

Measuring color differences in gonioapparent materials used in the automotive industry

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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 of such experiment. Successful color-difference formulas are necessary for industrial quality control and artificial color-vision applications. A color-difference formula must be accurate under a wide variety of experimental conditions including the use of challenging materials like, for example, gonioapparent samples. Improving the experimental design in a previous paper [Melgosa et al., *Optics Express* 22, 3458-3467 (2014)], we have tested 11 advanced color-difference formulas from visual assessments performed by a panel of 11 observers with normal color vision using a set of 56 nearly achromatic color pairs of 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 the AUDI2000 formula were optimized obtaining small improvements. However, a power function from results provided by the AUDI2000 formula 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.

1. Introduction

A color-difference formula just provides a number ΔE from instrumental color specifications of two color stimuli having a visually-perceived color difference ΔV [1]. Note that while ΔV is the subjective answer of the human visual system (unknown in many aspects), ΔE is an objective instrumental measurement. Industrial color-quality control requires successful color-difference formulas providing ΔE values which accurately predict subjective visual assessments of the color differences perceived by average observers under a wide variety of viewing conditions. 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, it is recommended to use the CIEDE2000 color-difference formula [7], which has been jointly proposed as a standard by the International Commission on Illumination (CIE) and the International Organization for Standardization (ISO) [11]. This recommendation mainly promotes uniformity of practice, enabling easier communication between manufacturers/users.

Gonioapparent materials or materials with flop effects represent a big challenge for color-difference evaluation in current automotive industry. The next definitions from the American Society for Testing and Materials (ASTM) [12] are considered relevant for this kind of materials: “Appearance” is “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”; “flop” is “a difference in appearance of a material viewed over two widely different aspecular angles”; and “aspecular angle” is the “viewing angle measured from the specular direction, in the illuminator plane unless otherwise specified”.

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 the AUDI2000 formula 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 controlled amounts of lightness flop. In a first step, our current results may be used to start the development of a modified AUDI2000 color-difference formula with improved performance with respect to the original one.

2. 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 produced by AkzoNobel for the automotive industry, considering the next specific criteria:

1) The samples in all our color pairs were nearly achromatic ($C^*_{ab} < 10$) and their total color differences were predominantly lightness differences. From our spectroradiometric measurements, the average color differences of our 56 color pairs was 3.1 CIELAB units, and the average percentage of lightness difference in the total CIELAB color difference was 79.8%.

2) Our 56 color pairs were spread around 10 color centers, in such a way that the two samples in all color pairs 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 the lightness flop for each color sample as $|\Delta L^*_{\gamma_{i+1}} - \Delta L^*_{\gamma_i}| / (\gamma_{i+1} - \gamma_i)$, where $\gamma_i = 15^\circ, 25^\circ, 45^\circ, 75^\circ$ and γ_{i+1} is the next standard aspecular angle to the angle γ_i (e.g. $\gamma_{i+1} = 25^\circ$ when $\gamma_i = 15^\circ$, or $\gamma_{i+1} = 110^\circ$ when $\gamma_i = 75^\circ$). The lightness flop for each color pair was defined as the average of the lightness flops of the two samples in the color pair. The color pairs in our experiment appropriately covered a relatively wide range of lightness flop. Thus, from measurements performed with a BYK-mac multi-angle spectrophotometer (aperture 23 mm; illuminant D65; CIE 1964 standard colorimetric observer) the flop in our color pairs ranged from 0 to 3.8 units, with average and standard deviations values of 1.7 and 0.8 CIELAB units, respectively.

These selection criteria of our color pairs were adopted to achieve 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 [17], the selected color pairs were nearly random and a gradual change in lightness flop in the assessed color pairs was not

considered, in such a way that the results found in such experiment are not very appropriate to propose a new weighting function for lightness in the AUDI2000 color-difference formula. Other relevant differences between our earlier experiment in [17] and the current one are as follows: 1) Now, we have used color pairs with the highest available size (10x10 cm) against the previous size of 3.5x3.7 cm used in [17]. In this way the lightness flop is more evident to observers in the current experiment; 2) To have a reasonable number of visual measurements, allowing the whole experiment could be performed in a period of about 3 months, now we have not considered all 6 standard viewing geometries for each color pair as made in [17], which forced us to assess only a reduced number of 28 color pairs. Now, we assessed 56 color pairs selecting only specific viewing angles, in particular those close to the specular direction, because they are particularly important in gonioapparent materials. Specifically, the number of color pairs assessed at the different angles were 26 (15°), 26 (25°), 3 (45°), and 1 (75°).

Each one of the 56 selected color pairs was visually assessed using a byko-spectra effect light booth (BYK Additives and Instruments) placed in a dark room, as recommended by international recommendations and usually made in the automotive industry. The interested reader may find general information on how works this light booth in [18]. The distance between color pairs and observer's position in the byko-spectra effect light booth is 50 cm, approximately. After an adaptation time of around 3 min, each color pair was presented to each observer in a random order, and the task of the observer was to judge the magnitude of the perceived color difference in the color pair using the Gray Scale for Change in Colour of the Society of Dyers and Colourists [19], which was placed just above the color pairs. Each observer performed 3 non-sequential assessments of each color pair, in such a way that a total of 56 (pairs) x 11 (observers) x 3 (replications) = 1848 assessments were recorded. The visual sessions never lasted more than 20 min to avoid observers' fatigue. All our instrumental color measurements for next analyses were performed using a Konica Minolta CS2000 spectroradiometer placed on a tripod at the same position than the head of the observer, in such a way that the spectroradiometer just measured what the observer sees. The reference white for transformations to CIELAB and computations of color coordinates in other color spaces was a calibrated PTFE plaque placed at the positions of the samples and measured also with our spectroradiometer. Before computation 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 [20], considering as reference white the average of the reference whites placed in the positions of the two samples. This transformation was made to take into account slight differences (in some cases negligible) in the measured color of the reference white placed on the left and right samples of the test color pairs or on the 9 color pairs in the Gray Scale of the Society of Dyers and Colourists. Three independent spectroradiometric measurements were performed for the two samples in each of the 56 color pairs, 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 [17]. Here we will only indicate that AUDI2000 is a CIELAB-based color-difference formula (see Eq. (1)) with the structure of CIE94 [6]. The weighting function for lightness in the AUDI2000 color-difference formula is named S_{L,γ_i} , and it is given in Eq. (2):

$$\Delta E_{AUDI2000,\gamma_i} = \left[\left(\frac{\Delta L_{\gamma_i}^*}{S_{L,\gamma_i}} \right)^2 + \left(\frac{\Delta C_{ab,\gamma_i}^*}{S_{C,\gamma_i}} \right)^2 + \left(\frac{\Delta H_{ab,\gamma_i}^*}{S_{H,\gamma_i}} \right)^2 \right]^{1/2} \quad (1)$$

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

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 $i=1, \dots, 56$ color pairs). In the past few years the *STRESS* index [21] 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 [22], 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* (see Eq. (3)). While the *STRESS* index gives the same weight to all color pairs (i.e. $w_i = 1$; $i=1, \dots, 56$), the *WSTRESS* index assigns different weights to each color pair, those with higher accuracy (lower inter-observer variability) having a higher weight. Following Berns [23], here we have adopted as weight a reciprocal variance, defined as the square of the average visual difference of all observers divided by 4 times their standard deviation (both measured in CIELAB units), as shown in Eq. (3):

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

3. 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 [17]. After this transformation, the *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 in [17] where some of the observers participating in the experiment were not experienced. However, in the current experiment most observers had considerable previous experience in visual color-difference experiments. Even so, a first analysis of the visual results in the current experiment indicated that the answers from some observers in some color pairs appeared as outliers. Accordingly, 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, respectively. This procedure resulted in 73 removed visual answers (i.e. about 4% of total answers) and a new lower inter-observer variability of 18.2 units. Therefore, 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. After removing outliers, the standard deviation of the 3 visual assessments performed in each color pair was on the average 0.78 CIELAB units.

Table 1 shows *STRESS* and *WSTRESS* values for each one of the color-difference formulas tested in this paper. The parametric factors in all tested color-difference formulas were assumed as 1. For the CAM02-SCD and CAM02-UCS color-difference formulas, we adopted 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 shown in Table 1, the best predictions (lowest *STRESS* and *WSTRESS* values) of our visual experimental results were found for the AUDI2000 color-difference formula, followed by the CAM02-SCD, CAM02-UCS, CIEDE2000 and DIN99d color-difference formulas. In fact, from values in Table 1 it can be concluded that, at a confidence level of 95%, any of these four color-difference formulas is significantly different to the AUDI2000 formula.

This result agrees with the one reported in our earlier experiment in [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 *STRESS* value of 27.3 units achieved by the AUDI2000 color-difference formula in our current experiment is considerably higher than the inter-observer variability (18.2 units), which means that the AUDI2000 formula 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 assigned to the color pairs with higher uncertainty in observers' visual assessments.

Table 1. Performance of 11 advanced color-difference formulas against the 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.

Color-Difference Formula	<i>STRESS</i>	<i>WSTRESS</i>
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

We have optimized independently the four coefficients (a_i ; $i=1, \dots, 4$) in the weighting function for lightness of the AUDI2000 color-difference formula (Eq. (2)). Table 2 shows the original values of each one of these coefficients (second column) and the optimized ones, both, from results in our previous experiment in [17] (third column) and from results in current experiment (fourth column). Last column in Table 2 shows the *STRESS* values from the optimized coefficients in the current experiment. As we can see, all optimized coefficients except a_1 are enough different to the ones in the original AUDI2000 color-difference formula. However, taking into account that the original AUDI2000 color-difference formula achieved a *STRESS* value of 27.3 for the results in the current experiment (see Table 1), we can see that, unfortunately, in the best case the optimized coefficients in our experiment only produced a small decrease in *STRESS* values around 2 units (see Table 2, last column), which means a very small improvement of the original AUDI2000 formula. Likely, a simultaneous optimization of the four coefficients involved in Eq. (2) may produce a higher *STRESS* decrease. By comparing the third and fourth columns in Table 2, it can be also noted that the values of the coefficients minimizing *STRESS* in our earlier experiment in [17] were enough similar to those found in the current experiment, 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 the previous 0.01 value, because for highly achromatic homogeneous colors this last value may lead to values of the weighting function for lightness close to zero (see Eq. (2)), resulting in very high unacceptable/anomalous values of AUDI2000 color differences.

Table 2. Original and (two sets of) optimized coefficients (a_i ; $i=1,\dots,4$) in the AUDI2000 color-difference formula (Eq. (2)). The *STRESS* value for the original AUDI2000 formula was 27.3. Columns 3 and 4 in the last row show exponents α improving the original AUDI2000 formula (in the case of the two values marked with asterisks this improvement was only 0.02 *STRESS* units).

Coefficients	Original Values [14]	Optimized Values in [17]	Current Optimized Values	<i>STRESS</i> for Current Optimized Values
a_1	1.0	1.1	1.1	27.3*
a_2	0.67	0.5	0.3	25.2
a_3	0.002	0.01	0.01	27.3*
a_4	0.33	0.01	0.7	26.0
α	1.0	0.82	0.65	18.7

Finally, from last row in Table 2 it is worth to mention that an exponent $\alpha=0.65$ in the original AUDI2000 color-difference formula produced a very important decrease of about 8.6 units in the *STRESS* value found in our current experiment. The use of this kind of power functions ($\Delta E' = \Delta E^\alpha$) in color-difference formulas was originally proposed by Attridge and Pointer [24], and it has been proved also useful in other previous experiments [25], including the one in [17] where the optimum value for the exponent α was 0.82. Interestingly, the value of 18.7 *STRESS* units found with $\alpha=0.65$ (Table 2, last column) is very close value to the 18.2 *STRESS* units corresponding to the inter-observer variability in our current visual experiment.

4. Conclusions 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 tested the weighting function for lightness in the AUDI2000 color-difference formula, complementing results found in another previous experiment [17]. Our current results confirm that AUDI2000 is a good color-difference formula while its weighting function for lightness seems to be not optimal. Beside some advances, we must conclude that the proposal of a modified weighting function for lightness in the AUDI2000 formula 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 new visual assessments using color pairs with chroma and hue flops, because current color pairs and results are mainly related to lightness flop. The option of a power function as a second-step transform to improve the results achieved by the original or optimized AUDI2000 formulas seems very promising. The possibility of developing a total-difference formula involving coarseness and sparkle in addition to color, as previously suggested by other authors [26], must be also considered in future improvements of current AUDI2000 color-difference formula.

Acknowledgments

Authors are grateful to all volunteer observers at the Department of Optics of the University of Granada (Spain) participating in the visual 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 FIS2013-40661-P and DPI2011-30090-C02, with European Research Development Fund (ERDF), as well as by the National Science Foundation of China (grant number 61178053).

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