Measuring Color Differences in Gonioapparent Materials Used in the Automotive Industry

Manuel Melgosa[1*], Luis Gómez-Robledo[1], Guihua Cui[2], Changjun Li[3], Esther Perales[4], Francisco M. Martínez-Verdú[4] and Thomas Dauser[5]

[1]*Department of Optics, University of Granada, 18071 Granada (Spain)*

[2]*University of Wenzhou, Wenzhou 325035 (China)*

[3]*School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan 114051 (China)*

[4]*Color and Vision Group, Department of Optics, Pharmacology and Anatomy, University of Alicante, 03690 Sant Vicent del Raspeig, Alicante (Spain)*

[5]*AUDI AG, I/PG-C41, 85045 Ingolstadt (Germany)*

[*]E-mail: mmelgosa@ugr.es

1. Abstract

This paper illustrates how to design a visual experiment to measure color differences in gonioapparent materials, and how to assess the merits of different advanced color-difference formulas trying to predict the results in such experiment. Color-difference formulas try to predict visually-perceived color differences by observers with normal color vision from objective instrumental color measurements. Successful color-difference formulas are necessary for industrial quality control and artificial vision applications. A color-difference formula must work accurately under a wide variety of experimental conditions, including the use of challenging materials like, for example, gonioapparent samples. We have tested 11 advanced color-difference formulas from visual assessments performed by 11 observers using a set of 56 nearly achromatic color pairs with automotive gonioapparent samples. Best predictions of our experimental results were found for the AUDI2000 color-difference formula, followed by color-difference formulas based on the color appearance model CIECAM02. Parameters in the original weighting function for lightness in AUDI2000 were optimized obtaining small improvements. However, a non-linear transform in AUDI2000 considerably improved results, producing values close to the inter-observer variability in our visual experiment. Additional research is required to obtain a modified AUDI2000 color-difference formula significantly better than the current one.

2. Introduction

A color-difference formula provides a number ΔE from instrumental color specifications of two given color stimuli having a visually-perceived color difference ΔV [1]. Note that while ΔV is the subjective answer of our human visual system (unknown in many aspects), ΔE is just a fast objective instrumental measurement. Industrial color-quality control requires appropriate color-difference formulas providing ΔE values accurately predicting subjective visual assessments of color differences (i.e. ΔV values) from final users. For example, in the automotive industry, the different parts of cars are produced by different manufactures using different materials, and reliable color-difference formulas are necessary for automatic pass/fail color decisions. In the past years a number of color-difference formulas have been proposed for industrial applications [2-10]. Currently, the color-difference formula jointly recommended by the International Commission on Illumination (CIE) and the International Organization for Standardization (ISO) [11] is CIEDE2000 [7].

Gonioapparent materials or materials with flop effects represent a big challenge for color-difference evaluation in current automotive industry. According to the American Society for Testing and Materials (ASTM) [12], "appearance" can be defined as "the aspect of visual experience by which things are recognized", "goniochromatism" is the "change in any of all attributes of color of a specimen on change in angular illuminating-viewing conditions but without change in light source or observer", and "flop" is "a difference in appearance of a material viewed over two widely different aspecular angles". In the middle of the 90's AUDI developed a tolerance formula for the approval of effect paint batches when colors with strong flop effects were important in the automotive sector [13]. Latter this formula was

modified to predict color tolerances for solids (homogeneous) as well as for effect (goniochromatic) colors, leading to the AUDI2000 color-difference formula [14], currently employed by different manufacturers in the automotive industry. It is important to note that nowadays AUDI2000 is the only available color-difference formula considering flop effects. In previous works we have tested the performance of the AUDI2000 and other advanced color-difference formulas for different visual datasets with homogeneous colors [15, 16], as well as for a reduced dataset of 28 color pairs involving some gonioapparent samples [17]. The results found in this last experiment indicated that AUDI2000 performs very well, but its weighting function for lightness (i.e. the dependence of perceived lightness differences with flop) may be not optimal. Current paper reports new experimental results using color pairs with different amount of lightness flop, which may be useful to develop a modified AUDI2000 color-difference formula with improved performance with respect to the original one.

3. Materials and methods

We have performed a visual experiment where a panel of 11 experienced observers with normal color vision assessed a set of 56 color pairs with different amounts of lightness flop. These color pairs were selected from a set of 476 samples (specifically produced by AkzoNobel for the automotive industry), using the next criteria:

1) The samples in all our color pairs were nearly achromatic (C^*_{ab}<10) and their total color differences were predominantly in lightness: $|\Delta L^*| > 2\ [|\Delta C^*_{ab}|+|\Delta H^*_{ab}|]$. From our spectroradiometric measurements, the average color differences of our color pairs was 3.1 CIELAB units, and the average percentage of lightness differences in total CIELAB color difference was 79.8%.

2) A total of 10 color centers were considered in our experiment, and the two samples in each color pair came from the same color center. Therefore, the two samples in all our color pairs had very similar textures (i.e. coarseness and sparkle) as well as very similar magnitudes of lightness flop. We measured lightness flop for each color sample as $|\Delta L^*_{\gamma i+1} - \Delta L^*_{\gamma i}| / (\gamma_{i+1} - \gamma_i)$, where γ_i = 15°, 25°, 45°, 75° and γ_{i+1} is the next standard aspecular angle to the angle γ_i (e.g. γ_{i+1} = 25° when γ_i = 15°, or γ_{i+1} = 110° when γ_i = 75°). The lightness flop in each color pair was the average of the lightness flops in the two samples. The color pairs in our experiment appropriately covered a lightness flop range from 0 to 3.8 units.

These criteria for the selection of our color pairs are in agreement with one of the main goals in our current paper: To test the performance of the weighting function for lightness in the AUDI2000 color-difference formula. In fact, in the design of our earlier experiment described in Ref. 17, the range in lightness flop in the color pairs was not considered, in such a way that the results found were not very useful to propose a new weighting function for lightness in AUDI2000. Other differences between our earlier experiment in Ref. 17 and the current one are that now: 1) We used color pairs with the highest available size (10 cm x 10 cm) in order lightness flop may be more evident; 2) we considered only some selected viewing angles (i.e. not all 6 viewing geometries for each color pair), in order to have a reasonable number of color pairs allowing the experiment could be performed in a period of 3 months.

The color pairs were visually assessed using a byko-spectra effect light booth placed in a dark room. The selected color pairs were presented to each observer in a random order, and the task of the observer was to judge the magnitudes of the color differences using the Gray Scale for Change in Colour of the Society of Dyers and Colourists [18]. Each observer performed 3 non-sequential assessments of each color pair, in such a way that a total of 56 x 11 x 3 = 1848 were recorded during different visual sessions, which never lasted more than 20 min to avoid observer's fatigue. All our instrumental color measurements were performed using a Konica Minolta CS2000 spectroradiometer placed at the same position than the head of the observer, in such a way that we measure just what the observer sees. The reference white for transformations to CIELAB and other color spaces was a calibrated PTFE plaque placed at the positions of the samples and measured also with our spectroradiometer. Before computations of color differences, the tristimulus values of the two samples in each color pair were transformed using the chromatic adaptation transform CAT02 employed in CIECAM02 [19], considering as reference white the average of the reference whites placed in the positions of the two samples. Three independent instrumental measurements were performed for the two samples in each color pair, and, on the average, the standard deviation of such measurements was 0.58 CIELAB units.

A detailed description of the AUDI2000 color-difference formula can be found in Ref. 17. Here we will only indicate that AUDI2000 is a CIELAB-based color-difference formula (see Eq. (1)) with the structure of CIE94 [6], and the weighting function for lightness in AUDI2000, named S_{L,γ_i} , is given in Eq. (2):

$$\Delta E_{AUDI2000,\gamma_i} = \sqrt{\left(\frac{\Delta L^*_{\gamma_i}}{S_{L,\gamma_i}}\right)^2 + \left(\frac{\Delta C^*_{ab,\gamma_i}}{S_{C,\gamma_i}}\right)^2 + \left(\frac{\Delta H^*_{ab,\gamma_i}}{S_{H,\gamma_i}}\right)^2} \tag{1}$$

$$S_{L,\gamma_i} = a_1\left(\frac{\left|L^*_{\gamma_i+1} - L^*_{\gamma_i}\right|}{\gamma_{i+1}-\gamma_i}\right)^{a_2} + a_3 C^*_{ab,45^o} + a_4 = 1.0\left(\frac{\left|L^*_{\gamma_i+1} - L^*_{\gamma_i}\right|}{\gamma_{i+1}-\gamma_i}\right)^{2/3} + 0.002C^*_{ab,45^o} + 0.33 \tag{2}$$

The merit of a color-difference formula may be assessed by different indices measuring the strength of the relationship between ΔE_i and ΔV_i values (i.e. computed and perceived color differences for the i=1,…, 56 color pairs). In the past few years the *STRESS* index [20] became increasingly popular to assess the merit of color-difference formulas. *STRESS* values are in the range 0-100, low values indicating better performance of a color- difference formula. *STRESS* can be also used to measure intra- and inter-observer variability [21], as well as to know whether two different formulas are or not statistically significantly different with respect to the visual data [20]. Here we have used the *STRESS* index and a weighted *STRESS* index, named *WSTRESS*, defined in Eq. (3). While *STRESS* gives the same weight to all color pairs (i.e. w_i =1 ; i=1,…, 56), *WSTRESS* assign different weights to each color pair, those with higher accuracy (lower inter-observer variability) having higher weight. Following Berns [22], we have adopted as weight a reciprocal variance equal to the square of the average visual differences divided by 4 times their standard deviations (both measured in CIELAB units), as shown in Eq. (3):

$$WSTRESS = \left(\frac{\sum_{i=1}^{56} w_i\left(\Delta E_i - F_1\Delta V_i\right)^2}{\sum_{i=1}^{56} w_i F_1^2 \Delta V_i^2}\right)^{1/2} \;;\; F_1 = \frac{\sum_{i=1}^{56}\Delta E_i^{\,2}}{\sum_{i=1}^{56}\Delta E_i \Delta V_i} \;;\; w_i = \left(\frac{Average\ \Delta V_i\ (i=1,...56)}{4\ St.\ Dev.\ \Delta V_i\ (i=1,...56)}\right)^2 \tag{3}$$

4. Results and discussion

The raw visual color-difference values reported by our observers were transformed into true visual differences, according to the procedure described in Ref. [17]. After this transformation, *STRESS* values corresponding to the intra- and inter-observer variability in our experiment were 16.2 and 19.9 units, respectively. These values are lower than the 25.2 and 23.2 units found in our earlier experiment described in Ref. [17], which may be attributed to the fact that in the current experiment most observers had previous experience in visual color-difference experiments. A first analysis of our visual results indicated that the answers from some observers in some color pairs were outliers. It was decided to remove in all further analyses the visual answers below Q1-1.5*(Q3-Q1) or above Q3+1.5(Q3-Q1), where Q1 and Q3 are the first and third quartiles in the population of all visual answers. This resulted in 73 removed color answers (i.e. about 4% of total answers) and a new lower inter-observer variability of 18.2 units. After removing outliers, the standard deviation of the 3 visual assessments performed in each color pair was on the average 0.78 CIELAB units. Any color-difference formula providing *STRESS* results below this value of 18.2 units may be considered satisfactory, because it can be considered as equivalent to an average individual observer participating in our experiment.

Table 1 shows *STRESS* and *WSTRESS* values for each color-difference formula considered in our experiment. Parametric factors in all tested color-difference formulas were assumed as 1.0. For the CAM02-SCD and CAM02 formulas, we assumed average surround, a neutral background with L^*=24.2 and illuminance on the plane of the samples equal to 1800 lx, according to the viewing conditions in our experiment. As we can see in Table 1, the best predictions (lowest *STRESS* and *WSTRESS* values) of our visual results were found for the AUDI2000 color-difference formula, followed by the CAM02-UCS, CAM02-UCS, CIEDE2000 and DIN99d color-difference formulas. In fact, at a confidence level of 95% any of these four color-difference formulas was significantly different to AUDI2000. This result is in agreement with the one reported in our earlier experiment in Ref. 17, where AUDI2000, CAM02-SCD

and CAM02-UCS were the best color-difference formulas without statistically significant differences among them. Anyway, it must be noted that the 27.3 *STRESS* value achieved for AUDI2000 in our current experiment is considerably higher than the inter-observer variability (18.2 units), which means that AUDI2000 must be improved to perform like a real average visual observer. Table 1 also shows that *WSTRESS* is always lower than *STRESS*, which means that the average similitude between perceived (ΔV) and computed (ΔE) color differences increases when a lower weight is given to the color pairs visually assessed with lower accuracy.

Color-Difference Formula	*STRESS*	*WSTRESS*
CIELUV [2]	33.4	29.7
CIELAB [3]	35.0	32.6
CMC [4]	40.8	33.8
BFD [5]	43.4	34.2
CIE94 [6]	36.2	34.2
CIEDE2000 [7, 11]	32.0	28.1
DIN99d [8]	31.5	28.4
AUDI2000 [14]	27.3	23.9
CAM02-SCD [9]	28.6	24.2
CAM02-UCS [9]	29.3	24.8
OSA-GP-Euclidean [10]	40.6	31.2

Table 1 . Performance of 11 advanced color-difference formulas against visual results in our experiment, measured by the *STRESS* and *WSTRESS* indices. Lower values of these indices (always in the range 0-100) indicate better performance.

We have optimized independently each one of the 4 coefficients involved in the weighting function for lightness in the AUDI2000 color-difference formula (see Eq. (2)), considering only one significant decimal figure in each coefficient. Table 2 shows the original values of each one of these coefficients and the optimized ones, together with their corresponding optimized *STRESS* values (last column in Table 2). As we can see, all optimized coefficients except a_1 are enough different to the original ones in AUDI2000, but the optimized values only produced a small decrease in STRESS values around 2 units in the best case, which means a small improvement of the original AUDI2000 formula. We estimate that a simultaneous optimization of the 4 coefficients involved in Eq. (2) may produce some higher *STRESS* decrease. It can be also noted that in our earlier experiment described in Ref. 17, the values of the coefficients minimizing *STRESS* enough similar to those found in the current experiment (see Table 2), with the exception of the a_4 coefficient. In fact, the optimized value a_4=0.7 in the current experiment is much more convenient than previous 0.01 value, because for nearly achromatic and solid (homogeneous) samples this last value may lead to values of the weighting function for lightness which are close to zero (see Eq. (2)), producing very high unacceptable values of AUDI2000 color differences.

Finally, it is worth to mention that an exponent α=0.65 in the original complete AUDI2000 color-difference formula produced a very important decrease of about 8.6 units in the *STRESS* value found in our current experiment, as shown in last row of Table 2. The use of this kind of non-linear optimization in color-difference formulas was originally proposed by Attridge and Pointer [23], and it has proved useful in other different previous experiments [24], including the one in Ref. 17 where the optimum value for this exponent was 0.82. Note that 18.7 *STRESS* units found with α=0.65 is a very close value to the 18.2 STRESS units corresponding to the inter-observer variability in our current visual experiment.

Coefficients	Original Values [14]	Previous Optimized Values [17]	Current Optimized Values	*STRESS* for Current Optimized Values
a_1	1.0	1.1	1.1	27.31
a_2	0.67	0.5	0.3	25.16
$-a_3$	0.002	0.01	0.01	27.31
a_4	0.33	0.01	0.7	26.01
α	1.0	0.82	0.65	18.70

Table 2 . Original and optimized coefficients in the AUDI2000 color difference formula (Eq. (2)) with the optimized STRESS values. Original *STRESS* value was 27.33. Last row indicates the exponent to be added into AUDI2000 original formula.

5. Conclusion and future work

This paper illustrates how to design a visual experiment to measure color differences in gonioapparent materials, and how to assess the relative merits of different color-difference formulas trying to predict the visual results in such experiment. More specifically, we tried to test the weighting function for lightness in the AUDI2000 color-difference formula, complementing results found in another recent experiment performed by us [17]. Our current results confirm that AUDI2000 is a good color-difference formula while its weighting function for lightness may be not optimal. Beside some advances, we must say that the proposal of a modified weighting function for lightness in AUDI2000 requires further experimental results with additional color pairs and corresponding analyses. These works are currently underway in our laboratories. In addition, an optimization of the whole AUDI2000 color-difference formula will require appropriate color samples and new experiments to analyze also chroma and hue flops. The possibility of a total difference formula involving coarseness and sparkle in addition to color may be also considered in the improvement of current AUDI2000 color-difference formula.

Acknowledgments

We are grateful to all volunteer observers at the Department of Optics of the University of Granada (Spain) who agreed to participate in our experiment. Samples used in the current experiment were produced and kindly provided to us by AkzoNobel Automotive & Aerospace Coatings, http://www.akzonobel.com/aac/aboutus/who_we_are/ (Sassenheim, the Netherlands). The loan of the byko-spectra effect light booth used in our experiment by BYK Additives and Instruments, https://www.byk.com/en/instruments/products/color-measurement.html is also strongly acknowledged. This research was supported by the Ministry of Economy and Competitiveness of Spain, research projects FIS2010-19839, FIS2013-40661-P and DPI2011-30090-C02, with European Research Development Fund (ERDF).

References

[1] M. Melgosa, A. Trémeau and G. Cui, *Colour Difference Evaluation*, in Advanced Color Image Processing and Analysis (Springer, 2013), Chapter 3.

[2] Commission Internationale de l'Éclairage (CIE), CIE Colorimetry – Part 5: CIE 1976 L*u*v* Colour Space and u',v' Uniform Chromaticity Diagram, ISO 11664-5:2009(E) / CIE S 014-5 E:2009 (CIE Central Bureau, Vienna, 2009).

[3] Commission Internationale de l'Éclairage (CIE), CIE Colorimetry – Part 4: 1976 L*a*b* Colour Space, ISO 11664-4:2008(E) / CIE S 014-4 E:2007 (CIE Central Bureau, Vienna, 2007).

[4] F. J. J. Clarke, R. McDonald and B. Rigg, "Modification to the JPC79 colour-difference formula", J. Soc. Dyers Colour. 100, 128-132 (1984).

[5] M. R. Luo and B. Rigg, "BFD(l:c) colour-difference formula. Part I – Development of the formula", J. Soc. Dyers Colour 103, 86-94 (1987).

[6] Commission Internationale de l'Éclairage (CIE), Industrial colour-difference evaluation, CIE Publication 116-1995 (CIE Central Bureau, Vienna, 1995).

[7] Commission Internationale de l'Éclairage (CIE), Improvement to industrial colour-difference evaluation, CIE Publication 142-2001 (CIE Central Bureau, Vienna, 2001).

[8] 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).

[9] M. R. Luo, G. Cui and C. Li, "Uniform colour spaces based on CIECAM02 colour appearance model", Color Res. Appl. 31, 320-330 (2006).

[10] C. 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).

[11] Commission Internationale de l'Éclairage (CIE), Colorimetry - Part 6: CIEDE2000 colour-difference formula, Joint ISO/CIE Standard, ISO/CIE 11664-6:2014(E) (CIE Central Bureau, Vienna, 2013).

[12] American Society for Testing and Materials (ASTM), Standard terminology of appearance, ASTM E284 95a (1995).

[13] DIN 6175-2, "Farbtoleranzen für Automobillackierungen – Teil 2: Effektlackierungen," Deutsches Institut für Normung eV, Berlin, 2001-03.

[14] T. Dauser, AUDI AG, I/PG-C41, 85045 Ingolstadt, Germany (personal communication, 2012), http://www.detroitcc.org/files/Color%20Management%20at%20AUDI%20(DCC%20March%202012).pdf

[15] M. Melgosa, L. Gómez-Robledo, J. Martínez-García, E. Perales, F. M. Martínez-Verdú, and T. Dauser, "Testing a colour-difference formula for the automotive industry using the experimental visual datasets employed in CIEDE2000 development", in Proceedings CIE Centenary Conference (CIE, Paris, 2013), CIE x038:2013 Publication, pp. 465-469.

[16] J. Martínez-García, M. Melgosa, L. Gómez-Robledo, C. Li, M. Huang, H. Liu, G. Cui, M. R. Luo, and T. Dauser, "Testing the AUDI2000 colour-difference formula for solid colours using some visual datasets with usefulness to automotive industry", in Proceedings 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers and Applications. Published as Proc. SPIE Vol. 8785, 87858P, doi: 10.1117/12.2026601.

[17] M. Melgosa, J. Martínez-García, L. Gómez-Robledo, E. Perales, F. M. Martínez-Verdú and T. Dauser, "Measuring color differences in automotive samples with lightness flop: A test of the AUDI2000 color-difference formula", Opt. Express 22, 3458-3467 (2014).

[18] http://www.sdcenterprises.co.uk/products/testing.asp See also ISO 105-A02:1993, "Test for colour fastness – Part A02: Gray scale for assessing change in colour," International Organization for Standardization (Geneva, Switzerland).

[19] Commission Internationale de l'Éclairage (CIE), A colour appearance model for colour management systems: CIECAM02, CIE Publication 159-2004 (CIE Central Bureau, Vienna, 2004).

[20] 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).

[21] M. Melgosa, P. A. García, L. Gómez-Robledo, R. Shamey, D. Hinks, G. Cui, and M. R. Luo, "Notes on the application of the standardized residual sum of squares index for the assessment of intra- and inter-observer variability in color-difference experiments", J. Opt. Soc. Am. A 28, 949-953 (2011).

[22] R. S. Berns and B. Hou, "RIT-DuPont supra-threshold color-tolerance individual color-difference pair dataset", Color Res. Appl. 35, 274-283 (2010).

[23] G. G. Attridge and M. R. Pointer, "Some aspects of the visual scaling of large colour differences – II", Color Res. Appl. 25, 116-122 (2000).

[24] M. Huang, H. Liu, G. Cui, M.R. Luo, N. Liao, M. Melgosa, Y. Zhang, and C. Zheng, "Assessing color differences in a wide range of magnitudes," Proceedings AIC Colour 2013 (Newcastle, UK, 2013), Volume 4, pp. 1533-1536.