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Investigation of color inconstancy and color gamut changes of printed images depending on the standard illuminants

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The main goals of this research are investigation and determination of color balance failure (color inconstancy) of offset printed images expressed by color difference depending on the material used and different standard illuminant conditions. For the experiment, we chose three of the most commonly used in practice illuminants – CIE D50 natural horizon daylight with color temperature 5003 K; CIE F2 cool white fluorescent, 4230 K; CIE A typical Tungsten-filament lighting, 2856 K. A special test form that has been used contains different control strips and measurement components include test chart TC6.02 with about 1000 color patches with different percent combinations of cyan, magenta, yellow and black. The paper, printing inks and printing presses employed in the experiment are some of most commonly used in practice for producing high quality color reproductions. A series of colorimetric and densitometric measurements were performed for different combinations of C, M, Y, K in single, double, triple and quadruple overprint for high tones, middle tones and dark tones. For estimating color balance failure for all the above mentioned measurements there have been calculated the color difference ΔE^*_{ab} and CMCCON02 depending on standard illuminants CIE D50, F2 and A. For the first time via experimental research in real production conditions (for offset printing method), 3D and 2D presentations and comparison of color gamuts and color gamut volumes for different illuminants were made. According to the results, CIE A has the biggest color gamut volume and CIE F2 – the smallest one. The results obtained are important from scientific and practical points of view. For the first time a methodology is suggested and implemented for examination and estimation of color shifts by studying a big number of color changes in various ink combinations for different illuminants.

Keywords: color difference, color inconstancy, standard illuminant, color gamut, volume of color gamut

1. Introduction

The offset printing method has a leader position in graphic arts technology. Quality parameters are accounted and defined in the International Standards. In prepress and printing processes we operate with parameters like screen frequency, imaging resolution, amplitude modulated or frequency modulated screen, ink quantity, registration of colors, ink sequence, pressure in printing zone and so on. The quality of printed image is a function of supporting the printing process parameters in precise boundaries. From the human perception viewpoint, the implementation of all the print quality parameters is not enough without using the correct illuminant. The valuation of quality of printing image can be finished only by the human eye and by colorimetric methods using equal color contrast system CIE $L^*a^*b^*$ and color difference ΔE^*_{ab}.

One of the biggest problems in color reproduction processes are color shifts occurring when the images are viewed under different illuminants. The colors of process inks on the printed sheet – cyan, magenta, yellow and black – and their combinations that match under one light source often appear different under the other. This problem is referred to as color balance failure or color inconstancy. That is why CIE defines a big number of standardized illuminants with different spectral contribution. The spectral contribution of different standard illuminants has a very big influence on human color perception, respectively on image quality.

According to CIE there are many standard illuminants, but the light conditions mostly used in practice are CIE F2 – cool white fluorescent in offices, and CIE A – typical Tungsten-filament lighting – at home [1]. According to ISO standards and ICC, the printed images should be viewed under CIE D50 lighting. With most pigment sets (CMYK inks solid and/or used together) the gray gradient and all color shift considerably when viewed under different illuminants [2, 3].

Metamerism and color inconstancy are the subject of wide research in the field of graphic arts, both being very important. In fact, color inconstancy is unavoidable. It means that the perceived color always changes under different illuminants. In some cases, this could become very serious [4, 5].

The optimum combinations of three- and four-chromatic inks were investigated to minimize color inconstancy and keep a relatively large color gamut simultaneously, which can be done without compromising the reproduction colorimetric accuracy. The color inconstancy of prints can be limited to a relatively lower range by optimizing the ink set for minimizing the color inconstancy of all ink combinations [5, 6].

A multi-ink color-separation algorithm was tested with spectral data from several targets. For evaluation purposes, use was made of an index of color inconstancy calculated for illuminants D50 and F11. Using the CIECAT02 chromatic-adaptation transform, corresponding colors were calculated from each illuminant to D65. Many ink combinations have appreciable color inconstancy. The only way to change the color inconstancy index statistics is to change the spectral properties of the inks [4].

Studies have been made for color transformations between three illuminant source pairs (D50–A, D50–D65 and D65–A) using five CATs (Bradford, von Kries, *XYZ* scaling, CMCCAT97 and CMCCAT00). Research was made on 8190 color patches that were printed with inkjet printer. One of the major advantages of using CATs is their ability to transform CIE tristimulus values obtained under one illumination source into *XYZ* values related to a different illumination source in cases when spectral data are unavailable. The best method is one that gives smallest color differences between calculated *XYZ* values from spectral data and adapted *XYZ* values. Of the five models examined, Bradford CAT exhibited the best performance since the observed color differences were found to be the lowest regardless of the illumination pair used, and the smallest color differences were generated with D50–D65 CATs and the biggest ones with D65–A models [7].

The calculation of CMCCON02 involves two parts – the calculation of CAT02 for predicting corresponding colors, and the calculation of color difference between the color appearance of the specimen under a reference and a test illuminant. The recommended color inconstancy index, CMCCON02 provides a good measure for indicating the degree of color inconstancy. The CAT02 transform was used to predict the corresponding colors, X_c, Y_c, Z_c under illuminant D65 from the X, Y, Z values of the sample under test illuminant, and a suitable color difference equation was used to calculate the color difference (ΔE) together with individual color difference components (ΔL, ΔC and ΔH) between X_c, Y_c, Z_c and X_r, Y_r, Z_r. The magnitude of the ΔE value indicates the degree of color inconstancy. The direction of color change can be expressed by individual color difference components. A color difference value of zero indicates complete color constancy for the specimen tested. A color inconstancy index is capable of predicting the magnitude and direction of the change in color appearance between a sample viewed under a test illuminant and the same sample viewed under a reference illuminant (D65) [8].

The numerical color difference ΔE^*_{ab} between the color values of the corresponding color and the color under original illuminant is an adequate measure for the degree of color inconstancy $C_{\mathrm{CI}}(\Delta E) = \Delta E$. $C_{\mathrm{CI}}(\Delta E) = 0$ represents a completely color constant coloration for the chosen reference and test illuminant [9].

To obtain a correct gray balance of C, M and Y, one has to use the right illuminant when the ICC profile is generated. If spectral reflectance mode is used to measure the ICC profile Swatch, and if the light source that the final prints will be viewed under is known (and is other than D50), then the closest CIE standard illuminant to that light source can be selected when building the ICC. The experience shows that when a profile is generated for illuminant D50, the CIEDE2000 color difference will have very low values. But when the profile is built for illuminant A, the CIEDE2000 color difference values grow up, *i.e.*, the gray tones show color inconstancy if the prints with this profile are viewed under D50. To summarize, just building a profile “tuned” to a particular illuminant only ensures that the grays will be balanced when viewed under that illuminant and does not necessarily resolve the problem of color inconstancy for other illuminants. If more robust gray balance is desired under multiple illuminants, it is recommended to use more black ink when generating grays [10].

In the past, investigations of color shifts were made, but in most cases they were realized for limited numbers of few colors and experiments were not performed in real printing conditions with real printing inks and pigments. The printing ink sequence is very important, too, because every ink layer is semi-transparent and the upper ink layer functions like filter for the lower ink layer. In practice it is known that the different ink colors (C, M, Y, K) and image tones (highlights, midtones and darktones) lead to non-equal color shifts. To date, no research has been made into the influence of light sources on different ink colors and different image tones on color shifts and color gamuts.

In our previous paper [11], we have investigated color shifts on offset printed images and the changes in their color gamuts for glossy coated paper – one of the major grade materials defined in International Standards for printing. The results obtained show considerable and different color shifts depending on different ink colors and illuminants and also differences in color gamut volumes. For this reason it is important to investigate color shifts and changes in color gamuts for the most commonly used in printing industry paper grades.

The main goals of this research are investigation and determination of color balance failure (color inconstancy) of offset printed images expressed by color difference and color gamut changes under different standard illuminant conditions for offset uncoated paper. This material is one of the most commonly used in practice for printing of books, magazines, *etc*. The experiment was performed for a large number of color strips representing the whole visible spectrum. The big number of color patches investigated provides a comprehensive notion of color shifts and color gamut changes of printed image depending on different illuminants.

2. Experiment

We chose for the experiment three of the most commonly used in practice illuminants: CIE D50 (color temperature 5003 K), CIE F2 (4230 K) and CIE A (2856 K) [12, 13].

The test form that has been used contains different control strips and measurement components including test chart TC6.02 with about 1000 color patches with different percent combinations of cyan (C), magenta (M), yellow (Y) and black (K).

The prints were performed under standard prepress and printing conditions on sheet-fed offset printing press – Heidelberg SpeedMaster 74-5-P+L on offset paper 80 g/m^2. The ink printing sequence is K, C, M and Y. A series of colorimetric and densitometric measurements have been performed for different combinations of C, M, Y and K in single, double, triple and quadruple overprint for highlight, middle and dark tones.

From the already printed paper there are fortuitously taken printed sheets, which correspond to previously defined optimal inking 1.06 ± 0.1 D for cyan, 1.06 ± 0.1 D for magenta, 1.0 ± 0.1 D for yellow and 1.2 ± 0.1 D for black. In order to achieve the goals of the experiment, series of measurements of CIE $L^*a^*b^*$, Dv, print contrast, tone value increase have been made with spectrophotometer/densitometer of type SpectroEye and X-Y SpectroScan of X-Rite [14].

The measurement file from X-Y SpectroScan of X-Rite was supplied to the Profilemaker 5.0 software in order to generate the ICC profile. Profilemaker then builds an ICC profile containing a Color Look-up Table based transformation structure, which relates printer digital counts to CIELAB coordinates. The settings for creating the profiles are: size of profiles was chosen as *large*, viewing illuminant – D50, A and F2, gamut mapping intent – *logo classic*, perceptual rendering intent – *neutral* *gray*, separation: GCR3, total ink limited 280%. Calculation of the color gamut volume was made by CHROMiX Color Think Pro.

Our study was performed in accordance with the International Standards for printing, which includes ISO 12647-1, ISO 12647-2, ISO 13656, ISO 3664, and ISO 2846-1. They referred the target values of the main parameters of press, and the conditions for measurement and control.

For estimating the color balance failure color differences ΔE^*_{ab} are calculated for the same color fields depending on standard illuminants CIE D50, F2 and A. For this reason there are obtained three values of color difference: D50–A, A–F2 and D50–F2 for each color patch. The chosen color fields are in highlights, middle and dark tones for all single, double and triple overprint of cyan, magenta, yellow, and black.

All the data are measured under D50, A and F2 illuminants, *i.e.*, for all the parameters we obtain 3 data sets: for D50, A and for F2.

According to ISO 12647-1:2004 [15], color differences ΔE^*_{ab} have to be calculated based on CIE 1976 $L^*a^*b^*$:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{1}$$

The data from measurements (CIE $L^*a^*b^*$ values) were processed with Origin 7.0, where formulas necessary for calculation of color difference ΔE^*_{ab} are implemented.

In addition to calculation of ΔE^*_{ab}, for better assessment and for comparing visual perception and differences of colors depending on illuminants, we have calculated color inconstancy index CMCCON02 (according to ISO 105-J05:2007 [16] and ISO 105-J03:2009 [17]) for highlights, middle and dark tones for all single, double and triple overprints of cyan, magenta, yellow, and black (same color fields like ΔE^*_{ab}), represented in Figs. 1–3.

The first step for determination of CMCCON02 was calculation of tristimulus values – X, Y, Z and X_r, Y_r, Z_r for test illuminants – D50, A and F2 and reference illuminant – D65, respectively. The second step was calculation of R, G, B cone responses to the specimen and the perfect reflecting diffuser (PRD) (R_w, G_w, B_w), each under the test illuminant, and to the PRD (R_{wr}, G_{wr}, B_{wr}) under illuminant D65:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M_{\mathrm{CAT02}} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix} = M_{\mathrm{CAT02}} \begin{pmatrix} X_w \\ 100 \\ Z_w \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} R_{wr} \\ G_{wr} \\ B_{wr} \end{pmatrix} = M_{\text{CAT02}} \begin{pmatrix} X_{wr} \\ 100 \\ Z_{wr} \end{pmatrix} \tag{4}$$

where

$$M_{\text{CAT02}} = \begin{pmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{pmatrix} \tag{5}$$

The third step was calculation of corresponding RGB cone responses:

$$R_c = R\left(\frac{R_{wr}}{R_w}\right) \tag{6}$$

$$G_c = G\left(\frac{G_{wr}}{G_w}\right) \tag{7}$$

$$B_c = B\left(\frac{B_{wr}}{B_w}\right) \tag{8}$$

The fourth step was calculation of tristimulus values of the corresponding colors for illuminant D65:

$$\begin{pmatrix} X_c \\ Y_c \\ Z_c \end{pmatrix} = M_{\text{CAT02}}^{-1} \begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} \tag{9}$$

where

$$M_{\text{CAT02}}^{-1} = \begin{pmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{pmatrix} \tag{10}$$

The final step was calculation of the color difference ΔE_{CMC}. For this reason we determine $L^*a^*b^*$ values from X_c, Y_c, Z_c and X_r, Y_r, Z_r values. After that we have calculated chroma (C^*_{ab}) and hue (h_{ab}), differences between the values of the specimen and the reference – ΔL^*, Δa^*, Δb^*, ΔC^*_{ab}, ΔH^*_{ab}. Finally, we have obtained the color difference ΔE_{CMC} by the following equation:

$$\Delta E_{\mathrm{CMC}}(l{:}c) = \sqrt{\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*}{cS_C}\right)^2 + \left(\frac{\Delta H^*}{S_H}\right)^2} \tag{11}$$

where $l = c = 1$ for perceptibility measurements of graphic arts.

3. Results and discussion

3.1. Comparing color differences – ΔE^*_{ab} and CMCCON02 for different illuminants and combinations of CMYK

The experimental data, representing the color differences – ΔE^*_{ab} and CMCCON02 between process colors dot area for single, double and triple overprints depending on standard illuminants used are given in Figs. 1–3.

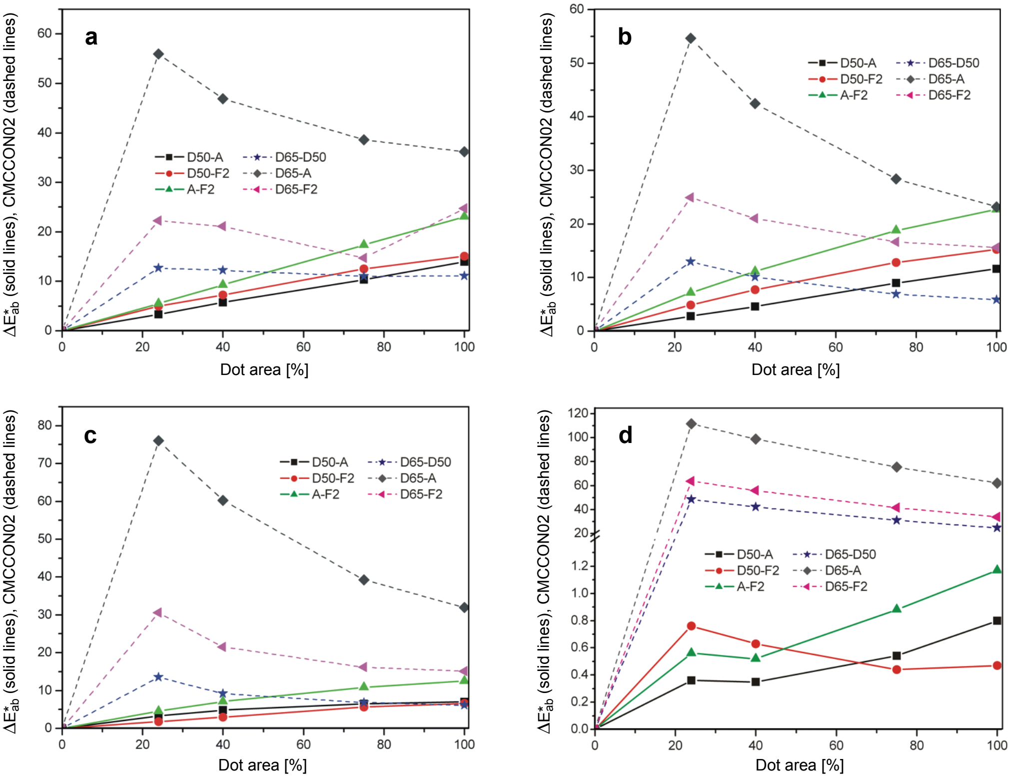

Fig. 1. ΔE^*_{ab} (solid lines) and CMCCON02 (dashed lines) by different illuminants in the highlights, middle and dark tones for single overprint of cyan (**a**), magenta (**b**), yellow (**c**) and black (**d**).

The graph in Fig. 1**a** shows that for cyan the smallest color difference ΔE^*_{ab} is obtained for illuminant pair D50–A and the smallest CMCCON02 is obtained for illuminant pair D65–D50, and the biggest ΔE^*_{ab} is for A–F2 and biggest CMCCON02 is for D65–A. For magenta (Fig. 1**b**) the biggest E^*_{ab} and CMCCON02 are obtained for A–F2 and for D65–A, and the smallest E^*_{ab} and CMCCON02 – by D50–A and D65–D50. For the yellow (Fig. 1**c**), the biggest ΔE^*_{ab} and CMCCON02 are obtained by A–F2 and D65–A, respectively and the smallest by D50–F2 and D65–D50. For black (K) (Fig. 1**d**), ΔE^*_{ab} values are significantly smaller than those of C, M and Y, but CMCCON02 values are very big.

For all three illuminants and for C, M and Y the minimum value for ΔE^*_{ab} is obtained in highlights, grows up in middle tones and reaches the maximum value in dark tones. This phenomenon can be explained by the fact that the color difference ΔE^*_{ab} from different illuminants is proportional to the increase of ink quantity on printed sheet.

For all process inks and for all illuminants in this research the CMCCON02 has maximal value in highlight tones, decreases in middle tones and has a minimum value

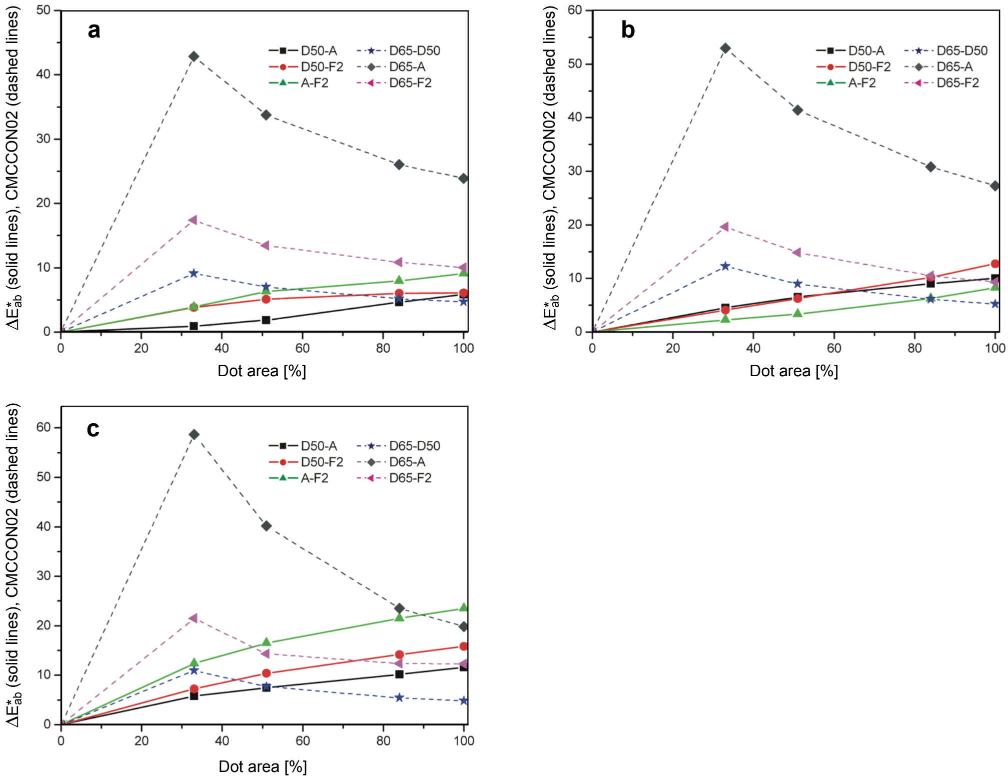

Fig. 2. ΔE^*_{ab} (solid lines) and CMCCON02 (dashed lines) by different illuminants in the highlights, middle and dark tones for double overprint of cyan and magenta (**a**), cyan and yellow (**b**), and magenta and yellow (**c**).

in dark tones. This result can be explained, by the fact that CMCCON02 is adapted and based on human perception features. The human eye is more sensitive in highlights and less sensitive in middle and dark tones. That is why CMCCON02 has maximal value in highlights and minimal value in dark tones.

The graphs for 2-overprint of cyan and magenta and magenta and yellow (Figs. 2**a** and 2**c**) show that the lowest values of E^*_{ab} and CMCCON02 are for D50–A and D65–D50, respectively. The biggest values of E^*_{ab} and CMCCON02 are obtained by A–F2 and D65–A, respectively. For double overprint of cyan and yellow (Fig. 2**b**), the biggest E^*_{ab} and CMCCON02 are obtained by D50–F2 and D65–A, and the smallest – by A–F2 and D65–D50.

For all illuminants the minimal values for ΔE^*_{ab} are in the highlights and the maximal are in the dark tones. For CMCCON02 the minimal values are in the dark tones and maximal in highlights. This phenomenon can be explained in the same way as that for the single overprint values of color differences – ΔE^*_{ab} and CMCCON02.

For 3-overprint of cyan, magenta, yellow and magenta, yellow, black (Figs. 3**a** and 3**c**) the lowest values of E^*_{ab} and CMCCON02 are obtained by D50–A and

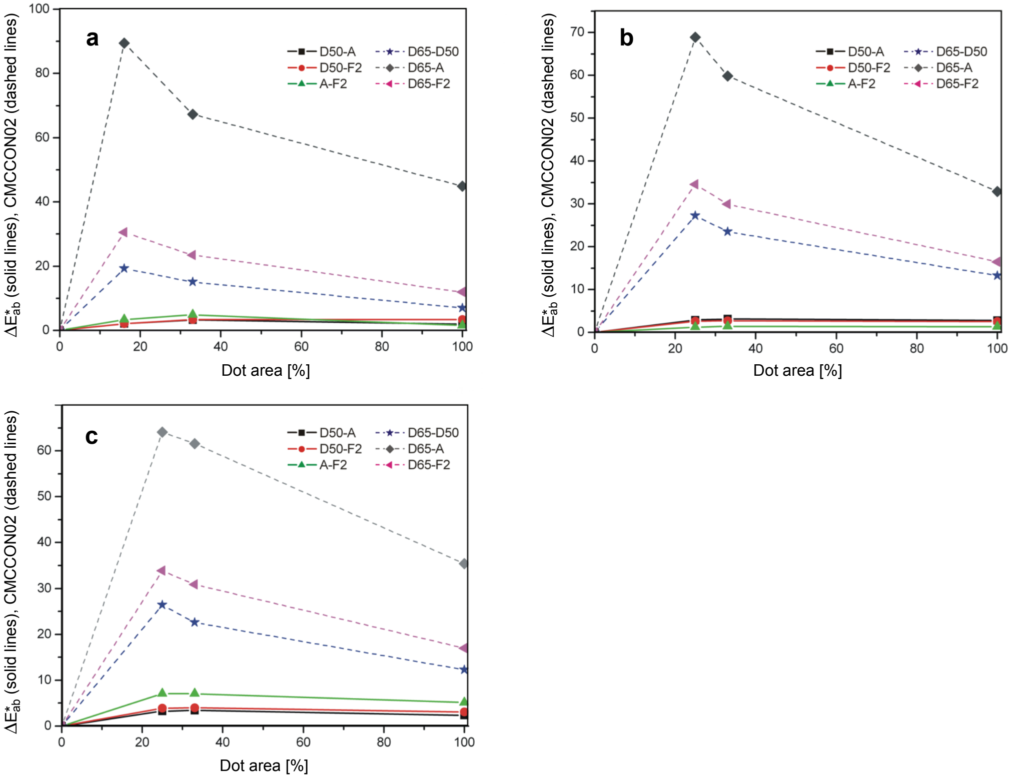

Fig. 3. ΔE^*_{ab} (solid lines) and CMCCON02 (dashed lines) by different illuminants in the highlights, middle and dark tones for triple overprint of cyan, magenta and yellow (**a**), cyan, yellow and black (**b**) and magenta, yellow and black (**c**).

D65–D50, respectively, and the biggest values are obtained by A–F2 and D65–A. For triple overprint of cyan, yellow, black, the biggest E^*_{ab} and CMCCON02 are obtained by D50–A and D65–A, and the smallest by A–F2 and D65–D50.

The lowest value of E^*_{ab} for 1-overprint on C, M and Y is 1.76 (in the high tones for Y), for 2-overprint on C, M, Y and K is 0.93 (in the high tones for C + M), and for 3-overprints – 1.2 (in the high tones for C + Y + K), all of them for different illuminant transitions.

The lowest value of CMCCON02 for 1-overprint on C, M and Y is 5.81 (in the dark tones for M), for 2-overprint on C, M, Y and K it is 4.72 (in the dark tones for C + M), and for 3-overprints – 6.92 (in the dark tones for C + M + Y), all of them for different illuminant transitions.

The highest value of E^*_{ab} for 1-overprint on C, M and Y is 23.11 (in the dark tones for C), for 2-overprint on C, M, Y and K it is 23.53 (in the dark tones for M + Y), and for 3-overprints – 7.1 (in the high tones for M + Y + K).

The highest value of CMCCON02 for 1-overprint on C, M and Y is 111.75 (in the high tones for K), for 2-overprint on C, M, Y and K it is 58.64 (in the high tones for M + Y), and for 3-overprints – 89.41 (in the high tones for C + M + Y).

3.2. Comparing 2D and 3D color gamuts for different illuminants

The graphical presentation of color gamut – 3D and 2D gives us valuable and comprehensive information about colors that can be reproduced in specific conditions. A 3D gamut presentation gives us general information of the asymmetric color body.

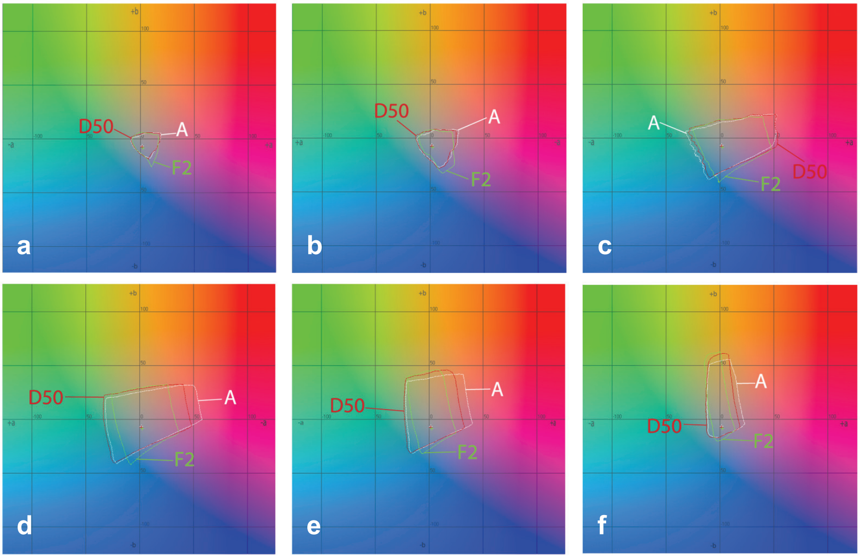

Fig. 4. 2D color gamut of colors under different illuminants: $L = 30$ (dark tones) – **a**; $L = 40$ (middle tones) – **b**; $L = 50$ (middle tones) – **c**; $L = 60$ (middle tones) – **d**; $L = 70$ (highlight tones) – **e**; $L = 80$ (highlight tones) – **f**.

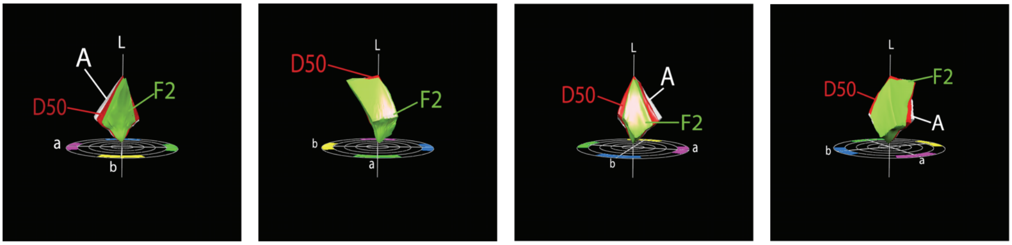

Fig. 5. 3D color gamut of colors under different illuminants.

A 2D gamut presentation at different cross-sections of CIE L^* coordinate, provides more detailed information for analysis and comparison purposes.

So far, we have not found in the specialist literature any 2D and 3D presentation nor a comparison of color gamuts for different printing conditions and different illuminants.

In Figure 4, for a more comprehensive characterization of color shift changes resulting from standard illuminant transition, a 2D color gamuts are presented for dark, middle and highlight tones. These 2D color gamuts are chosen because the human eye has a different sensitivity in dark, middle and highlight tones.

Figure 4 shows that in the dark tones (Fig. 4**a**) the color gamut of CIE F2 is considerably bigger in the violet area, near to CIE A and CIE D50 in yellow-red area and lesser in the other areas. In the middle tones (Figs. 4**b**–4**d**) the color gamut of CIE A is biggest in the blue-green area and in the other areas is very similar to the color gamut of CIE D50. In the highlights (Figs. 4**e** and 4**f**) CIE A has the biggest color gamut in violet-red area. CIE D50 has the biggest color gamut in green-blue area, and CIE F2 – in blue-violet area.

Figure 5 shows and graphically compares the 3D color gamuts viewed from different angles and perspectives for the three standard illuminants.

3.3. Comparing color gamut volume for different illuminants

In addition to the graphical presentation of 3D and 2D color gamuts, we have calculated and obtained volumes of 3D color gamuts. Table 1 shows gamut volumes for the three standard illuminants.

According to Tab. 1 and Fig. 5, CIE A has the biggest color gamut volume and CIE F2 the smallest one. The data show big differences between volumes up to 30%. This phenomenon is very important from practical point of view, because the volume

Table 1. Calculated color gamut volume.

Standard illuminant	Color gamut volume
CIE A	179 799
CIE F2	126 156
CIE D50	154 855

of colors is one of the most important factors that impacts human perception and auditory indulgence of print quality.

3.4. Comparing color values in CIELAB color space for different illuminants and combinations of CMYK

In addition to the calculation of color differences, color gamuts and volumes of color gamuts, it is necessary to compare the color coordinates of important colors for printing industry for different illuminants.

The graphs in Fig. 6**a** represent CIE a^*b^* coordinates of 40% single overprint by illuminants D50, A and F2 of cyan, magenta and yellow. Figure 6**b** shows CIE a^*b^* coordinates of 100% double overprint by illuminants D50, A and F2 of cyan and magenta, cyan and yellow and magenta and yellow. The graph in Fig. 6**c** represents CIE a^*b^* coordinates of 100% triple overprint by illuminants D50, A and F2 of

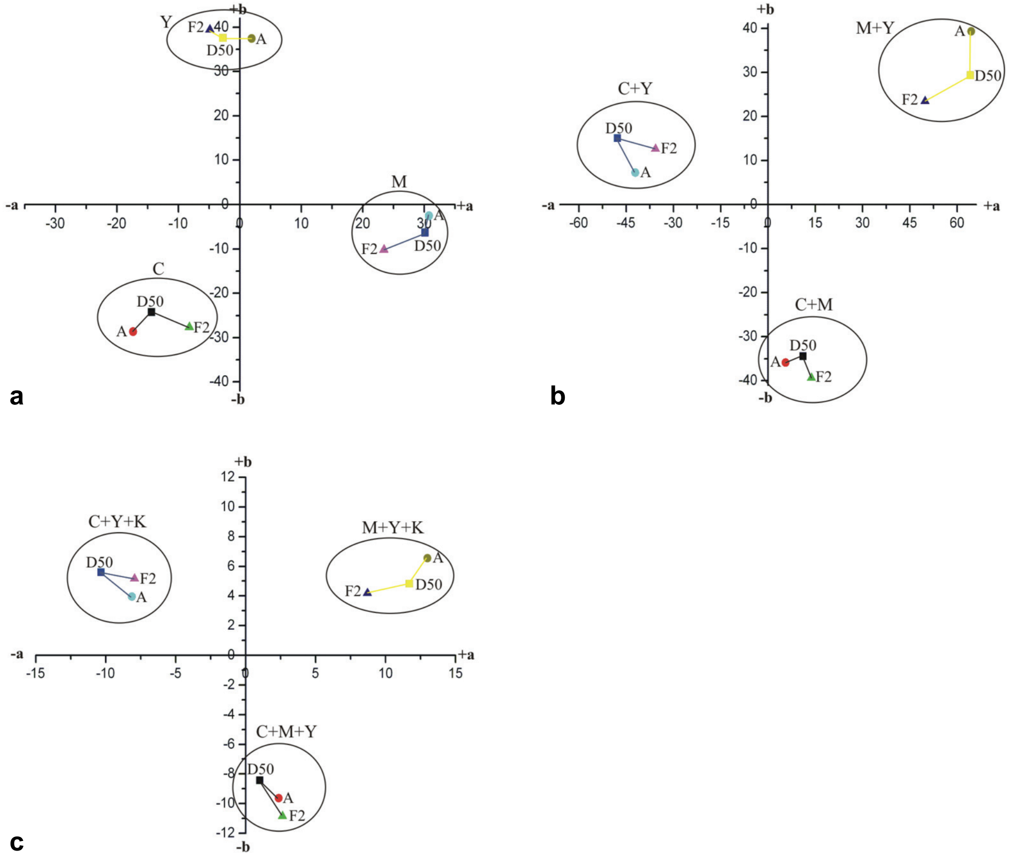

Fig. 6. CIE a^*b^* of colors under illuminants A, D50 and F2 for single overprint of 40% tone value of C, M and Y (**a**); double overprint of 100% solids (**b**); and triple overprint of 100% solids (**c**).

cyan, magenta and yellow, cyan, yellow and black and magenta, yellow and black. The graphs clearly show visible color shifts for single, double and triple overprint of cyan, magenta, yellow and black.

4. Conclusions

The results obtained are important from scientific and practical points of view. For the first time, some methodology is suggested and implemented for examination and estimation of color shifts, color gamut and color gamut volume changes by studying a big number of color changes in various ink combinations for different illuminants for offset paper.

For first time via experimental research in real production conditions, there were made 3D and 2D presentations and comparison of color gamuts and color gamut volumes for different illuminants. According to the results, CIE A has the biggest color gamut volume and CIE F2 the smallest one. This means that the viewing conditions and illuminants have a big influence not only on color shifts, but on the number of reproduced colors. The data show big differences between the volumes – up to 30%. This phenomenon is very important from practical point of view, because the volume of colors is one of the most important factors that impacts human perception and auditory indulgence of print quality. In this way, for the chosen standard illuminant, we can predict whether a particular color or even some part of the visible spectrum can be reproduced.

For all three illuminants and for C, M and Y, the minimum value for ΔE^*_{ab} is obtained in highlights, grows up in middle tones and reaches the maximum values in dark tones. This phenomena is valid for all single, double, triple overprints and can be explained by the fact that the color difference ΔE^*_{ab} from different illuminants is proportional to the increase of ink quantity on printed sheet.

For all process inks and for all illuminants in this research CMCCON02 has maximal value in highlight tones, decreases in middle tones and has a minimum values in dark tones. This result is valid for all single, double, triple overprints and can be explained by fact that CMCCON02 is adapted and based on human perception features. The human eye is more sensitive in highlights and less sensitive in middle and dark tones. That is why CMCCON02 has maximal value in highlights and minimal value in dark tones.

It is clearly visible from the experimental results that for all combinations of process colors – CMYK, there are big differences between the values of ΔE^*_{ab} for each of the standard illuminants. The results are similar for CMCCON02 – there are big differences, even greater than ΔE^*_{ab} for each of the standard illuminants. The results show that values of CMCCON02 are different and many times greater than E^*_{ab}. This fact results from the difference between calculation formulas for CMCCON02 and for ΔE^*_{ab}. In calculations for CMCCON02 we use chromatic adaptation transforms. Moreover, the equations for ΔE^*_{ab} and CMCCON02 are much different. The reference illuminant is different: D50 for ΔE^*_{ab} and D65 for CMCCON02. The ΔE^*_{ab} equation is not very accurate for saturated colors, and CMC color difference formula takes into account three components: lightness, chroma and hue tolerances.

The results show that the CMCCON02 has the biggest values in D65–A, and lowest in D65–D50 for all colors.

In Table 2, the summarized data for color differences and different color transitions are shown. The ΔE^*_{ab} data are calculated for reference D50, as requested by the ISO standards for graphic industry. The CMCCON02 values are calculated for D65 reference, because CMCCON02 standards request this.

Table 2. Summarized data for ΔE^*_{ab} and CMCCON02 for different color transitions.

Illuminant transition	ΔE^*_{ab}			CMCCON02		
	Minimal	Average	Maximal	Minimal	Average	Maximal
CIE D50–A	0.93	6.24	13.92	–	–	–
CIE D50–F2	1.76	7.72	15.87	–	–	–
CIE A–F2	1.54	10.41	23.53	–	–	–
CIE D65–F2	–	–	–	9.31	17.66	30.60
CIE D65–D50	–	–	–	4.72	9.15	19.21
CIE D65–A	–	–	–	19.86	42.84	89.41

The color difference ΔE^*_{ab} has biggest values for A–F2, and the lowest for D50–A, and CMCCON02 has the biggest values was for D65–A and the lowest for D65–D50.

From the human visual perception viewpoint, for evaluation of color inconstancy there should be used CMCCON02, because the human eye is most sensitive to hue differences, then chroma and finally lightness and CIE ΔE^*_{ab} do not take this into account.

From the perspective of the practice in the printing industry and International Standards for printing we have to use CIE ΔE^*_{ab}. This color difference has both advantages such as speed and accuracy in calculation of the differences between colors, and disadvantages, including inaccuracy when taking into account visual perception.

Nevertheless, all the data from both approaches prove that there are significant colors shifts and they are visible for the human perception. The color shifts are different for single, double, triple overprints and for highlights, midtones and dark tones.

5. Future research

In the future, we shall compare the results of this research with data collected by the methods of modeling, statistics and visual assessment of test images viewed by different illuminants by a group of experts. The results will show which formula is appropriate to evaluate the color inconstancy in printing industry, and whether the results obtained by chromatic adaptation transforms will match the results from visual assessment.

In the future, based on the data collected from this research, a mathematical model could be developed describing relationships between color shifts and gamut changes and ink colors and quantity. Certainly, this will be very useful for predicting correct color reproduction in different light conditions.

Research should be performed for the other major types of printing papers defined in ISO standards.

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