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Reproducibility comparison among multi-gonio-spectrophotometers

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New color-measuring instruments known as multi-gonio-spectrophotometers have recently been created to measure and characterize the goniochromism of special-effect pigments in many materials with a particular visual appearance (metallic, interference, pearlescent, sparkle or glitter). These devices measure the gonio color appearance from the spectral relative reflectance factor and the L*a*b* values of the sample with different illumination and observation angles. These angles usually coincide with requirements marked in ASTM and DIN standards relating to the gonio color appearance characterization, but little is known about the extent of agreement between these new instruments. The main purpose of this study, therefore, is to compare several multi-gonio-spectrophotometers at a reproducibility level according to ASTM E2214-08 guidelines. In particular, we compared 2 X-Rite multi-gonio spectrophotometers (MA98 and MA68II), a Datacolor multi-gonio spectrophotometer (FX10) and a BYK multi-gonio spectrophotometer (BYK-mac). These instruments share only 5 common measurement geometries: 45ºx:-30º (as 15º), 45ºx:-20º (as 25º), 45ºx:0º (as 45º), 45ºx:30º (as 75º), 45ºx:65º (as 110º). Specific statistical studies were used for the reproducibility comparison, including a Hotelling's test and a statistical intercomparison test to determine the confidence interval of the partial color differences ΔL*, Δa*, Δb*, and the total color difference ΔE^{*}_{ab}. This was conducted using a database collection of 88 metallic and pearlescent samples, which were measured 20 times without replacement for all the instruments. The final findings show that in most measurement geometries, the reproducibility differences between pairs of instruments are statistically significant, although in general there is a better reproducibility level at certain common geometries for newer instruments (MA98 and BYK-mac). This means that these differences are due to systematic or bias errors (angle tolerances for each geometry, photometric scales, white standards, etc.), but not exclusively to random errors. However, neither of the statistical tests used is valid to discriminate and quantify the detected bias errors in this comparison between instruments.

Keywords: color measurement; instrumentation; goniochromism; color tolerances

Introduction

In recent years, technological innovation in all areas has led, among other things, to the appearance of new materials such as metallic and pearlescent objects developed from special-effect pigments that produce goniochromatic effects, i.e. they present notable color changes under differently illumination-viewing conditions. These pigments are used in many industrial activities, such as automotive coatings, cosmetics, plastics, security inks, building materials and the visual simulation of virtual environments. Their popularity is due to the fascinating interplay of colors and to effects produced by the various materials used in their layered structures [1-3]. Refractions and reflections of light at and within these layers cause interferences that yield certain colors [4], in an attempt to replicate natural colors seen in lesser animals such as butterflies and insects [5].

It is difficult to measure and characterize these kinds of color samples by conventional color measuring instruments based on an integrating sphere [6]. The optical behavior of these materials is determined by the spectral bidirectional reflectance distribution function (BRDF), defined as the spectral ratio between the radiance of the sample in a given direction and the irradiance over that sample. In recent years, various authors have proposed new multi-angle spectrophotometers made from multi-spectral imaging systems [7-10] to allow for direct measurements of the spectral BRDF (sBRDF) of any material, even from remote sensing [11-12]. Measuring the sBRDF is not an easy task, and requires highly qualified resources, so some instruments are designed to measure the spatial distribution of the reflectance factor in different geometrical configurations. In most of these, three or five geometry configurations are implemented, as established by the DIN-6175-2 [13] and the ASTM E2194-03 and E2539-08 [14] standards, respectively. In particular, measurements at various angles of illumination for the same difference angle (± 15º) with respect to the specular direction yield an interference line that is peculiar to the particular interference pigment involved. Measurements made at a constant angle of illumination (e.g. 45°) for various angles of observation and difference angles yield an aspecular line. For many years, multi-gonio-spectrophotometers were used to characterize the aspecular line, such as the MA68II, which has been widely used over the past two decades. However new interference pigments have begun to appear on the market, leading to more complex multi-gonio-spectrophotometers with more measurement geometries in order to characterize the interference line.

Many authors have made comparisons between conventional spectrophotometers in recent years [15-20], yet there is a lack of research into multi-gonio-spectrophotometers used to characterize goniochromism [21]. ASTM E2214 [22] specifies a number of multivariate methods for analyzing reproducibility measurements. Reproducibility is understood intuitively to be the degree to which an instrument makes consistent measurements even when conditions are slightly changed, whereas repeatability is how well an instrument can repeat identical measurements.

Therefore, the purpose of this study is to compare the reproducibility of various multi-gonio-spectrophotometers, specifically the Datacolor FX10, X-Rite MA68II, X-Rite MA98 and BYK-mac models, following the ASTM E2214-08 rules for the five common measurement geometries in order to evaluate the extent to which their readings coincide. In particular, reproducibility analysis is performed only for the aspecular line, as the measurement geometries associated with the interference line are not common for all the instruments used in this study.

Materials and Methods

Instruments

A set of four multi-gonio-spectrophotometers were used to analyze the extent to which they coincided. The X-Rite MA68II multi-angle spectrophotometer (1) was designed for measuring color on metallic and pearlescent paint finishes and printing inks, and incorporates a single light source and 5 fixed (aspecular) viewing angles in accordance with the cited 20-year-old standards. The MA98 multi-angle spectrophotometer (2) is a new instrument from the X-Rite company, providing 10 measurement angles and 2 illumination angles, which in combination allow for 19 measurement geometries, 11 in-plane and 8 out-of-plane. The Datacolor FX10 (3) is an abridged multi-gonio-spectrophotometer with 10 measurement geometries, and includes the 5 geometries from the previous standards as well as a further 5, such as the light reflected at directions closer to the incidence direction. Finally, the BYK-mac spectrophotometer (4) measures both multi-angle color and sparkle characterization in a portable device. It also has the traditional 5-angle color measurement, and an additional color measurement behind the gloss for the color travel of interference pigments 45ºx:-60º (as -15º). Table 1 summarizes the 5 common geometries of these instruments.

Data collection

The database used contains 88 goniochromatic metallic and interference color samples collected from various technical color charts from different manufacturers. They were measured 20 times without replacement for all the instruments after a long stand-by period (more than 20 minutes). The average values were then considered in order to conduct the reproducibility study.

The spectral reflectance factors were measured from 400 to 700 nm, sampled every 10 nm and the colorimetric coordinates were obtained from each multi-gonio spectrophotometer for the CIE D65 illuminant and the CIE 10º standard colorimetric observer [23].

Experimental Procedure

The ASTM E2214 standard specifies that instrument differences can be calculated between pairs of instruments. By using this recommendation, 6 comparisons were possible: FX10 vs. MA68II, FX10 vs. MA98, FX10 vs. BYK-mac, MA68II vs. MA98, MA68II vs. BYK-mac, and MA98 vs. BYK-mac.

Firstly, from the mean values of 20 measurements for each sample, the partial and total color differences were calculated in the CIELAB color space for all the possible combinations. At an ideal reproducibility level, all color differences would be zero.

Secondly, as stated previously, a statistical study of the reproducibility comparison between devices was conducted, by calculating the average and mean square deviation of the colorimetric values. These statistical studies included Hotelling's test and a statistical intercomparison test.

Hotelling's T^2 test describes the acceptance volume of an instrument in terms of ΔL^*, Δa^*, and Δb^* relative values. This is a multivariate metric that indicates the tolerance volume of an instrument for a given statistical significance. T^2 is calculated from a given sample's color difference data and the population covariance matrix (S) of color difference data:

$$S = \begin{bmatrix} \mathrm{var}(\Delta L^*) & \mathrm{cov}(\Delta L^*, \Delta a^*) & \mathrm{cov}(\Delta L^*, \Delta b^*) \\ \mathrm{cov}(\Delta L^*, \Delta a^*) & \mathrm{var}(\Delta a^*) & \mathrm{cov}(\Delta a^*, \Delta b^*) \\ \mathrm{cov}(\Delta L^*, \Delta b^*) & \mathrm{cov}(\Delta a^*, \Delta b^*) & \mathrm{var}(\Delta b^*) \end{bmatrix} \quad (1)$$

$$T^2 = n \cdot [\Delta L^* \quad \Delta a^* \quad \Delta b^*]^T \cdot S^{-1} \cdot [\Delta L^* \quad \Delta a^* \quad \Delta b^*]$$

where the superscript T indicates matrix transpose and n is the number of measurements. Each T^2 value can be tested for significance with a given a probability by using the F-distribution:

$$F_{3,n-3} = \frac{(n-3)T^2}{3(n-1)} \quad (2)$$

The ASTM E2214 standard also includes a series of pairwise comparison tests based on statistics obtained from propagation of errors and the Chi-squared statistical distribution. This test uses the $g_{i,j}$ coefficients to compute interval estimates for the component differences, ΔL^*, Δa^*, and Δb^*. In the equation 3 is the form for the statistical test:

$$\alpha = \frac{mean(\Delta L^*)}{mean(\Delta E_{ab})}, \quad \beta = \frac{mean(\Delta a^*)}{mean(\Delta E_{ab})}, \quad \gamma = \frac{mean(\Delta b^*)}{mean(\Delta E_{ab})}$$

$$g_E = g_{11}\alpha^2 + g_{22}\beta^2 + g_{33}\gamma^2 + 2g_{12}\alpha\beta + 2g_{23}\beta\gamma + 2g_{13}\alpha\gamma \quad (3)$$

$$t_{\Delta E} = \sqrt{\frac{\chi_3^2}{n \cdot g_E}} \quad , \quad n = 88$$

where χ^2 is the chi-square value for 3 degrees of freedom. This critical value is very important in this study, as it fits the limit that can be established if the total color differences ΔE^*_{ab} are statistically significant, i.e. whether or not it is likely to have occurred by chance. Specifically, if the average is higher than the critical value (ΔE^*_{ab}) > $t_{\Delta E}$, the difference is significant, i.e. for that directional geometry the measurement data are unlikely to have occurred by chance. This would mean that differences between instruments are due to systematic or bias errors (angle tolerances for each geometry, photometric scales, white standards, etc.), but not exclusively to random errors.

Results

As stated previously, the ASTM E2214 standard specifies that instrument difference can be calculated between pairs of instruments, meaning that 6 comparisons were possible.

Table 2 shows the results of the colorimetric intercomparison. The average of the partial color differences, ΔL^*, Δa^* and Δb^*, and the maximum and minimum values of these partial color differences, are shown for each pair of instruments. The color differences shown here are clearly higher than perceptibility limits, in many cases passing usual industrial color tolerances or acceptability limits. However, it is interesting to consider that the colorimetric intercomparison between the X-Rite MA98 and the BYK-mac multi-gonio spectrophotometers shows acceptable results, as in all measurement geometries the average values for the colorimetric coordinates are always lower than 1.2 ΔE^*_{ab} units. The results obtained for the other intercomparisons are very similar, as can be observed in Table 2.

Another way to visualize the previous results is to graph the CIELAB color differences (Δb^* vs. Δa^* and ΔL^* vs. ΔC^*_{ab}) between each instrument, as this displays the behavior of individual samples. In particular, Figure 1 shows the CIELAB color differences for two pairs of comparisons: a) both X-Rite instruments (MA98 and MA68II); and b) the X-Rite MA98 and BYK-mac instruments. For the 45ºx:65º (as 110º) measurement geometry, all the points are around the origin for both comparisons, which indicates that the measurements were very similar. However, in general the other measurement geometries were more broadly spread around the color difference space. It is interesting to note that instruments from the same company but released ten years apart have more deviations, whereas new instruments from different companies (such as the BYK-mac and the X-Rite MA98) have less deviation, as can be seen in Figure 1 and Table 2. Furthermore, the measurements calculated for the geometry 45ºx:-30º (as 15º), close to the glossy measurement, are more broadly spread than for the other geometries, which can be expected due to the interference and metallic nature of the samples.

Table 3 shows the multivariate statistical results from the Hotelling's test. The results were generated with an algorithm in Matlab software. The hypothesis tested was whether or not the colorimetric differences (ΔL^*, Δa^*, Δb^*) between instruments were equal to zero. The results are shown for the statistical significance of 95%, equivalent to $\alpha = 0.05$. As can be observed, for the X-Rite MA98 and BYK-mac multi-gonio spectrophotometer pair (2 vs. 4) and the Datacolor FX10 and BYK-mac multi-gonio spectrophotometer pair (3 vs. 4), the P-values for all the measurement geometries are lower than the α value. This indicates that the instruments contribute in a statistically significative way to the color difference between instruments. For the other pairwise comparisons, some measurement geometries were found not to be statistically significant, such as the 45ºx:-30º (as 15º) measurement geometry for the comparison between the MA68II and the FX10.

The ASTM intercomparison test was conducted to determine the confidence interval of the partial color differences ΔL^*, Δa^*, Δb^* and the total color, by calculating the covariance matrix S and the critical value $t_{\Delta E}$ (in accordance with equations 3). This critical value is very important, because it fits the limit that can be established if the total color differences ΔE^*_{ab} are statistically significant, i.e. whether or nor it is likely to have occurred by chance. Table 4 shows the total color differences ΔE^*_{ab} and the critical value $t_{\Delta E}$ calculated for each measurement geometry between the all the instruments. Comparing the critical value $t_{\Delta E}$ and the average of the total color differences makes it possible to determine whether or not the differences are statistically significant. In most of the cases, all the measurement geometries for the comparisons are statistically significant because the averages are higher than critical values $\overline{\Delta E^*_{ab}} > t_{\Delta E}$, i.e. these geometries are unlikely to have occurred by chance. For some pairwise comparisons, certain measurement geometries were found that are not statistically significant, such as 45ºx:65º (as 110º) for the MA68II vs. MA98 comparison. These results also coincide with all results previously obtained by the Hotelling's test for color differences.

Other measurement geometries specified for the ASTM standards are the configuration of an illumination angle of 45º and a detection angle of -60º, implying an aspecular angle of -15º, (45ºx:-60º (as -15º)), and an illumination angle of 75º and a detection angle of 90º or 120º, implying an aspecular angle of +15º and -15º, respectively: 75ºx:0º (as +15), 75:-30º (as -15). These measurement geometries are common for 3 of the analyzed instruments (X-Rite MA98, Datacolor FX10 and BYK-mac) in the first case, and for 2 instruments (X-Rite MA98 and Datacolor FX10) for the other 2 measurement geometries. For this reason, the reproducibility level for these measurement geometries and instruments was also analyzed. The average of the partial color differences, ΔL*, Δa* and Δb*, and the maximum and minimum values of these partial color differences, were calculated (Table 5 and 6) for each instrument pair. For the 45ºx:-60º (as -15º) measurement geometry, the partial color differences are higher than in the other measurement geometries; this is expected because this geometry is very close to gloss measurement. Similarly, it is interesting to note that the higher differences are in the L* value, between 4 and 12 ΔE^*_{ab} units. However, systematic differences in reproducibility in the chromatic diagram Δa* vs. Δb* were not observed (Figure 2), as the measurements are broadly spread around the achromatic point. Similar behavior can be observed in the chromatic diagram ΔC^*_{ab} vs. ΔL*, in particular with the MA98 multi-gonio spectrophotometer, which codifies the samples more lightly and more strongly than the other 2 instruments do. Results obtained from the intercomparison and Hotelling statistical tests show that the instruments for this measurement geometry contribute in a statistically significative way to the color difference between instruments. The results are similar for the other measurement geometries; significant differences were found for both statistical tests, meaning that the differences between instruments are due to systematic or bias errors. Figure 3 shows that color differences are higher in the measurement geometry 75:-30º (as -15) than in the other geometry. In the a* vs. b* chromatic diagram, measurements are broadly spread around the achromatic point; however, in the C^*_{ab} vs. L* chromatic diagram, for the 75:-30º (as -15) measurement geometry the samples are codified more darkly by the FX10 instrument than by the MA98 instrument. However, for the other measurement geometry (75:0º (as +15), the samples are codified more lightly by the FX10 than by the MA98.

Conclusions and Discussion

This work evaluates various multi-gonio spectrophotometers to assess the reproducibility level from a data set of interference and metallic samples, and demonstrates that these instruments do not produce the same results, as significant differences were found due to systematic or bias errors.

Most of the measurement geometries are statistically significant. This means that these differences are due to systematic or bias errors (angle tolerances for each geometry, photometric scales, white standards, etc.), but not exclusively to random errors. However, the statistical tests used here are not valid for discriminating and quantifying the detected bias errors in this comparison between instruments. For the FX10 vs. MA68II and MA98 vs. FX10 pair comparisons, only the 45ºx:-30º (as 15º) measurement geometry nearest to the specular direction (135º), with a priori a large photometric scale, shows a pure statistical deviation. For the MA68II vs. BYK-mac pair comparison, only the 45ºx:30º (as 75º) measurement geometry has no significant differences.

These results also show the intrinsic difficulty in finding efficient methods for comparing reproducibility in multi-gonio-spectrophotometers, even between models from the same manufacturer. For instance, in the MA98 vs. MA68II comparison, only the 45ºx:65º (as 110º) measurement geometry (retro-reflection) passed the statistical comparison test. However, new instruments from different companies, such as the BYK-mac and the X-Rite MA98, have less deviation.

Appropriate tools are therefore needed to design instruments that offer more reliable measurement systems that avoid systematic differences between instruments, and that consequently instill trust in users as regards the color appearance measurements provided.

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References

1. Cramer WR, Gabel P. Measuring special effects. Paint & Coating Industry 2001;29(9):36-46.
2. Kirchner E, van den Kieboom GJ, Njo L, Super R, Gottenbos R. Observation of visual texture of metallic and pearlescent materials. Col. Res. Appl. 2007;32(4):256-266.
3. Pfaff G. Special effect pigments : technical basics and applications. Hannover: Vincentz Network; 2008. p. 218
4. Douma M. Causes of Colours. Volume 2010; 2008.
5. Berthier S. Iridescences: The Physical Colors of Insects. Paris: Springer; 2006.

6. Chorro E, Perales E, Martinez-Verdu FM, Campos J, Pons A. Colorimetric and spectral evaluation of the optical anisotropy of metallic and pearlescent samples. J. Mod. Optic. 2009;56(13):1457-1465.

7. Da Silva A, Andraud C, Lafait J, Robin T, Barrera RG. A model of the angular distribution of light scattered by multilayered media. J. Mod. Optic. 2004;51(3):313-332.

8. Dana KJ, Wang J. Device for convenient measurement of spatially varying bidirectional reflectance. J. Opt. Soc. Am. A 2004;21(1):1-12.

9. Pointer MR, Barnes NJ, Clarke PJ, Shaw MJ. A new goniospectrophotometer for measuring gonio-apparent materials. Color. Technol. 2005;121(2):96-103.

10. Ben-Artzi A, Egan K, Ramamoorthi R, Durand F. A precomputed polynomial representation for interactive BRDF editing with global illumination. ACM Trans. on Graphics 2008;27(2):Art. 13.

11. Li HS, Foo SC, Torrance KE, Westin SH. Automated three-axis gonioreflectometer for computer graphics applications. Opt. Eng. 2006;45(4):043605.

12. Hunerhoff D, Grusemann U, Hope A. New robot-based gonioreflectometer for measuring spectral diffuse reflection Metrologia 2006;43(2):S11-S16

13. DIN-6175-2. Tolerances for automotive paint - Part 2: Goniochromatic paints: Deutsches Institut für Normung; 2001.

14. ASTM-E2175-01. Standard practice for specifying the geometry of multiangle spectrophotometers. West Conshohocken: American Society for Testing and Materials; 2008.

15. Campos J, Pons A, Martín J. Reflectance changes in white reflectance standards measured in different instruments with 0/d geometry. 2005; Granada - Spain. p 41-44.

16. Campos J, Rubiño M, Castillo F, Pons A. Comparación de Instrumentos de Medida del Color. Opt. Pura Apl. 2008;37:113-118.

17. Taylor J, Hanson AR, Clarke PJ, Campos J, Pons A, Czepluch W, Jaaskelainen T, Hiltunen J, Gaudemer J, Soares O and others. Good Practice guide to surface colour measurement. European Publication SMT4-CT96-2140 EUR 19552EN 2000.

18. Wyble DR, Rich DC. Evaluation of methods for verifying the performance of color-measuring instruments. Part I: Repeatability. Col. Res. Appl. 2007;32(3):166-175.

19. Wyble DR, Rich DC. Evaluation of methods for verifying the performance of color-measuring instruments. Part II: Inter-instrument reproducibility. Col. Res. Appl. 2007;32(3):176-194.

20. Hanson AR, Pointer MR, Clarke PJ. The Uncertainty of Surface Colour Measurements made with Commercially Available Instrumentation and Recommended Calibration Protocols. Teddington: National Physical Laboratory; 2004.

21. Chorro E, Perales E, Navarro V, Alcón N, Rabal A, Martinez-Verdu FM. Reproducibility comparison between two multi-gonio-spectophotometers. 2009; Sydney - Australia. p 71.

22. ASTM-E2214. Standard practice for specifying and verifying the performance of color measuring instuments. West Conshohocken: American Society for Testing and Materials; 2008.

23. CIE-15:2004. Colorimetry. Vienna: Commision Internationale de L'Eclaraige; CIE, 2004.

TABLE LEGENDS

Table 1. Illumination and observation angles of the five common measurement geometries.

Table 2. Average, maximum and minimum values of the partial color differences obtained for each measurement geometry for the 6 possible combinations of multi-gonio-spectrophotometers.

Table 3. Hotelling's analysis T^2 for color differences of 88 samples measured by all the multi-gonio spectrophotometers (MA68II (1), MA98 (2), FX10 (3) and BYK-Mac(4)) with a confidence interval of 95%.

Table 4: Average and critical values of the total color differences ΔE^*_{ab} obtained for each common measurement geometry for all the possible comparisons.

Table 5. Average, maximum and minimum values of the partial color differences obtained and the results of the Hotelling's and inter-comparison test for the measurement geometry 45ºx:-60º (as -15º) for the inter-comparison pairs: MA98 vs. BYK-Mac, MA98 vs. FX10 and BYK-Mac vs. FX10.

Table 6. Average, maximum and minimum values of the partial color differences obtained and the results of the Hotelling's and inter-comparison test for the measurement geometries 75ºx:-30º (as -15º) and 75ºx:0º (as +15º) for the inter-comparison pair MA98 vs. FX10.

FIGURE LEGENDS

Figure 1. a) CIELAB color differences (Δb^* vs. Δa^* and ΔL^* vs. ΔC^*_{ab}) for the inter-comparison pair X-Rite MA98 and BYK-mac. b) CIELAB color differences (Δb^* vs. Δa^* and ΔL^* vs. ΔC^*_{ab}) for the inter-comparison pair X-Rite MA98 and MA68II.

Figure 2. CIELAB color differences (Δb^* vs. Δa^* and ΔL^* vs. ΔC^*_{ab}) for the inter-comparison pairs MA98 vs. BYK-mac, MA98 vs. FX10 and BYK-mac vs. FX10, for the measurement geometry 45ºx:-60º (as -15º).

Figure 3. CIELAB color differences (Δb^* vs. Δa^* and ΔL^* vs. ΔC^*_{ab}) for the inter-comparison pairs MA98 vs. FX10 for the measurement geometries 75ºx:-30º (as -15º) and 75ºx:0º (as +15º).

Table 1. Illumination and observation angles of the five common measurement geometries.

	ASTM/DIN measurement geometries				
Influx (incident) angle	45º	45º	45º	45º	45º
Efflux (detection) angle (aspecular)	120º (+15º)	110º (+25º)	90º (+45º)	60º (+75º)	25º (+110º)
CIE nomenclature	45ºx:-30º (as 15º)	45ºx:-20º (as 25º)	45ºx:0º (as 45º)	45ºx:30º (as 75º)	45ºx:65º (as 110º)

Table 2. Average, maximum and minimum values of the partial color differences obtained for each measurement geometry for the 6 possible combinations of multi-gonio-spectrophotometers.

	FX10 vs. MA68II														
	45ºx:-30º (as 15º)			**45ºx:-20º (as 25º)**			**45ºx:0º (as 45º)**			**45ºx:30º (as 75º)**			**45ºx:65º (as 110º)**		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	3.44	1.2	1.70	4.01	1.51	2.29	1.97	0.79	1.32	1.37	0.60	0.96	3.35	0.73	0.98
|Max|	11.66	6.74	7.85	15.25	9.65	10.53	7.43	4.67	4.93	3.77	2.57	3.53	16.65	4.00	4.48
|Min|	0.11	0.01	0.05	0.03	0.02	0.01	0.09	0	0	0.03	0.02	1.43	0.51	0.02	0.01
	FX10 vs. MA98														
	45ºx:-30º (as 15º)			**45ºx:-20º (as 25º)**			**45ºx:0º (as 45º)**			**45ºx:30º (as 75º)**			**45ºx:65º (as 110º)**		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	3.06	1.27	1.71	1.91	0.89	1.14	0.47	0.42	0.58	1.07	0.44	0.65	3.32	0.63	0.85
|Max|	15.42	7.70	9.59	6.82	5.18	4.77	2.15	2.58	2.30	4.15	1.69	2.51	17.29	2.80	3.18
|Min|	0.02	0	0.03	0.02	0.02	0.02	0.01	0	0	0.01	0.02	0.03	0.19	0	0
	FX10 vs. BYK- mac														
	45ºx:-30º (as 15º)			**45ºx:-20º (as 25º)**			**45ºx:0º (as 45º)**			**45ºx:30º (as 75º)**			**45ºx:65º (as 110º)**		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	2.95	1.41	2.20	1.39	0.78	1.07	0.87	0.61	0.74	1.07	0.53	0.80	3.73	0.74	1.04
|Max|	16.18	8.57	8.42	6.77	3.55	3.52	4.37	3.23	3.66	4.15	2.62	3.32	17.65	3.85	4.61
|Min|	0.03	0.02	0.02	0.01	0.01	0	0.03	0.02	0.01	0.01	0.01	0.01	0.46	0.02	0
	MA68II vs. MA98														
	45ºx:-30º (as 15º)			**45ºx:-20º (as 25º)**			**45ºx:0º (as 45º)**			**45ºx:30º (as 75º)**			**45ºx:65º (as 110º)**		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	3.75	11.64	7.94	3.40	1.23	1.80	1.95	0.67	1.10	1.03	0.36	0.64	0.75	0.34	0.54
|Max|	14.78	4.41	12.46	13.70	9.13	7.71	7.42	4.55	4.34	4.17	1.76	2.73	2.86	1.23	2.05
|Min|	0.03	0.02	0	0.35	0	0	0	0	0	0.07	0	0	0.01	0	0
	MA68 vs. BYK-mac														
	45ºx:-30º (as 15º)			**45ºx:-20º (as 25º)**			**45ºx:0º (as 45º)**			**45ºx:30º (as 75º)**			**45ºx:65º (as 110º)**		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	3.58	1.46	2.50	3.48	1.33	2.11	1.60	0.62	1.09	0.85	0.36	0.55	0.75	0.27	0.43
|Max|	15.54	9.94	13.41	15.68	9.37	9.51	8.25	4.52	5.16	3.19	1.78	2.38	2.38	1.38	1.54
|Min|	0.02	0.03	0.05	0.04	0	0	0	0.01	0	0.02	0.02	0	0	0	0
	MA98 vs. BYK- mac														
	45ºx:-30º (as 15º)			**45ºx:-20º (as 25º)**			**45ºx:0º (as 45º)**			**45ºx:30º (as 75º)**			**45ºx:65º (as 110º)**		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	0.71	0.70	1.20	1.21	0.57	0.66	0.75	0.32	0.38	0.50	0.25	0.36	0.59	0.33	0.41
|Max|	2.74	6.05	3.99	3.54	4.31	3.29	4.84	3.33	2.91	4.73	1.44	3.02	3.11	1.59	2.19
|Min|	0.10	0	0.13	0.02	0.01	0	0.01	0	0	0.02	0.01	0.01	0.02	0	0.01

Table 3. Hotelling's analysis T^2 for color differences of 88 samples measured by all the multi-gonio spectrophotometers (MA68II (1), MA98 (2), FX10 (3) and BYK-Mac(4)) with a confidence interval of 95%.

	1 vs. 2		1 vs. 3		1 vs. 4		2 vs. 3		2 vs. 4		3 vs. 4	
Geometry	**T^2**	**P**	**T^2**	**P**	**T^2**	**P**	**T^2**	**P**	**T^2**	**P**	**T^2**	**P**
45ºx:-30º (as 15º)	9.179	0.027	2.863	0.413	25.724	0.000	6.892	0.075	123.551	0.000	37.609	0.000
45ºx:-20º (as 25º)	18.919	0.000	56.6801	0.000	41.504	0.000	116.536	0.000	120.242	0.000	71.080	0.000
45ºx:0º (as 45º)	22.971	0.000	25.748	0.000	40.422	0.000	135.487	0.000	16.085	0.001	179.695	0.000
45ºx:30º (as 75º)	24.525	0.000	86.474	0.000	4.181	0.243	195.328	0.000	50.135	0.000	108.275	0.000
45ºx:65º (as 110º)	4.9535	0.175	221.450	0.000	20.245	0.000	203.360	0.000	25.560	0.000	175.397	0.000

Table 4: Average and critical values of the total color differences ΔE^*_{ab} obtained for each common measurement geometry for all the possible comparisons.

	MA68II vs. MA98				
	45ºx:-30º (as 15º)	**45ºx:-20º (as 25º)**	**45ºx:0º (as 45º)**	**45ºx:30º (as 75º)**	**45ºx:65º (as 110º)**
g_E	0.0044	0.0108	0.0397	0.1456	0.0469
$t_{\Delta E}$	4.4375	2.8254	1.4710	0.7679	1.3529
$\overline{\Delta E^*_{ab}}$	4.8906	4.4705	2.5647	1.3834	1.0953
	MA68II vs. FX10				
	45ºx:-30º (as 15º)	**45ºx:-20º (as 25º)**	**45ºx:0º (as 45º)**	**45ºx:30º (as 75º)**	**45ºx:65º (as 110º)**
g_E	0.0017	0.0229	0.0394	0.2437	0.1746
$t_{\Delta E}$	7.2097	1.9346	1.4766	0.5936	0.7013
$\overline{\Delta E^*_{ab}}$	4.4377	5.2983	2.7255	2.0080	3.7963
	MA68II vs. BYK-mac				
	45ºx:-30º (as 15º)	**45ºx:-20º (as 25º)**	**45ºx:0º (as 45º)**	**45ºx:30º (as 75º)**	**45ºx:65º (as 110º)**
g_E	0.0108	0.0209	0.0903	0.0320	0.2139
$t_{\Delta E}$	2.8148	2.0292	0.9751	1.6374	0.6336
$\overline{\Delta E^*_{ab}}$	5.1932	4.7554	2.2553	1.2179	1.0370
	MA98 vs. FX10				
	45ºx:-30º (as 15º)	**45ºx:-20º (as 25º)**	**45ºx:0º (as 45º)**	**45ºx:30º (as 75º)**	**45ºx:65º (as 110º)**
g_E	0.0045	0.1873	1.6328	1.0206	0.1746
$t_{\Delta E}$	4.3840	0.6772	0.2293	0.2901	0.7013
$\overline{\Delta E^*_{ab}}$	4.1866	2.6592	0.9710	1.4747	3.6381
	MA98 vs. BYK-mac				
	45ºx:-30º (as 15º)	**45ºx:-20º (as 25º)**	**45ºx:0º (as 45º)**	**45ºx:30º (as 75º)**	**45ºx:65º (as 110º)**
g_E	0.4592	0.4706	0.1859	1.0249	0.3536
$t_{\Delta E}$	0.4324	0.4272	0.6797	0.2895	0.4928
$\overline{\Delta E^*_{ab}}$	1.7485	1.7040	0.9916	0.7456	0.9064
	FX10 vs. BYK-mac				
	45ºx:-30º (as 15º)	**45ºx:-20º (as 25º)**	**45ºx:0º (as 45º)**	**45ºx:30º (as 75º)**	**45ºx:65º (as 110º)**
g_E	0.0214	0.1757	0.9641	0.4670	0.1130
$t_{\Delta E}$	2.0020	0.6991	0.2985	0.4288	0.8717
$\overline{\Delta E^*_{ab}}$	4.4661	2.1440	1.4553	1.6232	4.1997

Table 5. Average, maximum and minimum values of the partial color differences obtained and the results of the Hotelling's and inter-comparison test for the measurement geometry 45ºx:-60º (as -15º) for the inter-comparison pairs: MA98 vs. BYK-Mac, MA98 vs. FX10 and BYK-Mac vs. FX10.

45ºx:-60º (as -15º)	*MA98 vs. BYK- mac*			*MA98 vs. FX10*			*BYK- mac vs. FX10*		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	3.87	1.37	2.01	12.55	3.08	4.26	8.75	2.31	2.92
|Max|	9.47	7.16	6.45	29.58	12.44	15.50	21.53	10.29	12.35
|Min|	1.09	4.03	5.15	1.02	9.82	11.56	0.18	8.40	8.15
P	0.000			0.000			0.000		
$t_{\Delta E}$	0.806			1.622			0.037		
$\overline{\Delta E^*_{ab}}$	4.988			14.278			10.169		

Table 6. Average, maximum and minimum values of the partial color differences obtained and the results of the Hotelling's and inter-comparison test for the measurement geometries 75ºx:-30º (as -15º) and 75ºx:0º (as +15º) for the inter-comparison pair MA98 vs. FX10.

	75ºx:-30º (as -15º)			*75ºx:0º (as +15º)*		
	ΔL*	**Δa***	**Δb***	**ΔL***	**Δa***	**Δb***
Average	4.15	1.73	2.68	2.21	1.18	1.89
|Max|	16.23	8.15	12.29	5.96	4.00	6.05
|Min|	0.641	9.61	6.51	10.86	6.03	4.89
P		0.000			0.000	
$t_{\Delta E}$		1.325			1.206	
$\overline{\Delta E^*_{ab}}$		5.660			3.507	

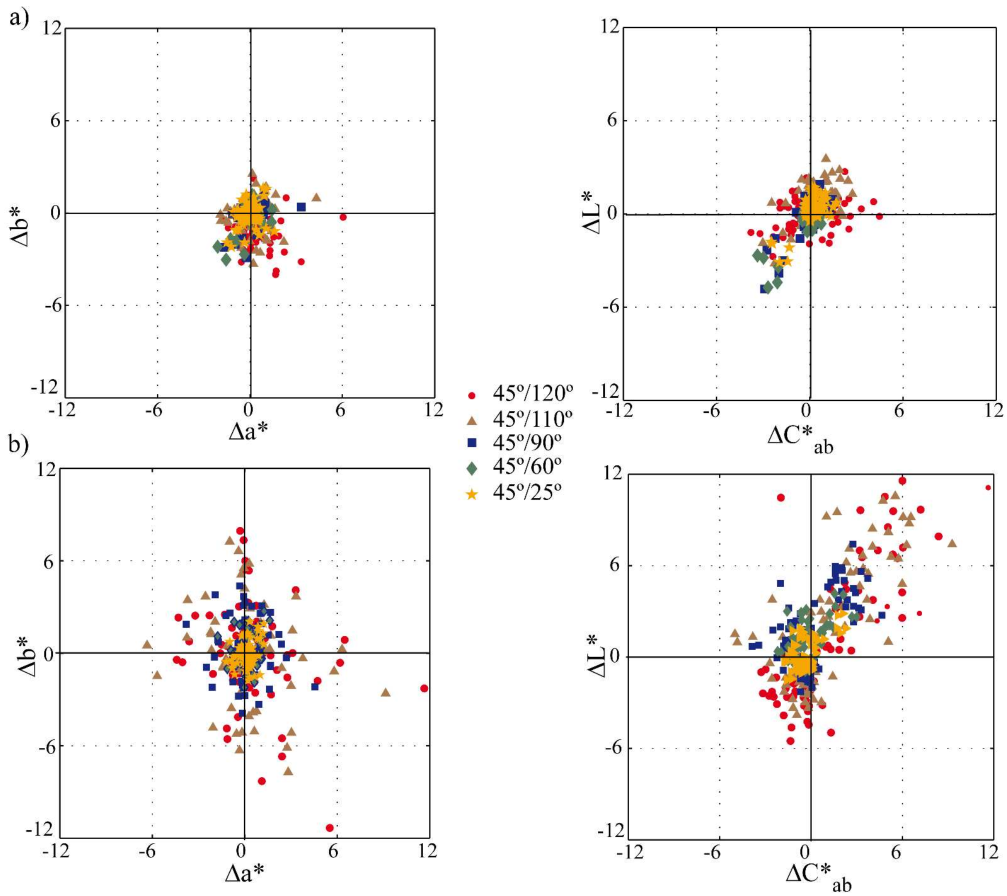

Figure 1. a) CIELAB color differences (Δb* vs. Δa* and ΔL* vs. ΔC*ab) for the inter-comparison pair X-Rite MA98 and BYK-mac. b) CIELAB color differences (Δb* vs. Δa* and ΔL* vs. ΔC*ab) for the inter-comparison pair X-Rite MA98 and MA68II.
134x121mm (600 x 600 DPI)

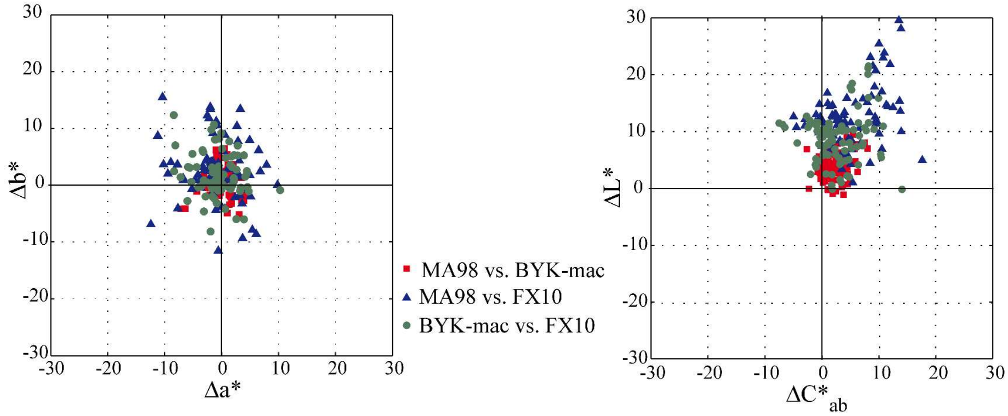

Figure 2. CIELAB color differences (Δb* vs. Δa* and ΔL* vs. ΔC*ab) for the inter-comparison pairs MA98 vs. BYK-mac, MA98 vs. FX10 and BYK-mac vs. FX10, for the measurement geometry 45ºx:-60º (as -15º).
144x60mm (600 x 600 DPI)

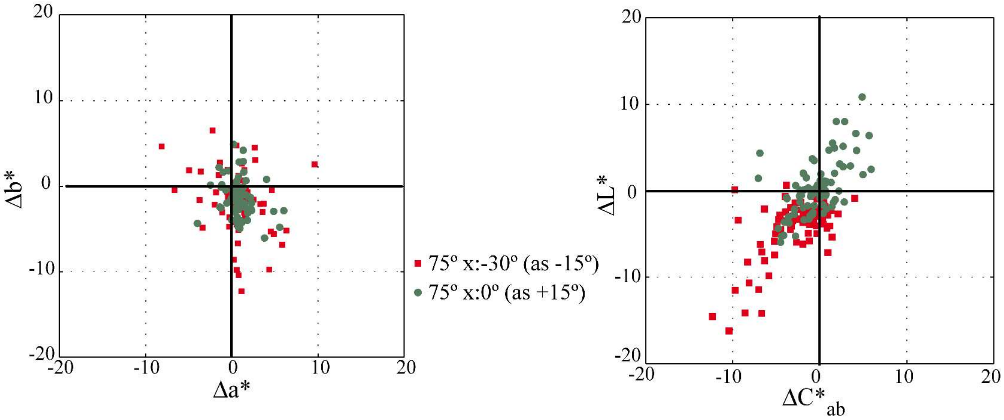

Figure 3. CIELAB color differences (Δb* vs. Δa* and ΔL* vs. ΔC*ab) for the inter-comparison pairs MA98 vs. FX10 for the measurement geometries 75ºx:-30º (as -15º) and 75ºx:0º (as +15º).
141x59mm (600 x 600 DPI)