL value '+' is lighter and '–' for darker, ΔC value represents the difference in chroma '+' for brighter /

*Corresponding author e-mail: malathyj@hotmail.com

Manuscript received March 15, 2015. Accepted for publication August 17, 2015.

more saturated and '–' for duller / less saturated and ΔH value represents shift in hue angle '+' for increase in hue angle and '–' for decrease in hue angle). There are several color space options available for implementing pass/fail tolerance program. Determining instrumental tolerance limit for leather is a difficult process due to variations in shade from/within customer to customer and product to product with stringent acceptance levels. Hence, it is necessary to select instrumental method that gives the best correlation with the visual color perception. Four color difference formulae, viz., CIE1976, CIE94, CIE 2000 and CMC(2:1) were selected for the present study and their suitability for color assortment for an achromatic color like grayish black was investigated. The characteristic feature of the four color formulae are summarized as follows.

CIE1976 (ΔE^*_{ab})

CIE1976 is the first color difference formula recommended by CIE (Commission de lÉclairage) for surface color evaluation and used in many color industries that include leather.[2] CIE1976 color formula is based on the CIE LAB[3] color space. In CIE LAB color notation, L* axis represents lightness value, ranging from 0 (black) to 100 (white). a* axis value is '+' for redder and 'a' value is '–' for greener; similarly b* axis value is '+' for yellower and 'b' value is '–' for bluer. There are no maximum and minimum values for a* and b*, however in practice they are numbered as -128 to + 127 (256 levels). Difference between two color samples is often expressed as Delta E, also called ΔE. ΔE values show how far the two samples are visually apart in the color sphere and is defined as an Euclidean distance in a uniform space, which include difference in lightness L*, red-green difference in terms of a* and yellow-blue difference in terms of b*. The mathematical equation to compute overall the color difference is given in Equation 1. It was reported by Mc Donald that L*a*b* color notation is not visually uniform[4] and several experimental investigations have proved that DE_{ab} CIELAB 76 does not agree well with visual perception.[5-11]

$$\Delta E_{ab} = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

CIE1994 (ΔE^*_{94})

Considerable work was also done in the area of developing color difference equations, which describe perceived color difference for practical use in coloration industry. An attempt was made by CIE in 1994 to correct the visual non-uniformity of L*a*b* by assessing lightness, chroma and hue in different proportions.[11-12] The CIE1994 color difference equation was developed based on CIE LCH color notation with two sets of coefficients (K_L, K_C, K_H and S_L, S_C, S_H) that account for effects influencing color difference judgment and CIELab's lack of visual uniformity.[13] In CIE LCH notation, L* axis represents lightness ranging from 0-100. C* axis represents chroma or intensity or 'saturation' ranging from 0-100. For unsaturated colors such as grey, black or white C*= 0. For very high chroma (saturation) or intense colors or pure colors C*=100. The h* axis represents hue and is represented in degrees. h^o is ranging from 0° (red) through 90° (yellow), 180° (green), 270° (blue) and back to 0°.

CIE 1994 (Equation 2) employs simple linear functions of chroma and hue to obtain S_C, S_H and unity to S_L. It also includes parametric assessing functions K_L, K_C and K_H[14] to provide better correlation to visual difference.[15,16] In the present study, parametric functions assumes K_L=2, K_C =1 and K_H = 1.

$$\Delta E_{94} = \sqrt{\left(\frac{\Delta L^*}{K_L S_L}\right)^2 + \left(\frac{\Delta C^*}{K_C S_C}\right)^2 + \left(\frac{\Delta H^*}{K_H S_H}\right)^2} \quad (2)$$

Where S_L = 1, S_C = 1 + 0.045C* and S_H = 1+0.015C*

CIE2000 (ΔE^*_{00})

An attempt was made to improve upon CIE 1994 equation by adding more assessing factors depending on the hue angle of the color which resulted in CIE2000.[17,18,19] CIE2000 (Equation 3) color difference equation is complicated but does not tend to show improvement in correlation with visual differences.

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)} \quad (3)$$

Color Measurement Committee (ΔE^*_{cmc})

CMC equation (Equation 4) was created by the Color Measurement Committee of the Society of Dyers and Colourists of Great Britain.[20] It is a British standard and drafted as an ISO standard[21] and used in many industries.[20,22] CMC[23,24] and CIE94 DE calculation defines a tolerance ellipsoid corresponding to hue, chroma and lightness[15] and is distinct from the rectangular co-ordinates of CIELAB color space. In CMC (2:1) (Equation 4)[17] DE is similar to the CIE94 DE (Equation 2) in terms of assessing on the lightness, chroma, and hue of the colors. CMC(2:1) equation employs hyperbolic regression analysis model to compute ellipsoidal semi-axes (lS_L, cS_C, S_H) (Equation 5, 6 and 7); l and c refers to constants 1,1 or 2,1 depending on the tolerance given to lightness and chroma co-ordinates. The size and the shape of the CMC tolerance ellipsoid vary for each color and hence ellipsoidal volume of acceptance varies.

$$\Delta E_{CMC} = \sqrt{\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*}{cS_C}\right)^2 + \left(\frac{\Delta H^*}{S_H}\right)^2} \quad (4)$$

S_L

$$-\,if\ L < 16 \rightarrow S_L = 0.511 \qquad -\ \text{if } L > 16 \rightarrow S_L = \frac{0.040975 * L}{1 + 0.01765 * L} \quad (5)$$

S_C

$$\rightarrow S_C = \frac{0.0638 * C}{1 + 0.0131 * C} + 0.638 \quad (6)$$

S_H

$$\rightarrow S_H = (FT + 1 - F) * S_C \quad \text{of which } F = \left[\frac{C^4}{C^4 + 1900}\right]^{1/2} \quad (7) \quad (7)$$

$$\text{and } T = 0.36 + |0.4Cos(35 + h)| \quad \text{Expect if } 164^\circ < h < 345^\circ \quad \text{or } T = 0.56 + |0.2Cos(168 + h)|$$

Performance of the above color difference formulae (Equation 1, 2, 3 and 4) for leather substrate with minor and perceptible color variations on leathers was evaluated. Statistical analysis with regression technique was used to correlate visual and instrumental color analysis. Determination of tolerance limits in terms of quantifiable values for acceptable shade groups was also addressed in the present study.

MATERIALS AND METHODS

Materials

A commercial batch of dyed suede garment leathers (220 leathers) in grayish black shade from a leather manufacturing in Chennai, India was chosen for the study. The buyer's sample was used as standard for assessment of color variation. The color on the suede side of the standard and each sample in the experimental batch of leathers is given in Figure 1. 221 leather samples were separately compared for visual as well as instrumental color analysis.

Methods

Visual Assessment of Color Tolerance

Twenty experienced color matching experts of leather industry were selected for the study and D65 light source representing average daylight was used for viewing. The standard was compared against each leather sample and visual color matching was decided as "pass" or "fail" as per the color perception of each expert. The assessment of leather samples made by the experts was recorded as '0' for fail and '1'for pass. Logit regression analysis[25] was used to convert the recorded binary data response in terms of visual difference (DV) using Equation 8, which is a modified form of the equation reported by H. Mangine et.al.[26]

$$DV = 2 + log_e \frac{S_i + 0.5}{N_i - S_i + 0.5} \quad (8)$$

S_i is the number of experts who found the match acceptable and N_i is the total number of experts. The main difference between the current modified Equation 8 and the equation reported by Mangine *et al*. is the use of constant 2, which was obtained by trial and error method to get positive DV value as well as meaningful correlation with instrumental DE values. The average of the visual difference for all 20 experts was computed and listed in Table I.

Instrumental Color Analysis

Reflectance measurements were carried out using Premier Colorscan reflectance spectrophotometer interfaced with a computer. Before commencing color measurement, the instrument was calibrated against white MgO tile. D65 illuminant with 10-degree standard observer including UV component and excluding specular component with D°8 geometry were set for measurement of reflectance. The reflectance of each sample was measured in the visible range 400-700nm at 10nm intervals. A 25 mm aperture was used for reflectance measurement and two readings were taken at six different locations on each leather and the average was computed[8]. The color values corresponding to the average reflectance value for 12 (2 readings x 6 locations) measurements were computed and are given in Table II. Overall color difference value (DE) was computed using CIE1976 (DE_{ab}), CIE1994 (DE_{94}), CIE2000 (DE_{00}) and CMC (DE_{CMC}) as described in Equations 1 to 4 and are given in Table II.

Curve Fitting and Statistical Analysis

Statistical analysis was carried out to test four instrumental color formulae that correlate best with the visual color perception. In the case of instrumental pass-fail decision, DE less than 1 is considered as 'pass' and greater than 1 as 'fail'. For statistical interference, paired t-test was conducted to distinguish if there is a significant difference between the visual and instrumental pass/fail data. A paired t-test[27-29] compares the mean difference between the pass-fail ratios of visual and instrumental methods. P-value obtained from t-test is compared to the critical value 0.05 (5% significance level).

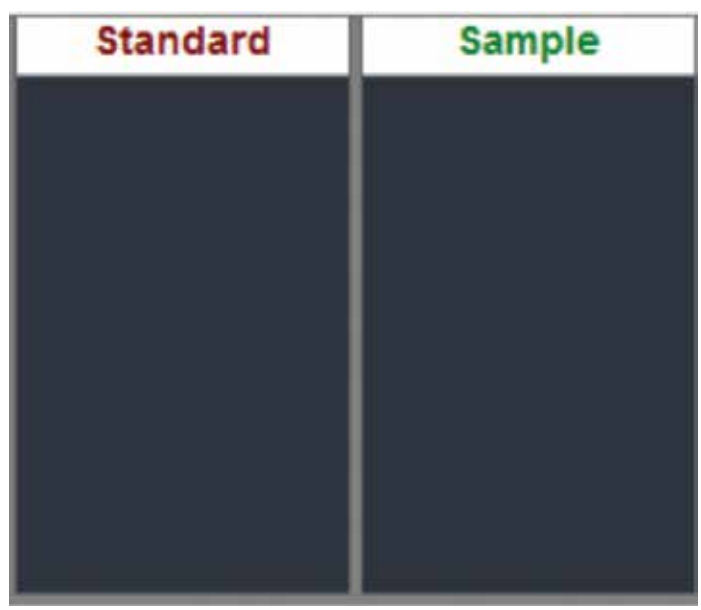

Figure 1. Surface color of the leather sample.

TABLE I
Summary of visual assessment data.

Specimen ID	No. of Experts Acceptance ratio	No. of Experts Rejection Ratio	Pass Ratio	ΔV
Lea_sam_1	19	1	0.95	3.11
Lea_sam_2	17	3	0.85	2.70
Lea_sam_3	12	8	0.60	2.17
Lea_sam_4	12	8	0.60	2.17
Lea_sam_5	14	4	0.70	2.35
Lea_sam_6	12	8	0.60	2.17
Lea_sam_7	5	15	0.25	1.55
Lea_sam_8	1	19	0.05	0.89
Lea_sam_9	4	16	0.20	1.44
Lea_sam_10	1	19	0.05	0.89
Lea_sam_11	1	19	0.05	0.89
Lea_sam_12	1	19	0.05	0.89
Lea_sam_13	4	16	0.20	1.44
Lea_sam_14	8	12	0.40	1.83
Lea_sam_15	2	18	0.10	1.13
Lea_sam_16	0	20	0.00	0.39
Lea_sam_17	16	4	0.80	2.56
Lea_sam_18	8	12	0.40	1.83
Lea_sam_19	8	12	0.40	1.83
Lea_sam_20	8	12	0.40	1.83
Lea_sam_21	20	0	1.00	3.61
Lea_sam_22	12	8	0.60	2.17
Lea_sam_23	12	8	0.60	2.17
Lea_sam_24	10	10	0.50	2.00
Lea_sam_25	9	11	0.45	1.92
Lea_sam_26	9	11	0.45	1.92

Table I continues on following page.

Table I continued.

Lea_sam_27	16	4	0.80	2.56
Lea_sam_28	14	6	0.70	2.35
Lea_sam_29	20	0	1.00	3.61
Lea_sam_30	20	0	1.00	3.61
Lea_sam_31	18	2	0.90	2.87
Lea_sam_32	20	0	1.00	3.61
Lea_sam_33	6	14	0.30	1.65
Lea_sam_34	20	0	1.00	3.61
Lea_sam_35	11	9	0.55	2.08
Lea_sam_36	20	0	1.00	3.61
Lea_sam_37	3	17	0.15	1.30
Lea_sam_38	2	18	0.10	1.13
Lea_sam_39	7	14	0.35	1.74
Lea_sam_40	4	16	0.20	1.44

TABLE II
Instrumental color difference values.

Specimen ID	L*	a*	b*	C*	H*	ΔE^*_{ab} CIE 76	ΔE^*_{94} CIE 94	ΔE^*_{00} CIEDE 2000	ΔE^*_{CMC} CMC(2:1)
Lea_std	21.07	1.10	-9.36	9.43	276.73	-	-	-	-
Lea_sam_1	20.29	1.05	-9.10	9.16	276.61	0.82	0.80	0.58	0.66
Lea_sam_2	20.75	1.14	-8.56	8.63	277.66	0.87	0.66	0.63	0.75
Lea_sam_3	21.19	1.01	-8.09	8.16	277.20	1.28	0.92	0.92	1.09
Lea_sam_4	21.06	0.86	-8.03	8.08	276.14	1.35	0.97	0.99	1.16
Lea_sam_5	21.19	0.86	-8.34	8.38	275.96	1.06	0.76	0.78	0.91
Lea_sam_6	20.87	0.92	-8.11	8.16	276.55	1.28	0.93	0.93	1.09
Lea_sam_7	21.36	0.98	-7.82	7.88	277.20	1.58	1.16	1.14	1.34
Lea_sam_8	19.70	1.09	-7.78	7.86	278.01	2.09	1.78	1.50	1.74
Lea_sam_9	19.71	1.23	-10.31	10.38	276.88	1.66	1.51	1.15	1.35
Lea_sam_10	20.66	1.11	-7.65	7.73	278.32	1.77	1.31	1.29	1.52

Table II continues on following page.

Table II continued.

Lea_sam_11	21.28	0.80	-11.05	11.08	274.18	1.72	1.21	1.29	1.54
Lea_sam_12	21.75	0.79	-7.66	7.70	275.93	1.86	1.43	1.36	1.58
Lea_sam_13	22.35	0.52	-9.29	9.31	273.26	1.41	1.38	1.20	1.28
Lea_sam_14	19.98	1.10	-8.38	8.45	277.53	1.47	1.30	1.04	1.22
Lea_sam_15	19.79	1.07	-8.15	8.22	277.52	1.77	1.55	1.25	1.46
Lea_sam_16	22.78	0.56	-11.09	11.10	272.96	2.49	2.14	1.90	2.17
Lea_sam_17	20.27	1.02	-10.05	10.11	275.88	1.05	0.93	0.75	0.87
Lea_sam_18	21.75	0.74	-8.14	8.17	275.24	1.45	1.15	1.09	1.24
Lea_sam_19	22.12	0.71	-8.51	8.54	274.86	1.41	1.26	1.07	1.20
Lea_sam_20	22.41	0.74	-10.26	10.29	274.18	1.65	1.52	1.27	1.42
Lea_sam_21	21.21	1.05	-9.26	9.32	276.55	0.18	0.16	0.13	0.15
Lea_sam_22	19.89	1.32	-10.10	10.18	277.49	1.40	1.29	0.99	1.15
Lea_sam_23	21.91	0.64	-9.86	9.88	273.76	1.07	1.00	0.95	1.02
Lea_sam_24	20.22	1.25	-10.28	10.35	276.97	1.25	1.06	0.87	1.04
Lea_sam_25	20.65	1.00	-7.73	7.80	277.47	1.69	1.26	1.22	1.44
Lea_sam_26	19.89	1.32	-10.10	10.18	277.49	1.40	1.29	0.99	1.15
Lea_sam_27	20.33	1.19	-9.82	9.90	276.99	0.87	0.80	0.61	0.71
Lea_sam_28	21.97	0.96	-10.37	10.41	275.34	1.35	1.15	0.98	1.15
Lea_sam_29	20.66	1.18	-9.55	9.62	277.09	0.46	0.44	0.33	0.37
Lea_sam_30	21.07	1.06	-9.41	9.47	276.50	0.06	0.05	0.06	0.06
Lea_sam_31	20.64	1.21	-10.16	10.23	276.86	0.91	0.70	0.63	0.76
Lea_sam_32	21.52	1.14	-9.55	9.62	276.87	0.49	0.47	0.35	0.39
Lea_sam_33	22.33	0.74	-9.71	9.74	274.40	1.36	1.33	1.06	1.16
Lea_sam_34	20.91	1.20	-9.30	9.38	277.43	0.20	0.19	0.20	0.20
Lea_sam_35	22.03	0.81	-10.18	10.21	274.60	1.29	1.15	1.00	1.13
Lea_sam_36	21.07	1.06	-9.41	9.47	276.50	0.06	0.05	0.06	0.06
Lea_sam_37	19.79	1.07	-8.15	8.22	277.51	1.77	1.55	1.25	1.46
Lea_sam_38	22.28	0.89	-10.39	10.44	274.93	1.61	1.42	1.18	1.35
Lea_sam_39	20.33	1.05	-7.75	7.82	277.80	1.78	1.38	1.29	1.51
Lea_sam_40	22.28	0.89	-10.39	10.44	274.93	1.61	1.42	1.18	1.35

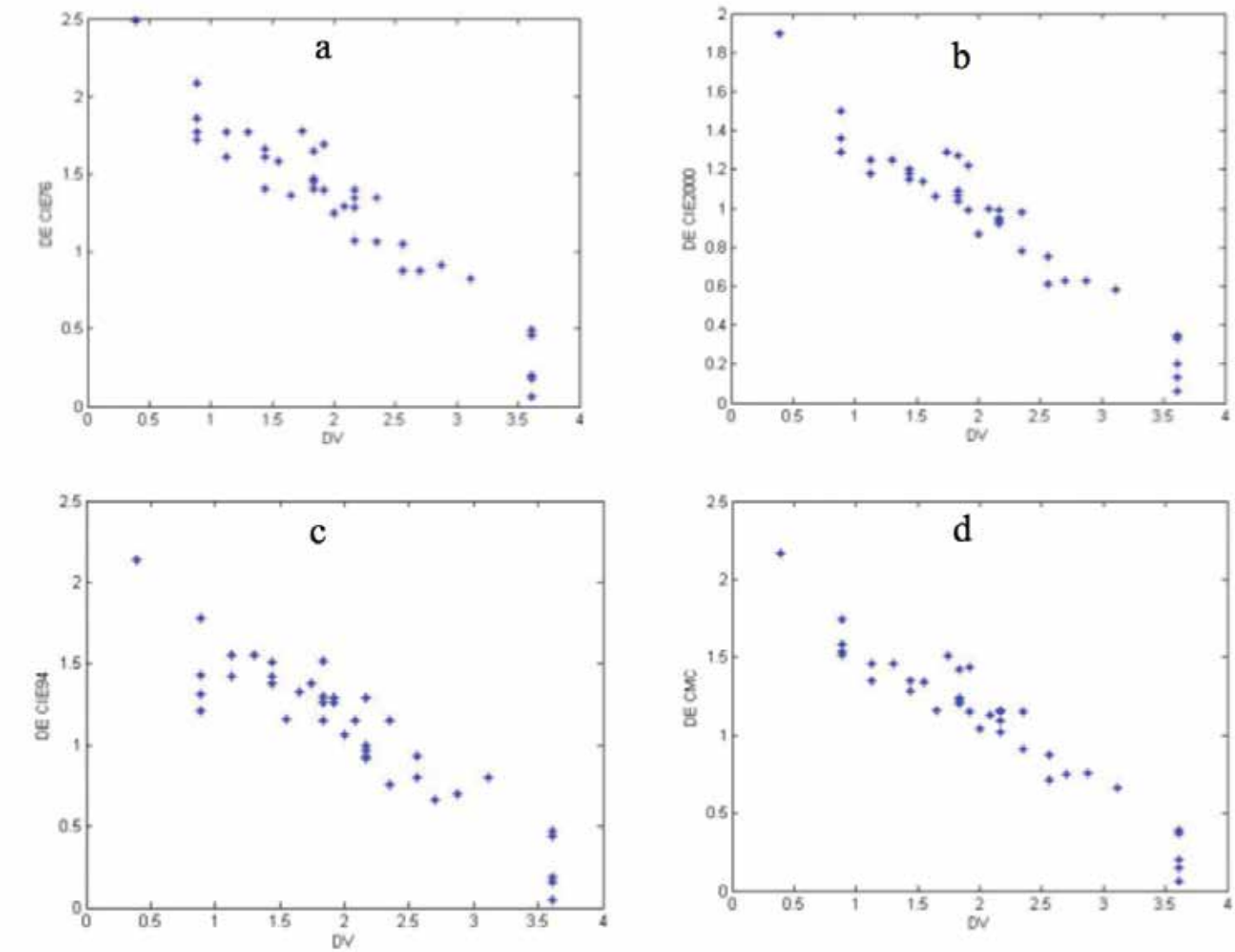

Figure 2. Scatter plots of visual color difference (DV) versus color difference equations (a) DE CIE76, (b) DE CIE2000, (c) DE CIE94 and (d) DE CMC.

Expert pass/fail opinion was converted to visual color difference DV using Equation 8 to find out the order of correlation between the visual color difference with that of the four Instrumental color difference formulae. Scatter plots of visual color difference data (DV) and the four color difference equation (DE) were plotted (Fig. 2). The curve that best fits the visual and instrumental color difference was chosen using linear regression analysis using SYSSTAT software. The coefficient of determination (R^2) was used as a measure to rank the order of correlation.

RESULTS AND DISCUSSION

CIE L*a*b* and LCH color notations were used to quantify color in terms of numerical values. The color values obtained from these systems can describe the magnitude of variations between the standard and the sample in a way understandable to the human observer.

Statistical Color Analysis

Statistical analyses were carried out to understand the correlation between human color perception and instrumental methods of color analysis. Visual pass-fail ratios and color difference DV value computed using Equation 8 is given in Table I. Instrumental color difference DE values for each formula were computed from reflectance values using the Equations 2 to 5 and are given in Table II. The results of paired t- test comparing the mean binary visual and instrumental pass/fail decision are listed in Table III. There is no significant difference between visual and CIE1994 (DE_{94}), CIE2000 (DE_{00}) and CMC (DE_{CMC}) as p-value is greater than 0.05. However, there is a significant difference between visual and CIE76 (DE_{ab}) as p-value is less than 0.05. As given in Table III, it can be observed that CIE94 and CMC(2:1) have similar p value of 0.32 indicating good relation with human perception. Scatter plots of visual color difference data (DV) versus CIE76 (DE_{ab}), CIE1994 (DE_{94}), CIE2000 (DE_{00}) and

CMC (DE_{CMC})DE values are shown in Figure 2. The figure clearly shows a linear trend between visual and instrumental color differences suggesting that the correlation follows a simple linear regression model. Coefficient of determination (R^2) was also used to assess the goodness of fit between the visual color difference (DV) and CIE76 (DE_{ab}), CIE1994 (DE_{94}), CIE2000 (DE_{00}) and CMC (DE_{CMC})DE and the results are given in Table IV. CMC(2:1) equation yields the highest R^2 value of 0.87 followed by CIE1994 with a value of 0.83. The R^2 value of CIE2000 (DE_{00}) and CIE76 (DE_{ab}) formulae are 0.72 & 0.70. The best fit regression model results in R^2 value closer to 1.0. However, the R^2 value of CIE76 (DE_{ab}), CIE1994 (DE_{94}), CIE2000 (DE_{00}) and CMC (DE_{CMC}) investigated in the present study resulted in range between 0.70 to 0.87. The suede nap exhibiting writing effect might have contributed to lower R^2values. Based on the statistical analysis, CMC(2:1) method with p-value (0.32) and R^2 value (0.87) was concluded as the best method for getting a close conformity with visual color perception.

Analysis on Instrument and Visual Color Perception

Detailed analysis was also carried out on visual and instrumental color values. The tolerance given to hue, chroma and lightness differ according to human perception. For an average observer, the order of sensitivity is arranged as hue > chroma > lightness. Figure 3a, 3b and 3c show quantitative differences between customer standard and batch samples in terms of lightness, chroma and hue. In Figure 3, minimum and maximum L, C, H values are shown in extreme end of the horizontal line respectively. Samples that are lying above the line have '+' variations when compared to the standard in the respective L, C, H coordinates and similarly samples lying below the line have '–' variations. It is observed from Table II, that the L value for standard is 21.01, samples having L values of 19.43, 23.18 show more difference in terms of lightness (Figure 3a). Hence, the samples having extreme L values were rejected by the experts. Color difference based on chroma is given in Figure 3b. Lightness and chroma difference for lea-sam_1(sample Id) are -1.23 and -0.22 and for lea_sam_7 values are 0.47 and -1.31 respectively (Table I). Lea_sam_1 has lightness difference value greater than 1 and the difference in chroma is negligible. 19 experts accepted lea_sam_1, whereas lea_sam_7 was rejected by 15 experts (Table II). It can be observed that difference in lightness value is less and difference in chroma is large. This inference indicates experts accept higher lightness difference when differences in chroma values are lower. CMC(2:1) formula gives the lightness to chroma (l:c) ratio as 2:1, indicating the system is more sensitive to chroma difference than the lightness difference. This observation is found to be in line with human observers for natural material like leather. Lea_sam_14 and lea_sam_22 have similar lightness difference value with chroma values almost similar in quantity but differing in the direction(+/-). Lea_sam_14 (Dc = -0.99) is duller and lea_sam_22 (Dc = +0.98) is brighter shade. From visual perception data (Table 2), it can be noticed that the experts preferred to accept brighter shades as compared to duller shades. Color difference based on hue is given in Figure 3c. Color values given in Table I &II indicate that there is less difference in chroma for lea_sam_31 and lea_sam_35. Expert evaluators rejected lea_sam_35 due to the variation in hue but accepted lea_sam_31. These observations show that the human perception is more sensitive to hue difference than difference in chroma.

Color Sorting with Two Dimensional Grouping

Color analysis of hue, chroma and lightness as discussed above (Figure 3a, 3b, 3c) indicate the acceptable level of tolerance required for instrumental pass/fail decision. Two dimensional grouping was carried out based on minimum and maximum hue and chroma values. Samples were divided into 16 regions (4x4) with hue values (H) on x-axis and chroma values (C) on y-axis (Figure 4). The distribution of the samples in each region may vary from batch to batch. Sample in C2 H3 region (chroma value 9.28 and hue value 276.2) and a sample in C3 H3 region (chroma 10.12 and hue 276.25) show difference in chroma greater than 0.8 with similar hue values. Above observation indicate expert evaluators accept difference in chroma when the hue is similar. Sample in H2C1 region (hue 274.85; chroma 9.51) and sample in H3C1 region (hue 276.45; chroma 9.52) show similar chroma values with difference in hue and hence unaccepted. As given in Table II, the hue value of the buyer swatch is 276.73, which is in H3 region. Two dimensional grouping based on hue and chrome as seen in Figure 4 show 9 samples were categorized under H1 region, 25 samples under H2 region, 145 samples under H3 region and 42 samples under H4. Samples in H3 region have meager hue variations compared to standard. Samples in H2 and H4 are adjacent or in line with the standard (H3) and hence may be passed with sub-grouping. Hence, samples under H3 region along with C1, C2, C3 and C4 region can be considered as one batch and used for the manufacture of a single product. Moreover, sample under H4 region with C1, C2, C3 and C4 can also be considered as second batch and taken for the manufacture of another product. The same principle is applicable to H2 with C1, C2, C3 and C4 region and may be passed as third batch. This sub-grouping (batch) is generally preferred by expert evaluators as they prefer brighter shades with meager variation within the batch. However, samples in H3 along with C1, C2, C3 and C4 region cannot be grouped and made into a single product with H4/H2 with C1, C2, C3 and C4 region due to variations in hue. Moreover, H1 with C1, C2, C3 and C4 region cannot be passed due to major variations in hue in comparison with standard. In the current study, 220 samples resulted in three batches of leathers that are grouped uniformly for making leather products. Setting tolerance by sub-grouping as described above minimizes the number of wrong decisions in the instrumental pass/fail decisions.

In this study a detailed color analysis for grayish black color data with lightness value (L* ranging from 19 to 28) varying

TABLE III
Paired t-test result for visual and instrumental pass-fail ratio.

Pair	Paired Differences				t	p-Value
	95% Confidence Interval of Difference					
	Mean	Standard deviation	Lower	Upper		
Vis-CIE76	0.75	0.33	-0.23	-0.02	-2.36	0.02
Vis-CIE94	0.65	0.16	-0.07	0.03	-1.00	0.32
Vis-CIE2000	0.70	0.26	-0.16	0.01	-1.78	0.08
Vis-CMC(2:1)	0.65	0.16	-0.07	0.03	-1.00	0.32

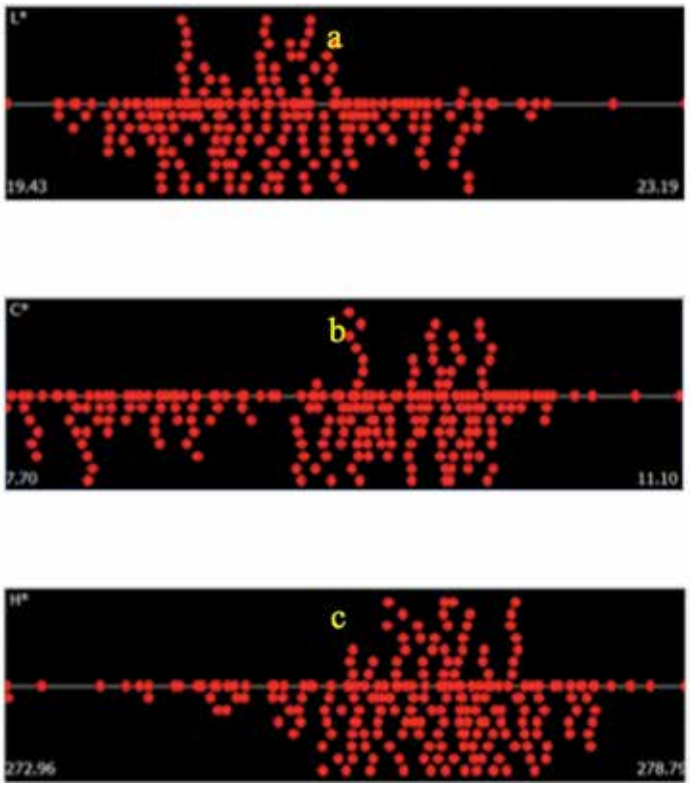

Figure 3. Instrumental color sorting based on L,C and H (a) Grouping based on Lightness (b) Grouping based on Chroma (c) Grouping based on Hue.

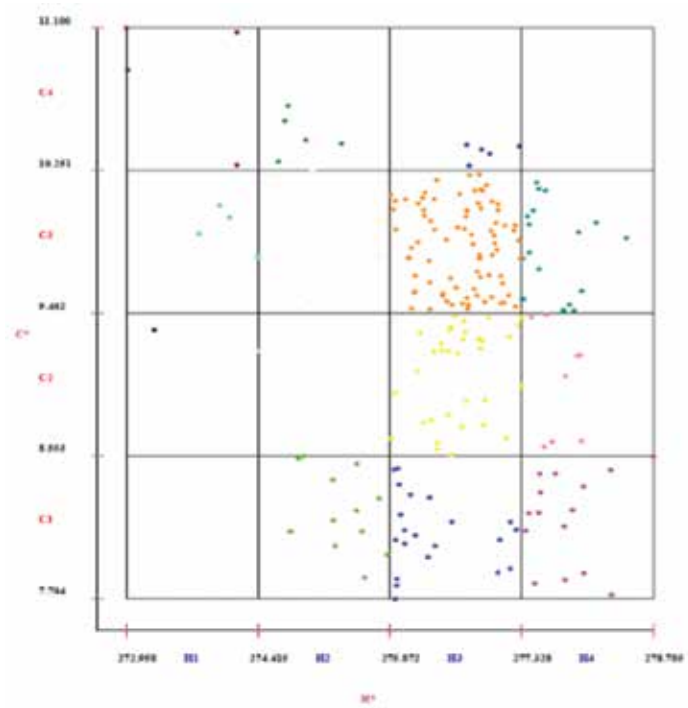

Figure 4. Color assortment based on hue and chroma (Editor note: For color see ezine at alcajournal.com.)

in hue and chroma was carried out. Pass/Fail decisions based on single number ΔE^*_{ab} value ($\Delta E > 1$ as fail and $\Delta E < 1$ as pass) does not correlate with visual assessment of color. Three dimensional tolerance limits based on L, C, h color space provides closer agreement to visual perception. The methodology for setting tolerance limits using two dimensional grouping based on hue and chroma along with lightness difference provides an objective solution for color sorting problem. Tolerance limits in terms of L,C, h vary for different spectral colors. Instrumental color sorting helps the buyer/seller to fix the tolerance of each color parameter (i.e. in terms of hue, chroma, lightness) providing consistent sorting which results in accurate and faster pass/fail decisions.

TABLE IV
Goodness of fit evaluated using coefficient of determination (R^2)

Colour Difference Equation	R^2
CIE76	0.70
CIE94	0.83
CIE2000	0.72
CMC(2:1)	0.87

CONCLUSIONS

Mathematical models were developed to correlate visual color difference and instrumental methods based on four color difference equations. Both t-test and coefficient of determination (R^2) showed that the equations from best to worst fit follows the order CMC(2:1) > CIE94 > CIEDE2000 > CIE76. For a substrate like leather with non-uniform and porous surface, CMC equation may be the best suited to correlate with visual color perception. A detailed analysis of the color values established that, for an average expert the order of sensitivity is arranged as hue > chroma > lightness. An objective solution for color sorting problem has been found by setting tolerance limits based on hue-chroma (two dimensional grouping) along with lightness led to closer conformity between visual and instrumental methods.

REFERENCES

1. Steen, D., Dupont, D.; Defining a practical method of ascertaining textile color acceptability. *Color. Res. Appl.* **27**, 391-398, 2002.
2. Colorimetry, 3rd Edition Commission Internationale de l'Eclairage (*CIE) technical report*, 15, 2004.
3. Melgosa, M.; Testing CIELAB-based color-difference formulas. *Color. Res. Appl.* **25**, 49-55, 2000.
4. McDonald, R.; Industrial pass-fail colour matching: Part I. Preparation of visual colour-matching data. *J. Soc. Dyers Color* **96**, 372, 1980.
5. Berns, R. S., Alman, D. H., Reniff, L., Snyder, G. D., Balonon-Rosen, M. R.; Visual determination of suprathreshold color-difference tolerances using probit analysis. *Color. Res. Appl.* **16**, 297, 1991.
6. Rieker, J., Fuchs**,** E.; Investigation of performance ability of pass / fail formulas for the colorimetric color matching. *Textilveredlung,* **22**, 361, 1987.
7. Luo, M. R., Kgg, B.; Chromaticity discrimination ellipsoids for surface colours. *Color. Res. Appl.* **11**, 25, 1986.
8. ISO/DIS 13655:1996 Graphic technology — Spectral measurement and colorimetric computation for graphic arts images. Geneva, Switzerland: *International Organization for Standardization*.
9. Kuehni, R.G.; Toward an improved uniform colour space. *Color. Res. Appl.* **24**, 253-265, 1999.
10. Kuehni, R.G.; Industrial Colour Difference: progress and problems. *Color. Res. Appl.* **15**, 261-265, 1990.
11. Industrial colour-difference evaluation, (Paris, CIE, 1995)*, CIE Publication*, 116.
12. Habekost, M.; Color difference equations and the human eye, *TAGA Proceedings,* 291-310, *2007.*
13. Billmeyer, S.; *Principles of Color Technology*, 3rd Edition, New York: Wiley & Sons, 2000.
14. Parametric effects in colour-difference evaluation, (Paris, CIE, 1993)*, CIE Publication*, 101.
15. Hunt, R. W.G.; *The Reproduction of Colour.* Chichester, England, John Wiley & Sons Ltd, 2004.
16. Luo, M .R., Rigg, B.; Colour difference formula, Part II Performance of the formula. *J. Soc. Dyers Color* **103**, 126,1987.
17. Lee, S. G., Shamey, R., Hinks, D., Jasper, W.; Development of a comprehensive visual dataset based on a CIE blue color center: Assessment of color difference formulae using various statistical methods. *Color. Res. Appl. **36**, 27-41, 2011.*
18. Granger, E.; A comparison of color difference data and formulas. *TAGA Proceedings,* 191-202, 2008.
19. Luo, M., Cui, G., Rigg, B.; The development of the CIE 2000 colour-difference formula: CIEDE2000. *Color. Res. Appl.* **26**, 340-350, 2001.
20. Clarke, F.J. J., Mcdonald, R., Rigg, B.; Modification to the JPC79 color-difference formula. *J. Soc. Dyers Color* **100**, 128-132, 1984.
21. British Standard, BS 6923, Method for calculation of small colour differences, 1988.
22. Malathy J., Venba, R., Jyothi, G., Jinandra Doss M.; Instrumental Assessment of levelness of Dyed Materials. *JALCA* **99**, 233-241, 2004.
23. Habekost, M.; Evaluation of digital proofs using the GRA CoL dataset and various color difference equations, *TAGA Proceedings,* 392-415, 2008.
24. McDonald, R.; European practices and philosophy in industrial color-difference evaluation. *Color. Res. Appl.* **15**, 249-260, 1990.
25. Berns, R.S.; Deriving instrumental tolerances from pass-fail and colorimetric data. *Color. Res. Appl.* **21**, 459-472, 1996.
26. Mangine, H., Jakes, K., Noel, C.; A Preliminary Comparison of CIE Color Differences to Textile Color Acceptability Using Average Observers. *Color. Res. Appl***.** **30**, 288-294, 2005.

27. Siegel, S.; Nonparametric statistics, *The American Statistician* **11**, 13–19, 1957.
28. Siegel, S., Castellan, N.; *J. Nonparametric statistics for the behavioral sciences*. Second Edition. New York: McGraw-Hill. 1988.
29. Welch, B. L.; "'Student' and Small Sample Theory". *J. Am. Statist. Assoc.* **53**, 777–788, 1958.