Visual and Instrumental Assessments of Color Differences in Automotive Coatings

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Abstract: The interest in gonioapparent pigments (metallic, pearlescent, interference, or diffractive) has increased in the last few years, especially for applications in the automotive industry. To assure a proper characterization of colors with gonioapparent pigments, commercial devices have appeared to characterize the color in different geometries, which are called multiangle spectrophotometers. As the gonioapparent pigments and multiangle instruments are relatively new, no studies exist regarding the instrumental-based procedure followed in the industry, and if the results provided are in agreement with the observer perception.

Consequently, the main objective of this study was to examine the correlation of the instrumental color differences with visual assessments. The instrumental color difference was calculated with the color difference formula AUDI2000 (specific for this sector) between the pairs of similar samples of three types of coated panels (solid, metallic, and pearlescent). The values measured by a telespectroradiometer in a directional lighting booth and the colorimetric values obtained by means of a multiangle spectrophotometer BYK-mac were considered for this purpose. Additionally, a visual experiment was conducted to quantify the color difference by using the gray-scale method.

The results revealed that an acceptable instrumental correlation existed despite the visual and the instrumental correlation being worse. In particular, it was checked that observers accepted a larger number of color pairs, that is, the visual color difference was smaller than the tolerance demanded by the industry (derived from AUDI2000). © 2015 Wiley Periodicals, Inc. Col Res Appl, 00, 000–000, 2015; Published Online 00 Month 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/col.21964

Key words: vision; color; color measurement; perception psychology; psychophysics; industrial inspection

INTRODUCTION

The interest in gonioapparent pigments applied in many industries (cosmetics, inks, etc.) continues increasing day by day, especially in the automotive sector. This sector has undergone many changes and updates in the last years[1,2] from employing only paints without special visual effects using many gonioapparent pigments, thus providing new and attractive visual effects by combining variable color and texture according to irradiation and viewing directions.

Goniochromatism is a change in any or all attributes of color of a specimen angular illuminating–viewing conditions are changed, but without change in light source or observer.[3] This happens when the material that is under evaluation includes gonioapparent pigments. Therefore, it is possible to classify the materials into three types according to the pigment recipe and its colorimetric behavior[4–6]: solid, metallic, and pearlescent or interference coatings (Fig. 1, right). The solid color includes only scattering and absorbing pigments, and hence, the

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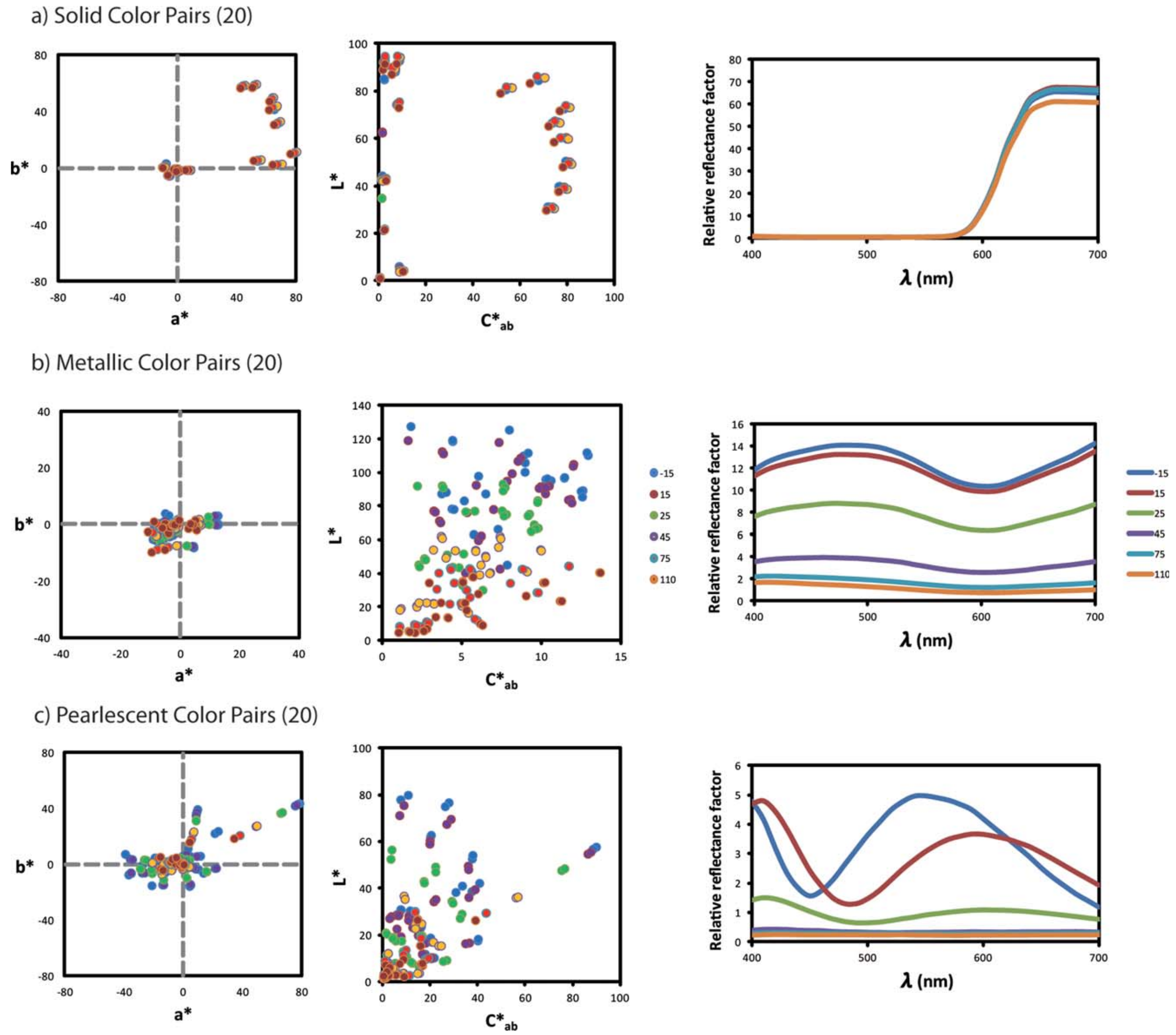

Fig. 1. Left: Color appearance of the 60 assessed color pairs. Right: Colorimetric behavior according to the pigment recipe.

perceived color does not show significant changes when the direction of lighting and/or detection is changed. The metallic coating includes metallic pigments that provide a color shift mainly in lightness. The pearlescent coating includes in its recipe pearlescent pigments (even solid pigments) that provide a color shift mainly in hue and a chroma change.

Currently, in the automotive sector, color quality of automotive coatings with gonioapparent pigments is performed by characterizing the color under different measurement geometries.[5,7–10] For this, commercial devices, called multiangle spectrophotometers, are able to characterize the color in different geometries, such as BYK-mac, or X-Rite MA98, which satisfy ASTM and DIN standards.[11–14]

Although multiangle spectrophotometers are commonly used in the automotive industry, there are few studies focused on the correlation between instrumental measurements and visual assessments by using rightly directional lighting booths.[15–17] In other words, there are no studies to check if the procedure followed in the industry, mainly based on the instrumental measures of a multiangle spectrophotometer, would match the decision that an observer would give.[18] The conventional approach using a diffuse lighting booth and an integrating sphere spectroradiometer is not valid for gonioapparent colors, and hence it is necessary to use a commercial directional lighting booth such as the gonio-vision box from Merck or the byko-spectra effect cabinet from BYK-Gardner.

The purpose of this study is to study the correlation of the visual and instrumental assessment of the color differences between pairs of similar samples. The instrumental measurements were made with two different measurement devices: BYK-mac multiangle spectrophotometer and PR-650 telespectroradiometer. In addition, a psychophysical experiment that included a directional lighting booth was designed to obtain the visual assessments to quantify the color difference by the comparison with a standard gray scale for color differences.

MATERIALS AND METHODS

A total set of 60 pairs of different samples from solid, metallic, and pearlescent pigments were selected (Fig. 1, left). For this study, knowing previously the pigment formulation of this panels was not important though it could be interested in other future studies, because we only focused in the optical and colorimetric behavior, not structural (pigments type, size, shape, etc.). Figure 1(a) (left) shows the a*b* and L*C* chromatic diagrams with the representation of the 20 solid color pairs. The different colors indicate the different measurement geometries, and the different symbol, circle, and square, the two color samples of one color pairs. Figure 1(b) (left) shows the representation at both chromatic diagrams for the metallic color pairs. Finally, Fig. 1(c) (left) shows the pearlescent color pairs. In this figure, it can be seen that the color gamut associated with the selected color samples and the behavior of each kind of pigment, solid, metallic, and pearlescent.

The color differences between pairs of samples were calculated by the color difference Formula (1) AUDI2000,[19,20] based on the CIELAB color space. This color difference formula was developed by and is used by AUDI, without being endorsed by any standardization body up to this point, with the main purpose to manage the color tolerances varying depending on the specific application, paint batch acceptance, color matching for add-on parts in the car body, refinish, and so forth.

AUDI2000 color difference formula was especially designed for materials with gonioapparent pigments; then, it considers the changes that these materials show depending on the angle of illumination and observation (flop) as follows:

$$\Delta E_\gamma = \sqrt{\left(\frac{\Delta L_\gamma}{s_{\Delta L,\gamma} g_{\Delta L}}\right)^2 + \left(\frac{\Delta C_\gamma}{s_{\Delta C,\gamma} g_{\Delta C}}\right)^2 + \left(\frac{\Delta H_\gamma}{s_{\Delta H,\gamma} g_{\Delta H}}\right)^2} \quad (1)$$

$$s_{\Delta L_{\gamma_i}} = \left(\frac{|L^*_{\gamma_i} - L^*_{\gamma_{i+1}}|}{\gamma_{i+1} - \gamma_i}\right)^{2/3} + 0.002C^*_{45} + 0.33 \quad (2)$$

$$= s_{\Delta L\gamma i,\mathrm{Flop}} + s_{\Delta L\gamma i,\mathrm{Solid}} + 0.33 \quad (3)$$

$$s_{\Delta C_{\gamma_i}} = 1.478\left(\frac{|C^*_{\gamma_i} - C^*_{\gamma_{i+1}}|}{\gamma_{i+1} - \gamma_i}\right) + 0.014C^*_{45} + 0.27 \quad (4)$$

$$= s_{\Delta C\gamma i,\mathrm{Flop}} + s_{\Delta C\gamma i,\mathrm{Solid}} + 0.27 \quad (5)$$

$$s_{\Delta H_{\gamma_i}} = 0.800\left(\frac{|C^*_{\gamma_i} - C^*_{\gamma_{i+1}}|}{\gamma_{i+1} - \gamma_i}\right) + 0.004C^*_{45} + 0.30 \quad (6)$$

$$= s_{\Delta H\gamma i,\mathrm{Flop}} + s_{\Delta H\gamma i,\mathrm{Solid}} + 0.30 \quad (7)$$

Where "*s*" are the weighting functions and "*g*" are the parametric factors for each term, lightness, chroma, and hue, and γ is referred to the measurement geometry, with $\gamma_i \in \{15°,\ldots,110°\}$. To obtain a weighting for the measurement angle of 110°, we use half the value of the flop term from the angle, 75°. For the negative effect angle −15°, we specified to use the weighting for the 15° angle multiplied by a factor 1.2..[20]

In this study, the instrumental evaluation is carried out using two different strategies. On the one hand, the color difference was calculated by using the measurement data performed by the commercial multiangle spectrophotometer BYK-mac. This is a device that measures the samples by contact in six different geometries. This methodology is called "direct measurement," and it is the usual procedure in the automotive sector.

On the other hand, a system consisting of the telespectroradiometer PR-650, and the directional lighting booth, the byko-effect spectra cabinet (from BYK-Gardner)[21] was used to obtain the real spectral color stimulus and the corresponding colorimetric values of all samples without contact, never used in the automotive sector, in spite of having directional lighting booths in this sector. The main advantage of this indirect system is that it collects exactly what the observer would perceive, the PR-650 has a telecentric lens, with a measuring area of 1° and the distance to the spot area was about 55 cm. For this reason, this methodology was called "(true) visual simulation." In addition, a reference white placed at the same position as the samples was measured with the spectroradiometer to allow transformations to CIELAB color space by means of the absolute XYZ values (in cd/m^2), enabling us to apply absolute colorimetry into relative colorimetry as it is usual in color appearance models.[22] The byko-effect cabinet was selected because it allowed measuring the same geometries of illumination/observation that the BYK-mac. It is important to mention that the luminaire of the byko-effect spectra cabinet is a not a good D65 simulator rather it is closer to a D50 simulator.[23,24] We referred to both methodologies as direct measurement and visual simulation; however, it is important to point out that both arise from different instruments. But, obviously, the method described above can be applied to other directional lighting booths, with or not the same nominal geometries common with other multiangle spectrophotometers.

The measurement geometries used were fixed by the multiangle spectrophotometer and the lighting booth: 45as-15, 45as15, 45as25, 45as45, 45as75, and 45as110, written by following ASTM standards (Fig. 2). These measurement geometries can be rewritten by following the CIE nomenclature[25] as: 45°x:−60°, 45°x:−30°, 45°x:−20°, 45°x:0°, 45°x:30°, and 45°x:65°, respectively. The illumination angle was constant for all the measurement geometries.

For the visual evaluation, a psychophysical experiment was conducted by using a gray chart of the Society of Dyers and Colourists[26] for qualifying the color difference perceived in the byko-spectra effect cabinet (Fig. 3, left). The gray chart used consisted of nine neutral gray chip pairs, which are ordered in increasing color difference.

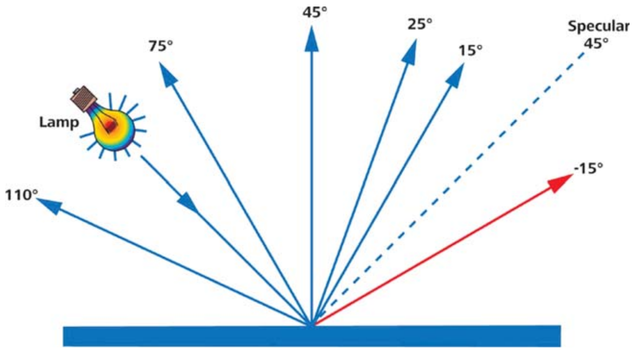

Fig. 2. Schematic representation of the illumination/measurement geometries used with the BYK-mac device for color characterization.

The gray scale was measured both with the BYK-mac for the experiment called "direct measurement," and with the PR650 for "visual simulation" experiment. To obtain true values for the calibrated visual assessment, that is, the visual color difference ΔV which is the subjective answer provided by the observers from the visual assessments, a transformation had to be done to the values that related to the color differences calculated from the instrumental measurements of the gray scale. The CIELAB color difference (ΔE^*_{ab}) was selected for this purpose as it is traditionally used for this transformation.[27] The gray pairs were measured at each angle, following the same methodology applied in the previous study,[19] and a fourth polynomial fitting was found to be the best to adjust the values in the scale color differences obtained through instrumental measurements for each of these observation angles (Fig. 3, right). Thanks to this adjustment, the visual color difference (ΔV) for a given angle can be interpolated and directly related to ΔE^*_{ab}. For this experiment, 10 observers were included (five men and five women) with normal color vision. In each 30-min session, the observer performed 120 evaluations, having a total of 1080 evaluations done in nine sessions (three repetitions in each session). The color pairs and the different measurement geometries were randomly presented to the observers. Before each session, the observer spent 3 min to adapt to the illuminance level and cabinet environment. The observer's task was to quantify the color difference in the test pair by comparing with the color differences shown in the several gray pairs (Fig. 3, left).

The STRESS index (standardized residual sum of squares) was used to evaluate the performance of the color difference formula with respect to the visual assessments obtained.[28,29] As a consequence, the lower the STRESS values, the better the correlation. In addition, the STRESS index was used not only to estimate the color difference performance but also to know how reliable the results were by determining the intra- and interobserver variability.[30]

The intraobserver variability refers to the differences between the results obtained when the same observer reported more than once on the same test pair. It was measured by the STRESS index, calculated from three repetitions for each observer at the same experiment. The interobserver variability refers to the differences between the results produced by different observers. It was also calculated by means of the STRESS index, considering the total average of the 10 observers and the mean value of three replicates of each observer.

RESULTS

The psychophysical assessments and the instrumental data allowed determining the instrumental and visual correlation regarding the experiment executed.

Observer Variability

The average intraobserver variability obtained in this experiment was 23.65 STRESS units and the average interobserver variability was 28.25 STRESS units. Although there were two observers who showed high intravariability, the calculated values were good compared with the previous studies.[19,31]

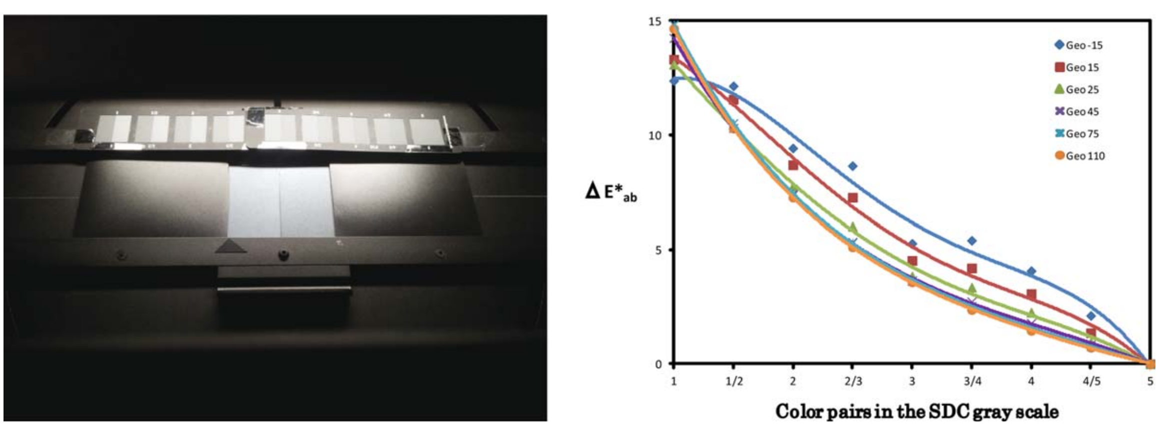

Fig. 3. Left: Which gray pair is closer to the color difference seen in the color pair? Right: CIELAB color differences for each one of the nine color pairs in the SDC gray scale. Fourth degree polynomial fit, R^2 (−15) = 0.9849, R^2 (15) = 0.9938, R^2 (25) = 0.9975, R^2 (45) = 0.9998, R^2 (75) = 1, and R^2 (110) = 1.

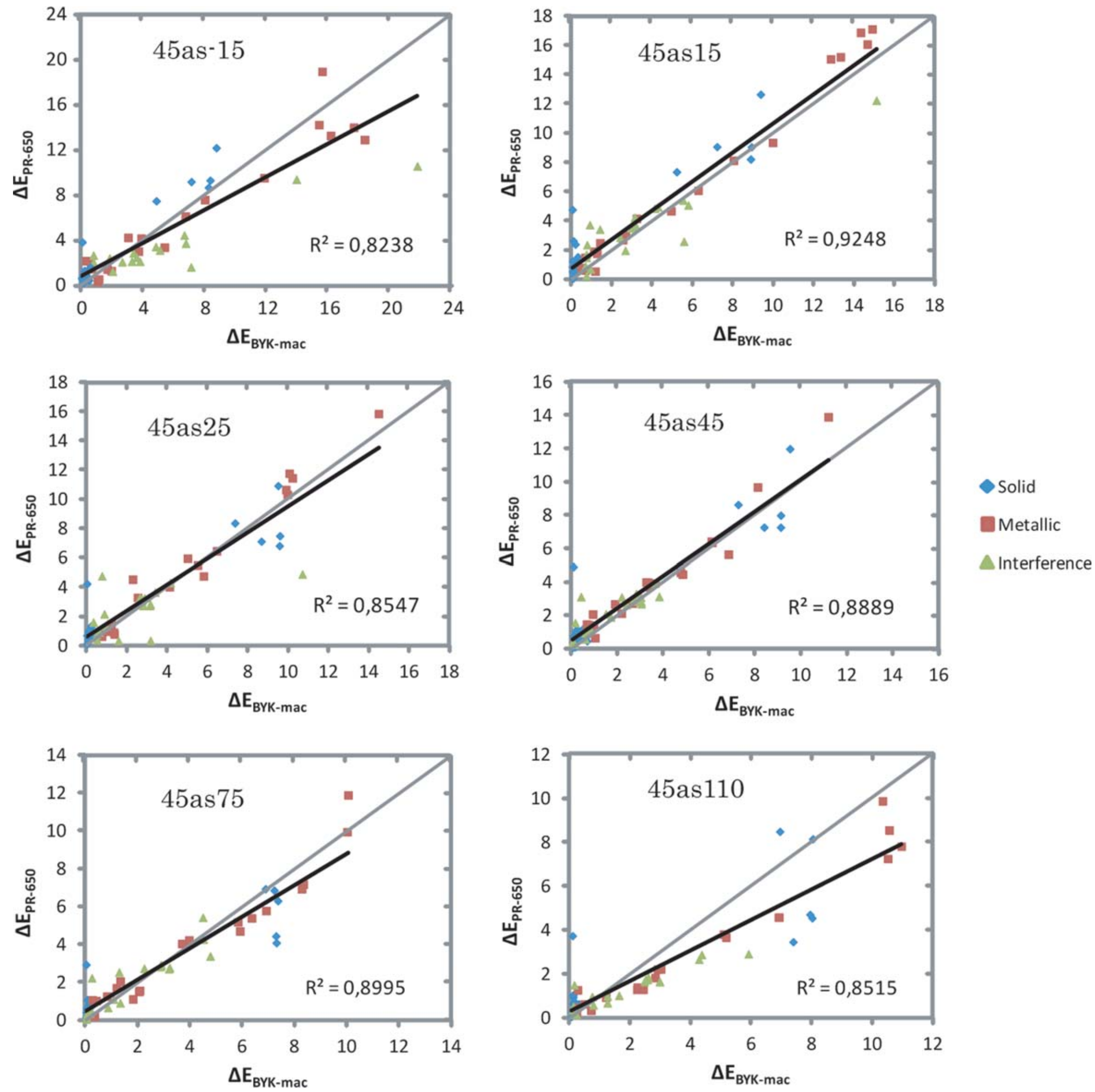

Fig. 4. Instrumental correlation obtained from the color differences of the instruments for the geometries 45as-15, 45as15, 45as25, 45as45, 45as75, and 45as110. Different colors are used to identify the sample type (blue, solid; red, metallic; and green, pearlescent pigment).

Instrumental Correlation

Before analyzing the visual and instrumental correlation, an instrumental correlation between the two measurement methodologies (direct measurement and visual simulation) was done. The AUDI2000 color difference ($\Delta E_{\mathrm{AUDI2000}}$) was calculated by considering the measurements from the BYK-mac multiangle spectrophotometer, fixating the D65 illuminant, and the measurement from the PR-650 telespectroradiometer from the true spectral stimuli, that is, the combination of the true lamp into the booth and the spectral reflectance of the panel for this measurement geometry. Next, a correlation of these instrumental data (BYK-mac and PR-650) was performed by using a graphical analysis in which the values of $\Delta E_{\mathrm{AUDI2000}}$ obtained in the different conditions were compared.

Ideally, a linear correlation of slope close to 1 in $\Delta E_{\mathrm{AUDI2000}}$ values was expected. These values were generated with both measuring instruments for each of the measurement geometries. In these conditions, a pair of panels would exhibit similar color differences by using the BYK-mac multiangle spectrophotometer ($\Delta E_{\mathrm{BYK\text{-}mac}}$) and by using the PR-650 telespectroradiometer and the cabinet ($\Delta E_{\mathrm{PR650}}$) although they were analyzed with the BYK-mac and the telespectroradiometer PR-650 plus the lightning booth, respectively. In addition, the correlation would be linear in spite the fact that the method that involves the telespectroradimeter and the lightning booth contains higher variability in the position/direction of the instrument, orientation of panels, and the spectral quality of the daylight D65 simulation installed into the lighting booth.

Plots in Fig. 4 show the correlations in terms of the color differences ($\Delta E_{\mathrm{PR\text{-}650}}$ and $\Delta E_{\mathrm{BYC\text{-}mac}}$) for the 60 color pairs classified by measurement geometry. There was a good correlation between both instruments and

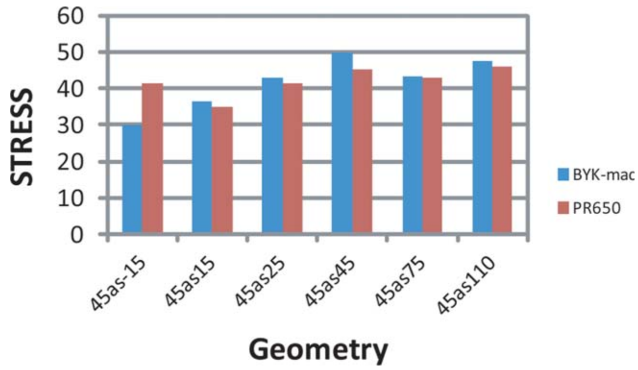

Fig. 5. STRESS values calculated for both instrumental color differences.

methods although it was not perfect. The differences found may be due to several factors. First, the fact that the light source (fluorescent lamp) was not the same. Although using the BYK-mac the reference illuminant is the D65, the light source of the byko lighting booth, both belonging to the same company, is closer to the D50 illuminant.[30,31] Second, the illumination/observation conditions may be slightly altered between various measurements, and this is especially relevant in goniochromatic samples where color strongly depends on the measurement configuration.

It is notable that the correlation between both methodologies was poorer for the geometry 45as-15. Although the 45as-15 and 45as15 geometries were equally close to the specular direction, the geometry of 45as-15 was experimentally the most conflicting as in this direction the intensity of the reflected light was higher than in other more distant specular geometries. In general, a great spreading was found for the geometries 45as-15 and 45as110. In addition, some color pairs did not follow a linear behavior as expected. As these measurement geometries are the extreme ones in both instrumental configurations, this could be the reason why a worse correlation is found, specifically because of some optomechanical design problems for applying telespectroradiometry on a tilted scene. However, for 45as25, 45as45, and 45as75 geometries which progressively move away from the specular peak, the intensity of the reflected light decreased the goniochromatic effects, there was less spreading in characterizing the samples and the results of color difference matched more closely for both procedures.

Visual and Instrumental Correlation

The next step was the evaluation of the visual and instrumental correlation. As it was mentioned before, the correlation was evaluated by the STRESS index. Therefore, this index was calculated for both instrumental color differences (BYK-mac and PR-650) by considering the visual differences obtained from the psychophysical experiment. In Fig. 5, a histogram is shown for the STRESS values calculated for both color differences and measurement geometry. As it can be seen, the results were very similar for both color differences. The STRESS average for all geometries was of 39.78 and 40.87 units for BYK-mac and PR-650 data, respectively. This result was already expected as the correlation between both instruments was acceptable as shown previously.

A set of color pairs was identified having high deviations between the visual assessment and the instrumental measurement, even for both methodologies. These are types of samples that would cause problems in the industry. Therefore, the multiangle spectrophotometer would not accept the color pair as a good color matching, but an observer would.

Furthermore, color pairs that generated conflicts, that is the response of the instrument was different from the observer's decision, were identified and selected. Therefore, a new analysis was done to show for each color pair, the correlation of both processes, instrumental and visual evaluation, in each measurement geometry. This analysis consisted of doing a representation (Fig. 6) by denoting with zones the criteria established by the AUDI color tolerances. In this way, it was easy to visualize if the samples presented acceptable color differences or not.

Based on the AUDI tolerance criteria, all samples with $\Delta E > 1.7$ units would be placed within the red zone and would be considered as different; samples with color differences between 1.4 and 1.7 would be at the yellow

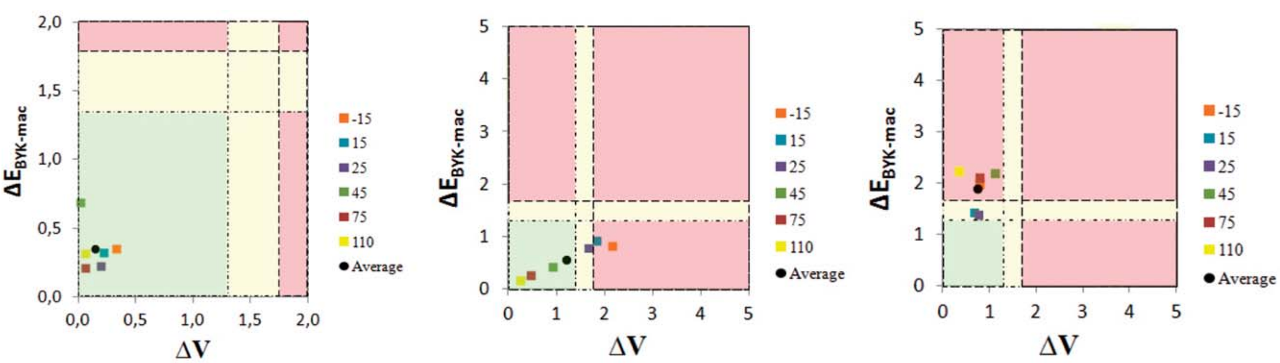

Fig. 6. Color differences for all the measurement geometries for (a) solid sample, (b) pearlescent sample, and (c) metallic sample following the criterion Passes/Not Passed. The green region means almost indistinguishable color differences, the red zone means rejected color pairs, and the yellow zone means critical color differences; samples need to be visually assessed by expert colorists.

zone, where samples should be studied with other visual tests to establish if they pass or not; finally, the green area would contain samples with $\Delta E < 1.4$, which could be considered almost indistinguishable.

Once the most troubled samples were identified and analyzed, three pairs of characteristic samples were selected as shown in Fig. 6. In this case, measurement data from the BYK-mac were used as it is a common instrument used in the automotive industry.

Figure 6(a) shows the color differences for all the measurement geometries for a solid sample. As it can be noticed, there was a good correlation between visual and instrumental assessments, which means that for both methodologies the color difference of the color pair was indistinguishable (green region). This situation should be the real one, where the information provided by the instrumental analysis and visual evaluation would be equivalent.

Figures 6(b) and 6(c) show an opposite situation. These examples correspond to pearlescent and metallic samples, respectively. In the pearlescent sample, the color pair was accepted by the BYK-mac (for all the measurement geometries) but rejected by the average observer. On the contrary, for the metallic sample the average observer accepted the color pair as a good color matching or approval, whereas the color difference calculated from the BYK-mac measurements was big enough to consider the color pair as not good or fail. Therefore, it would be interesting for car makers and coating providers to know what type of automotive colors or recipes (by hues, flops, etc.) are prone to be associated with the cases shown in these figures.

It is important to mention that with the PR-650 data, the results were similar to those obtained using the BYK-mac as in the majority of samples, pairs were accepted by observers, but rejected by the instrument, as for the BYK-mac.

CONCLUSIONS

The correlation between visual and instrumental evaluation was performed with a set of automotive samples. Two instrumental evaluations were conducted, a direct measurement with the BYK-mac multiangle spectrophotometer, and a visual simulation with the PR-650 telespectroradiometer and the byko-effect lighting cabinet, with the same measurement geometries setup than in the BYK-mac. The visual evaluation was conducted by a conventional psychophysical experiment where observers quantified the color difference in color pairs by using the gray-scale method. The observer variability showed that the observer responses were consistent enough.

First, a comparison between both instrumental evaluations was done. The results exhibited an acceptable correspondence between both methodologies. Nevertheless, a slight measurement mismatch that could be due to the illuminant–light source differences or different geometries configurations was found.

Second, the study of the visual and instrumental correlation was carried out. The performance of the AUDI2000 color difference with the visual assessments done by observers was evaluated by the STRESS index. The results revealed that it would be possible to obtain a better performance by improving the color difference formula as the observer variability was lower than the performance of the color difference. A detailed analysis was done for each color pair. A number of color pairs were identified to have instrumentally color differences far away from visual color differences. It was determined that the general tendency was that observers gave lower color difference values than those provided by the devices. This implies that observers accepted a larger number of valid color pairs compared with those accepted by the devices, despite being "experts" in color, although not color automotive engineers. Therefore, it could be concluded that there was not a perfect correlation between instrumental and visual evaluation and that it would be interesting to analyze which parameters can influence, and how, in this correlation failure related with commercial color devices typically used in the automotive sector. One approach would be to improve the AUDI2000 color difference formula or to propose a new one to obtain a better performance. Taking into account that the observer variability was lower than the performance of the color difference, it would be possible to improve the AUDI2000 color difference formula to find a better correlation with visual evaluations. Other strategies, even combining with the first approach, would be to use a better D65 simulator, a more powerful lamp for a higher level of illumination, better lighting uniformity, or even use a specified gray card with smaller steps to compare directional level colors. This experiment should also be done with professional colorists of the automotive industry and with normal observers (with no experience in colorimetry), to see whether the level of experience affects ΔV. Therefore, this justifies that it is necessary to apply both methodologies, visual and instrumental evaluation, to avoid this kind of discrepancies. Alternatively one could improve directional lighting booths, by using better D65 simulators and high illuminance levels, either based on current fluorescent lamps or based on new solid-state lighting sources as LEDs.

In conclusion, the new main contributions of this article is the use of telespectroradiometry for testing the visual and instrumental correlation in automotive coatings at the realistic way, showing that this instrumental technique for measuring the true spectral stimuli is necessary to understand and manage doubtful color pairs for the final color matching/approval. It can be applied to new experiments and studies crossing structural (formulation, pigment size, etc.) and colorimetric data.

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