Theoretical Implementation of the Color Inconstancy Index for Gonio-Apparent Automotive Coatings

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Abstract

Color inconstancy index (CON), well stablished and recommended by the ISO 105-J05 normative, is usually applied on textile solid colors, and not on gonio-apparent ones. In this work we propose a fast and easy implementation and virtual color assessment of this colorimetric index for these innovative colors, often used in many industries as automotive, cosmetics, computer graphics, plastics for electronic consumers, printing inks, etc.

Instead using the ΔE CMC(1:1) color difference formula, the ΔE AUDI2000 formula for the six measurement geometries recommended by the ASTM E2194 normative was used simulating the theoretical visual assessment in a directional lighting booth, and applied on some different panel sets, as the official AUDI palette composed by 117 colors, both solid, metallic and pearlescent. The theoretical directional lighting booth can select different standard illuminants (A, D65 as reference, and F11), daylight fluorescent simulators (D50, etc.) and light sources (as wLED, etc.).

The results showed that spectral reflectances with low chroma and lightness lead to minimum CON index. But, spectral reflectances with high chroma and middle lightness lead to maximum CON index. Additional interesting conclusions were also derived. For instance, for near-specular geometries the CON index is maximum due the high variability or contrast in the photometric scale of the spectral reflectance (higher to the conventional 100 %). Although the spectral content of the light source clearly influences on the CON index of a color panel, different relative spectra can provide different color travels in the same panel, and then high CON index, as for instance A vs. D65, or F11 and D65, or wLED vs. D65.

Consequently, depending on the industrial application and the end use (light & color interaction), the CON index for each color recipe (even design) can be analyzed in advance as a new colorimetric feature of any colored material.

Introduction

Nowadays, many colorimetric indexes can be applied to know some additional color quality parameters in materials and light sources. For instance, the CIE color rendering index of light sources [1, 2], though some panel sets are used as statistical sampling, is a basic feature of the light source compared to a reference illuminant (with the same color temperature). On contrast, the metamerism [1, 3] and inconstancy color [4] indexes are basically features of the colored material, and highly related with its color recipe or formulation, even synthesis process. But, the first one describes the color change of a color pair, with different spectral reflectances, seen under some illuminants (for instance, under D65 the pair is perceived equal; but, under a wLED lamp, the pair is unmatched). But, for the inconstancy color index, or for simplicity CON index [4], only one specimen is every time considered. Using the basic scene (Figure 1) to the CIE color rendering index, the purpose of the CON index is to evaluate the color difference formula into the same specimen, whose spectral reflectance is that related with the selected measurement geometry, simultaneously half-illuminated by two light sources.

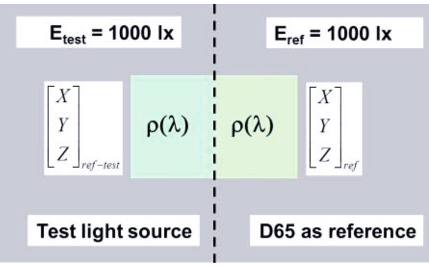


***Figure 1**. Basic scene used both for CIE color rendering and ISO inconstancy color indexes.*

As it is well stated, this perceived color difference only can be understood and calculated previously applying a chromatic adaptation transform [5] to the unrelated XYZ tristimulus values, converted into ref-test XYZ values. After that, and assuming a measurement geometry for illumination and observation, a conventional ΔE color difference formula can be applied by using the CIELAB color space. Nowadays, the CON index is proposed as ISO normative [6] for textile industry, and mainly recommending the CMC(1:1) color difference formula, though other formulae can be applied [4], as ΔE CIE2000, etc. That is, greater ΔE value, greater CON index. Therefore, from some years ago, this interesting colorimetric index is usually applied on new colors typically designed by conventional pigments/dyes, that is, colorants with isotropic optical behaviors.

But, in the last decades, the growing use of gonio-chromatic pigments in some industries, as automotive, cosmetics, plastics, printing, etc., even in virtual reality, digital cinema, etc., is highly demanding. These gonio-apparent colors are basically characterized for having different spectral reflectances, even surpassing the conventional photometric scaling limit in 100 % [7, 8], for many measurement geometries (Figure 2).

Our purpose for this work is a fast and easy implementation of the CON index for gonio-apparent panels. The initial hypothesis is the following: since the lower limit of the spectral reflectance is zero, but the upper limit for gonio-apparent panels is higher than 100 %, without limitations, will be the maximum CON indexes related to spectral reflectances higher than 100 %? Or can we predict it using in parallel CIELAB values, though simultaneously applied on some measurement geometries?

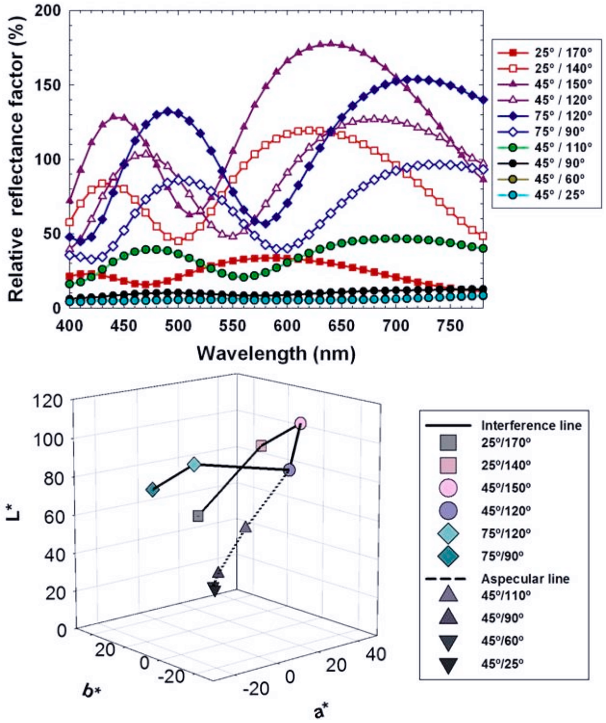


***Figure 2**. Example of pearlescent panel (Merck Colorstream ArticFire). Top: spectral reflectances using the multi-angle spectrophotometer Datacolor MFX-10. Bottom: corresponding gamut, or color travel, in CIELAB space.*

Methods and materials

Using the basic CON index algorithm (Figure 3), we propose to change the official ΔE CMC(1:1) color difference formula by the ΔE AUDI2000 formula [9], extensively used in the automotive industry, and able to predict the color variation in some measurement geometries, as those proposed by metallic colors [10, 11]. From a theoretical point of view, we use the spectral reflectances provided by a multi-angle spectrophotometer, as BYK-mac®, and we test the color change of the panel illuminated into a directional lighting booth, as byko-spectra effect®. But, the practical or visual test should be using a tele-spectro-radiometer and an improved directional booth in haploscopic mode, able to show half-illuminated panel for some measurement geometries (Figure 4). Therefore, greater ΔE AUDI2000, and its corresponding or well-correlated visual assessment, greater CON index. However, from a practical point of view, this interesting color perception phenomenon is difficult to be appreciated in daily situations because it is very complicated to remember this intrinsic color panel (or colored car body) without an ideal color memory and/or haploscopic viewing (Figure 1).

As gonio-apparent materials to be applied here, three panel sets were selected: 18 panels with known color recipes (some Merck Xirallic-type pigments with solid blue-green pigment), 56 panels with proprietary color recipes, and, the official AUDI palette composed of 117 colors, both solid, metallic and pearlescent. The theoretical directional lighting booth can select different standard illuminants (A, D65 as reference, and F11), daylight fluorescent simulators (D50, etc.) and light sources (as wLED lamp equipped in the gonio-vision-box®) (Figure 5).

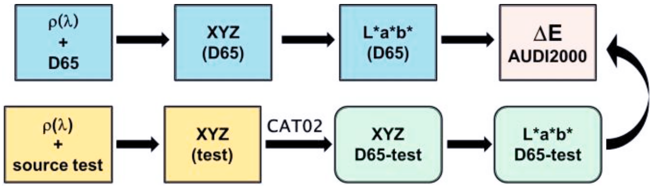


***Figure 3**. Scheme for calculating the CON index for gonio-apparent panels.*

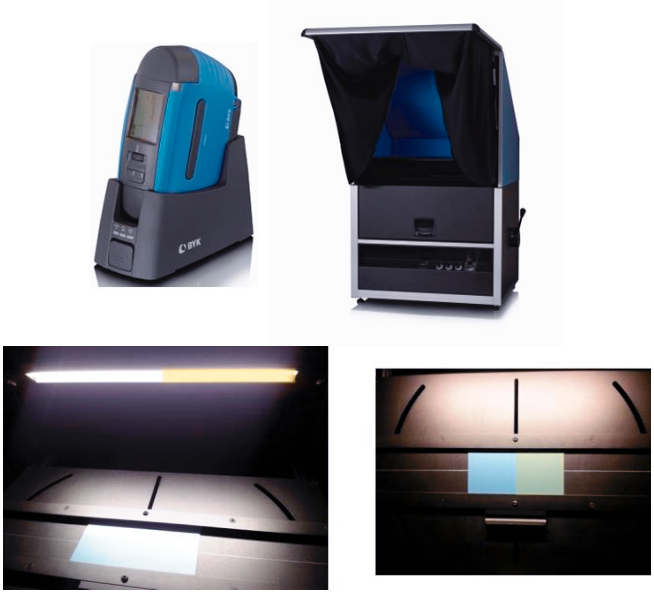


***Figure 4**. Top: left, multi-angle spectrophotometer BYK-mac®, right, byko-spectra effect cabinet® (BSE, with D50 fluorescent simulator). Bottom: left, theoretical set-up into the byko-spectra cabinet, right: visual simulation.*

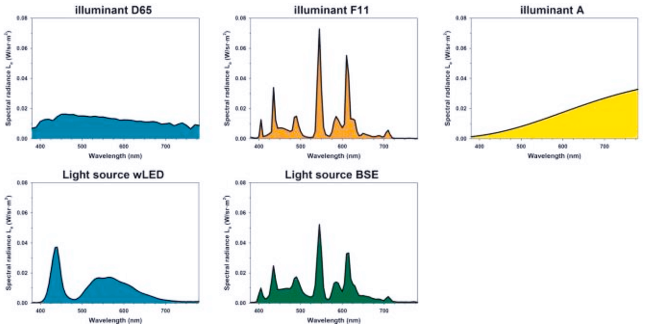


***Figure 5.** Normalized spectra to 1000 lx illuminance level of the illuminants and light sources used in this work.*

Next, we show a sort list of preliminary results, combining tables and graphs for helping to visualize better the CON index applied on gonio-apparent panels.

Panel set 1: CON index visualization no. 1

As said above, gonio-apparent specimens have small, medium or large color variation according to the measurement geometries. Typical colorimetric parameters used in some industries are the lightness and color flop, mainly based on some mathematical relationships of CIELAB parameters corresponding to some measurement geometries. However, in our opinion, the best and easy visualization mode for understanding the CON index is to graph the color travel for 6 geometries recommended by the ASTM E2194 normative in the 3D CIELAB space (Figures 2 & 6). Below, you can see the color travels for two panels of the set no. 1. In the panel no. 1, with Merck Iriodin pigment at maximum concentration, the color travel, composed by the colorimetric points according to the 6 measurement geometries (Table 1), shows different length and shape depending on the illuminant or light source. In the panel no. 10 (Figure 6, bottom), a mix of solid blue-green pigment and interference (micro-silver) pigment, the color travels are different, and very near for the illuminant D65 and the light source BSE (D50 fluorescent simulator), but not for a wLED light source. Therefore, the panel no. 10 shows high color inconstancy index for the pair D65-BSE, but high inconstancy color index for the pair D65-wLED, and overall for measurement geometries near the specular direction, that is, 45as-15, 45as15 and 45as25.

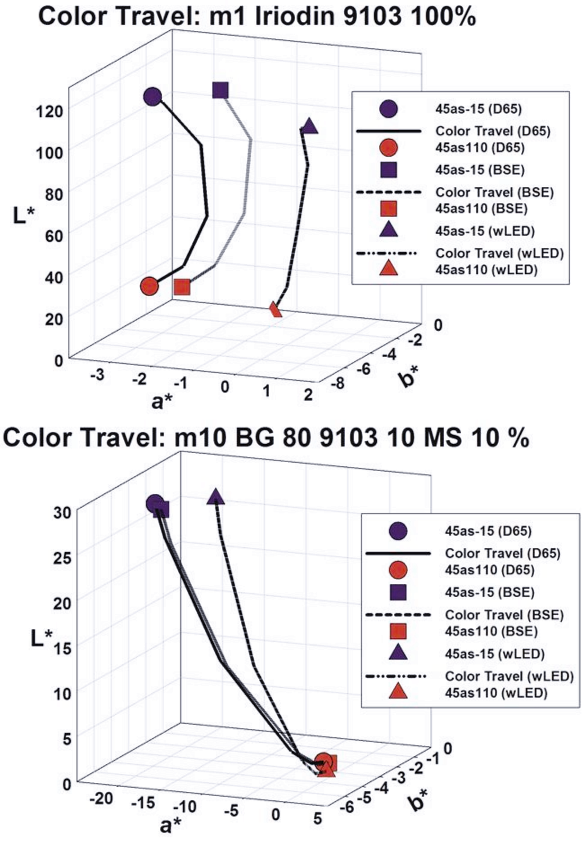


***Figure 6**. Examples of color travels of pearlescent panels under D65 illuminant, D50 fluorescent simulator (BSE) and wLED lamp.*

In Table 1, the AUDI2000 color differences are shown for this set and distributed into the 6 measurement geometries. Note that, in case of minimum CON index, or maximum color constancy, all panels should show minimal ΔE values. Obviously, these results shown here are linked to the comparison D65-BSE, so we might initially conclude the D50 fluorescent lamp installed into the byko-spectra cabinet could keep the color constancy of the most of gonio-apparent panels. Obviously, with the comparison D65-wLED the results would see very different, as we will show in the next analysis using other panel sets.

Table 1. ΔE AUDI2000 values for the panel set 1 according to the six measurement geometries recommended by the ASTM E2194 normative for metallic colors for the pair BSE-D65.

BSE vs. D65	ΔE_{max}	ΔE_{min}	Average
45as-15	3.49	0.58	1.53
45as15	3.50	0.68	1.60
45as25	4.44	0.94	2.53
45as45	3.38	1.25	2.25
45as75	3.21	1.58	2.19
45as110	3.26	1.47	2.05

Panel set 2: CON index visualization no. 2

Other qualitative visualization mode for understanding the CON index is to show the color shifts for some illuminants and light sources, after applying as in the previous example the CAT02 transform. For carrying out this, we apply the same CON implementation for a new panel set, composed by metallic and pearlescent 56 panels with proprietary color recipes (BASF Coatings). In Figure 7 you can see the corresponding gamuts in CIELAB planes under illuminants A, D65 and F11. With a quick look, it can be seen that the very dark and bluish colors, with low and middle chroma, show the longer color shifts. Curiously, very light and low chroma colors, whose spectral reflectances can overpass the 100 % photometric scale, show lower color shifts than those related with darker and bluish colors, whose spectral reflectances are very close to the lower limit of zero.

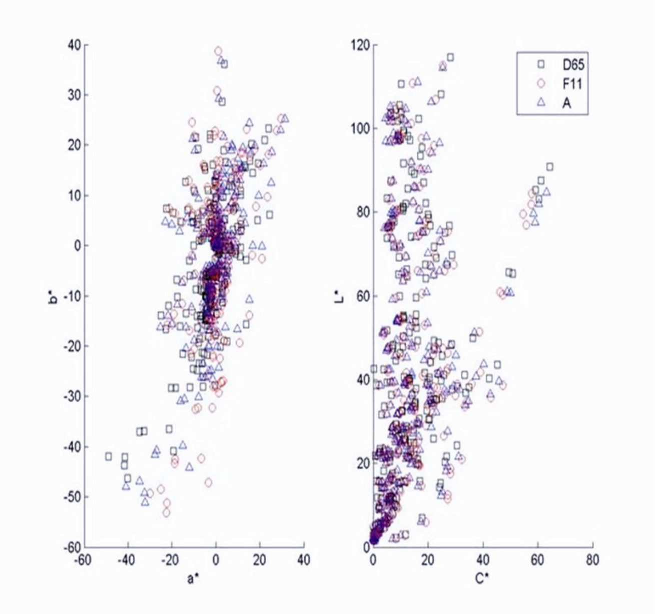


***Figure 7**. Corresponding color shifts of the panel set no.2 under the illuminants A (triangle), D65 (square) and F11 (circle).*

In Tables 2 and 3, the ΔE AUDI2000 values are again shown for this new set and distributed into the 6 measurement geometries, but separating the influence of two light sources (illuminant F11, and the wLED lamp of the gonio-vision-box® device). Note that, spite of previously applying the CAT02 transform, there are greater color differences, clearly distinguishable, and again higher for near-specular geometries. Therefore, the spectral content of the light source clearly influences on the CON index of a color panel, but it is an inherent feature of the specimen.

Table 2. ΔE AUDI2000 values for the panel set 2 according to the six measurement geometries recommended by the ASTM E2194 normative for metallic colors for the pair F11-D65.

F11 vs. D65	ΔE_{max}	ΔE_{min}	Average
45as-15	23.94	1.58	5.33
45as15	27.25	1.03	5.98
45as25	26.48	0.44	5.00
45as45	26.19	0.69	4.60
45as75	22.02	0.58	0.47
45as110	23.60	0.47	3.54

Table 3. ΔE AUDI2000 values for the panel set 2 according to the six measurement geometries recommended by the ASTM E2194 normative for metallic colors for the pair wLED-D65.

wLED vs. D65	ΔE_{max}	ΔE_{min}	Average
45as-15	34.87	1.47	8.88
45as15	35.25	0.83	9.53
45as25	35.59	0.76	8.77
45as45	39.32	0.09	8.75
45as75	33.62	0.08	7.21
45as110	33.58	0.09	7.32

Panel set no.3: CON index visualization no.3

For completing this analysis, we show the previous graph formats for a new panel set, belonging this time by the official AUDI palette, composed by 117 colors, both solid, metallic and pearlescent colors. For the set of illuminants and light sources used here, the AUDI color with maximum CON index is the "Sepangblau" (Figure 8), and the AUDI color with minimum CON index is the "Brilliantschwarz" (Figure 9). The statistical data, as shown above for other panel sets, show again a long spreading, mainly for the illuminant F11 and the wLED lamp (Tables 5 & 6).

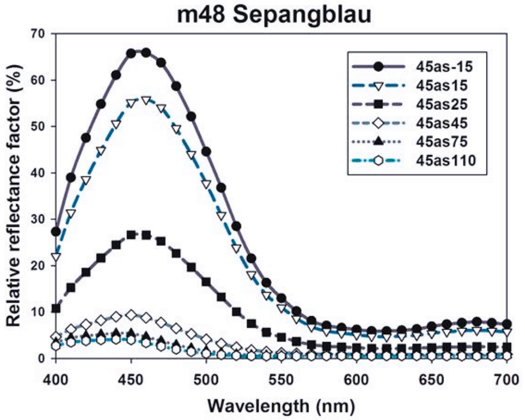
Table 5. ΔE AUDI2000 values for the panel set 3 according to the six measurement geometries recommended by the ASTM E2194 normative for metallic colors for the pair F11-D65.

F11 vs. D65	ΔE_{max}	ΔE_{min}	Average
45as-15	33.62	0.53	9.09
45as15	32.47	0.51	8.83
45as25	26.67	0.55	7.86
45as45	22.51	0.28	4.92
45as75	23.48	0.35	4.28
45as110	26.26	0.37	4.45

Clearly, it can be seen in both AUDI colors the influence of the spectral reflectance scaling for yielding inconstancy color index. High-contrast or range in spectral reflectance assures longer color shifts, even applying chromatic adaptation transform. This involves to high chroma and middle lightness values, and not necessarily spectral reflectances higher to the 100 % conventional limit for solid colors. But, in the opposite side, very low spectral reflectances, near absolute zero, warranty minimum inconstancy color index, as the glossy black of the AUDI palette.

Table 6. ΔE AUDI2000 values for the panel set 3 according to the six measurement geometries recommended by the ASTM E2194 normative for metallic colors for the pair wLED-D65.

wLED vs. D65	ΔE_{max}	ΔE_{min}	Average
45as-15	65.68	0.65	14.79
45as15	62.40	0.64	14.27
45as25	51.16	0.62	12.58
45as45	36.52	0.36	8.30
45as75	37.82	0.33	8.01
45as110	41.48	0.33	8.42



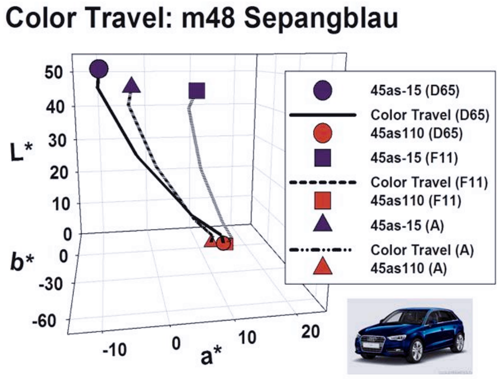


Figure 8. Spectral reflectances (top), and the color travels (bottom) under illuminants D65 (circle), F11 (square) and A (triangle), of the AUDI color "Sepangblau", with the maximum CON index in all AUDI palette.

Curiously, although the D50 simulator in the byko-spectra® cabinet seemed good even for D65 visual assessments, the data shown here (Table 7) indicate that some combinations of panels and geometries, mainly for near-specular direction, provide high CON indexes.

Therefore, the fluorescent lamp installed in this commercial directional lighting booth is not completely suitable for keeping the maximum visual and instrumental correlation. This conclusion is obviously coincident in case to apply the color rendering index to this D50 fluorescent lamp using the illuminant D65 as reference.

Table 7. ΔE AUDI2000 values for the panel set 3 according to the six measurement geometries recommended by the ASTM E2194 normative for metallic colors for the pair BSE-D65.

BSE vs. D65	ΔE_{max}	ΔE_{min}	Average
45as-15	17.43	0.24	4.43
45as15	16.62	0.23	4.32
45as25	13.89	0.27	3.85
45as45	11.82	0.14	2.43
45as75	12.19	0.15	2.16
45as110	13.48	0.16	2.25

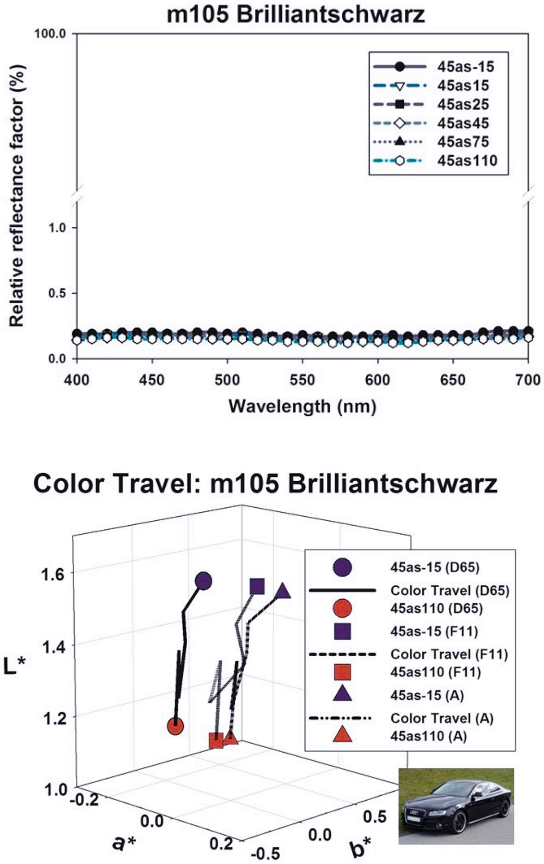


Figure 9. Spectral reflectances (top), and the color travels (bottom) under illuminants D65 (circle), F11 (square) and A (triangle), of the AUDI color "Brilliantschwarz", with the maximum CON index in all AUDI palette.

Finally, next we show the partial color differences (in the vertical axis, Figure 10) for this panel set. Here, you can see the relevance of these partial color differences in order to lead the total color difference or CON index under a illuminant and measurement geometry (Figure 9, only the "face" geometry: 45as45, or 45º/90º). Applying this final visualization mode for other illuminants and light sources studied here, and keeping the same measurement geometry (45as45), we can deduce the following:

- Illuminant A: ΔC* > ΔH* > ΔL*, except for the "reds" (ΔC* > ΔL* > ΔH*);
- Illuminant F11: ΔH* > ΔC* > ΔL*, except for the "grays" (ΔC* > ΔH* > ΔL*);
- D50 fluorescent lamp (BSE): ΔH* > ΔC* > ΔL*, except for the "grays" (ΔC* > ΔH* > ΔL*);
- wLED lamp: ΔH* ≅ ΔC* >> ΔL*, except for the "blues" (ΔH* > ΔC* >> ΔL*);

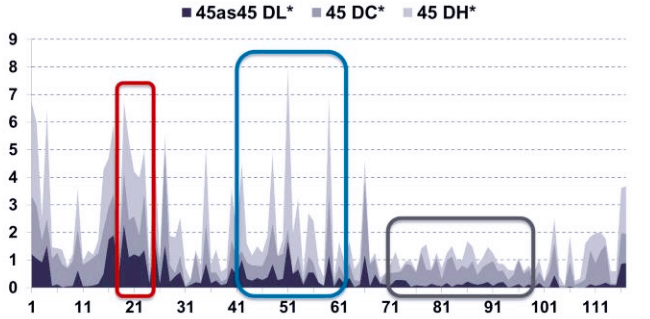


Figure 10. CIELAB partial color deviations of the official AUDI palette under the D50 simulator equipped in the byko spectra effect® cabinet and for the measurement geometry 45as45 (45º/90º). Colored boxes are used for showing some sub-gamuts (reds, blues and grays).

This global graph for this panel set can be analyzed panel by panel (or master, as it is usually in the automotive sector). For instance, in Figure 11 and Table 8 you can see the partial color deviations for the AUDI master with maximum CON index (Figure 10) for the illuminant and light sources selected in this work. Spite being a metallic blue (hue angle is approx. constant varying the measurement geometry), the high range in their spectral reflectances under some illuminants and light sources causes different interactions, and color perceptions about this specimen, difficult to appreciate in daily situations, as said above, because it is very complicated to remember this intrinsic color panel (or colored car body) without an ideal color memory and/or haploscopic viewing (left eye for the panel under the test light source, right eye for the same panel under the illuminant D65, as reference, as in Figure 1).

Table 8. Digital sRGB simulations of the AUDI Sepangblau color perceptions under some illuminants and light sources applying the CON algorithm. Blank cells means that the color is not reproducible in sRGB color space (conventional display).

Sepangblau	A	F11	BSE	D65	wLED
45as-15	---	---	---	---	🟦
45as15	---	---	---	---	🟦
45as25	---	---	---	---	🟦
45as45	🟦	🟦	🟦	---	🟦
45as75	🟦	🟦	🟦	🟦	🟦
45as110	🟦	🟦	🟦	🟦	🟦

As you can see above, it is not easy to show/perceive in related visualization mode the (corresponding) color perceptions after applying the CON index, and above all for the gonio-apparent colors, where many metallic and pearlescent colors have partially their color gamuts outside the conventional displays [12, 13].

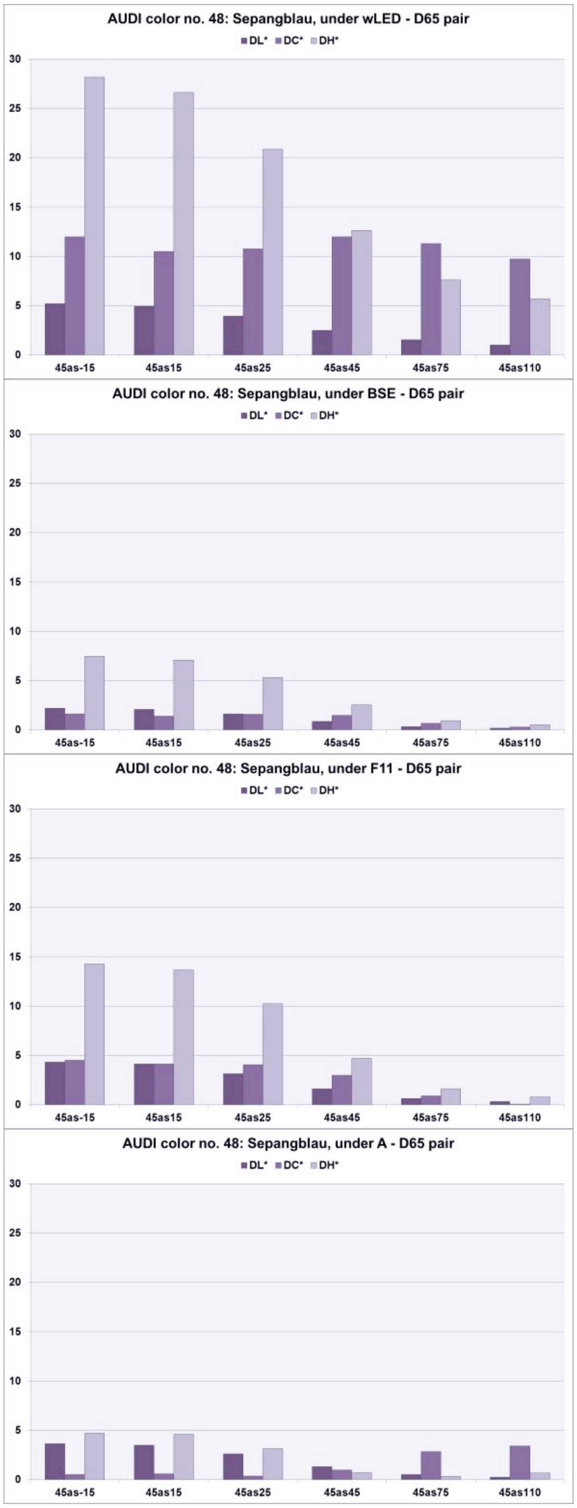


Figure 11. CIELAB partial color deviations of the AUDI Sepangblau master under some illuminant/lamp pairs for the six geometries from ASTM E2194 normative.

Discussion

The matter – light – human visual system interplay is very rich when the inconstancy color (CON) index is considered, and above all with regard to gonio-apparent colors. Unfortunately, the human color memory is not ideal, and in daily situations the haploscopic viewing of a half-illuminated colored material or specimen is not usual, and difficult to put on practice for many measurement geometries. In this work we have implemented from a theoretical point of view the current inconstancy color index for very innovative textured and colored materials [7, 12-16], present nowadays, and much more in future, in vehicles, cosmetics, 3D printing, etc.

For fitting the challenges involved in gonio-apparent colors, and keeping the core structure of the CON index algorithm in the chromatic adaptation transform, the ΔE AUDI2000 color difference formula was inserted instead of the official ΔE CMC(1:1). But, the basic CIELAB color space was mainly used for showing some visualization modes enabling the understanding and analysis of this intrinsic color phenomenon related to the colored material. To carry out this, three different gonio-apparent panels have been used, and with special focus on a current car maker palette.

The results showed that spectral reflectances with low chroma and lightness, near the zero limit of reflectance, lead to minimum CON index. But, spectral reflectances with high chroma and middle lightness lead to maximum CON index. Therefore, spectral reflectances higher than 100 % does not warranty maximum CON index, except in cases where they show high variability or contrast in the photometric scale. Although the spectral content of the light source clearly influences on the CON index of a color panel, different relative spectra can provide different color travels in the same panel, and then high CON index, as for instance A vs. D65, or F11 and D65, or wLED vs. D65. But, moreover, as it is demonstrated for the a D50 fluorescent lamp installed into a commercial lighting booth, the CON index is a supplementary test, and highly correlated with the CIE color rendering index, for knowing the color quality of light sources.

Conclusion

Consequently, depending on the industrial application and the end use (light & color interaction, viewing modes, even in computer graphics, etc.), the CON index for each color recipe (even design) can be analyzed in advance as a new colorimetric feature of any colored material or specimen, and not only for the textile industry.

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