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Ink - jet imprints in just noticeable color difference evaluation

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In this paper we investigated the possibility of using ink - jet printing technique for the purpose of just noticeable color difference (JND) evaluation. When performing color difference evaluations with printed samples, it is expected that colorimetric values of printed samples exhibit minimal deviation from the established target values. The uniformity of printed area and consistency in colorimetric values is also a must. The printing technique used may significantly influence the color reproduction, thus altering the targeted color difference. In order to evaluate the level of inconsistency influenced by the ink-jet printing technique, we chose five initial color centers, varied their lightness and hue in such a way that color difference between neighboring samples was 0.25 ΔE^*_{ab}. The samples were printed on uncoated 120 g/m^2 paper. For accurate quantification of color difference, we used CIELAB and CIE2000 color difference formulae as well as MCDM formula. It was shown that the expected color differences were not obtained in all cases and for all colors used. Although the CIE2000 formula gave slightly more accurate results than CIELAB, their performances were shown to be quite similar. It was shown that the variability is dependent on the color center as well as on the degree and direction of variation in lightness and hue. The study indicated that performing color difference evaluations on ink - jet imprints at the level of 0.25 up to 0.75 ΔE^*_{ab} units will be strongly influenced by printing inconsistency.

Key words: ink - jet printing, just noticeable color difference (JND), color difference formulae

INTRODUCTION

Color is one of the most important visual attributes in many industrial branches and is often associated with the concept of quality. It can be considered as a highly important commercial determinant of quality for a wide range of products. The color can be evaluated by instrumental or visual analysis. Visual analysis, often referred to as subjective, are based on human perception of color while the instrumental analysis are based on physical, objective evaluation of color stimuli using spectral measurements, measurements of the tristimulus values, relating to the quantitative description of the color appearance, lightness/brightness, hue or chroma/saturation [1-3].

Since the color could be measured, the topic of practical importance is the color-difference evaluation - precise definition of the magnitude of color differences between various colored stimuli. For that purpose, the series of color difference equations have been established, with more or less successful correspondence between changes in the physical description of a color stimuli and its appearance [1]. The aim of decades of research in this field was to establish the color difference formula which would be successfully used in just noticeable, small through moderate to large color differences evaluations with the magnitude which would be correlating the visual one [4-14].

Currently, there are at least six color difference equations available, including the so-called advanced formulae: CIELAB, CIELUV,CMC, BFD, CIE94, CIE00 [6-9,12-28], where most of them are based on CIELAB colorimetric system. From this variety arises several questions that should be attempted to be answered: the decision making criteria for the formula to be used, the compatibility of results accomplished using different formulae, applicability of each one under various conditions. So far, it is established that each of the formulae mentioned above performs best under a specific, more or less similar set of reference conditions. Each formula result in different values, which might, in some color regions, be quite significant [6].

Instrumental color measuring and evaluation processes, based on color-difference calculations, is usually performed between target color stimuli and corresponding reproduced match. The pass/fail decision is made on the basis of the established color difference threshold. The color difference threshold differs in ΔE^*_{ab} value depending upon the

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area of application and color difference formulae used: a difference of 5ΔE^*_{ab} may be acceptable in some applications, whereas for other, differences over 1 ΔE may be unacceptable.

Nevertheless, defined threshold should always be in compliance with an observer´s ability to detect a difference in colored stimuli. Thus, in terms of color-difference perceptibility, the smallest perceptible difference by the human eye, detected at 50 % probability, is known as a just-noticeable difference (JND) [7,8,10]. A theoretical CIELAB JND is deemed a difference of 1.0 ΔE^*_{ab}, with equal contributions from the L*, a* and b* errors [8,16,30]. In contrast, in another experimental study, encompassing the evaluation of uniform color differences, was reported an average value of 2.3 ΔE^*_{ab} for JND [24,30].Color difference of 1 ΔE^*_{ab} is normally detected in neutral colors, while more saturated colors require a slightly larger ΔE^*_{ab} in order to be detected by the untrained observer [24,31]. According to Ebner [32], CIELUV color difference of less than 1 ΔE^*_{uv} will not be perceptible, as well. The color differences up to 4 may or may not be perceptible, depending on the color itself, while the difference larger than 4, is highly likely to be perceived [32].

If the printed samples are tending to be used in experiments where a series of color tests are to be compared with a color reference in order to establish the color difference threshold (JND), it is obvious that those tolerances for prints cannot be even considered. It is inevitable for reproduced color to be influenced by printing technology, but the magnitude of the influence must be known and taken into consideration if performing color difference evaluations.

Driven by the findings stated above, we investigated the possibilities of using ink - jet printing technique for the purpose of just noticeable color difference (JND) evaluation tending to reveal to which extend the used printing technique alter the targeted color difference. For the analysis, we have chosen five CIE color centers (gray, green, red, blue and yellow) and varied their lightness and hue in order to achieve targeted color difference. The color difference calculations using L*a*b* values from ink-jet printed samples were performed using ΔE^*_{ab} and ΔE_{00} color difference equations.

METHODOLOGY

In order to evaluate the level of reproduction inconsistency which will be directly influenced by printing technique used, we chose five initial color centre [9] (Table 1). Their lightness and hue were varied in the steps of ΔE^*_{ab} 0.25, where the changes were made in both directions i.e. by lowering and increasing the values. When the lightness value was varied, hue value was left unchanged, and vice versa. The smallest color difference from the initial color was 0.25, while the largest was set to be 1.5. Since the lightness and hue were varied independently, we created 5 color test charts (Fig. 1) with lightness and 4 color test charts with hue variations (achromatic, gray color was omitted in hue variation analysis).

The targeted digital L*a*b* data of each color patch were calculated on the basis of expected color difference value ΔE^*_{ab}, L*a*b*/ C*h^0 values of five initial color centers and following formulae [2-3,33]:

ΔE^*_{ab} (CIELAB, $\Delta E76$) color difference:
$$\Delta E^*_{ab} = [\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}]^{1/2} \qquad (1)$$

where:

- ΔL^* - the lightness difference: $\Delta L^* = L^*_1 - L^*_2$,
- Δa^* and Δb^* - chromaticity differences: $\Delta a^* = a^*_1 - a^*_2$, $\Delta b^* = b^*_1 - b^*_2$
- L_1 a_1, b_1 - lightness and chromaticity coordinates of sample 1 (CIE color centre); L_2, a_2, b_2 - lightness and chromaticity coordinates of sample 2 (targeted color patch).

$$\Delta E^*_{ab} = [\Delta L^{*2} + \Delta C^{*\,2}_{ab} + \Delta H^{*\,2}_{ab}]^{1/2} \qquad (2)$$

Table 1. CIELAB chromaticity parameters of the test color centers. The CIE1931 Standard Colorimetric Observer was used in the calculations

Color center	L_1*	a_1*	b_1*	C_1*	h_1^o
Gray	61.65	0.11	0.04	0.12	20
Red	44.38	36.91	23.33	43.67	32
Yellow	86.65	-6.92	47.15	47.66	98
Green	56.09	-32.13	0.44	32.13	179
Blue	35.60	4.83	-30.18	30.56	279

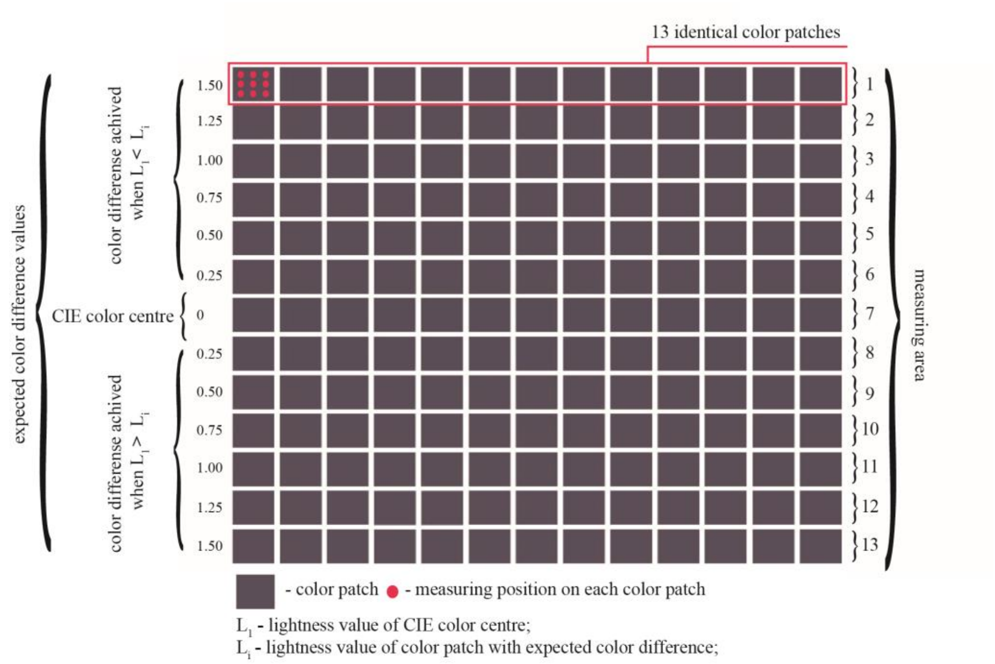

Figure 1. Example of generated color test chart and pictorial explanation of relevant elements (one color/variation in lightness value)

Chroma (ΔC^*_{ab}) differences: $\Delta C^*_{ab} = C^*_{ab,1} - C^*_{ab,2}$ (3)

Hue (ΔH^*_{ab}) differences:

$$\Delta H^*_{ab} = 2(C^*_{ab,1}\, C^*_{ab,2})^{1/2} \sin(\Delta h_{ab}/2) \quad (4)$$

$$\Delta h^*_{ab} = h^*_{ab,1} - h^*_{ab,2} \quad (5)$$

Chroma (C_{ab}^*): $C_{ab}^* = [(a^*)^2 + (b^*)^2]^{1/2}$ (6)

Hue angle (h_{ab}^*): $h_{ab}^* = \tan^{-1}(b^*/a^*)$ (7)

where a*, b* - chromaticity coordinates of the sample; $C^*_{ab,1}$ is chroma of sample 1 (CIE color centre); $C^*_{ab,2}$ - chroma of sample 2 (targeted color patch); $h^*_{ab,1}$ is hue angle of sample 1 (CIE color centre); $h^*_{ab,2}$ - hue angle of sample 2 (targeted color patch).

The L*a*b* data were then recalculated to RGB values (CIE D50 standard illuminant and standard 2° observer; 0-1 scale) and used for of the generation of color patches size of 2x2 cm (sRGB, .tiff format). For this purpose, we employed MATLAB® R2013a. The patches were used for color test chart creation in Adobe® Photoshop® CS6 software.

The created color test charts were printed on uncoated, single-weight matte 120 g/m^2 ink - jet paper using calibrated ink-jet printer Epson Stylus Pro 7800. The settings of a printer were according to manufacturers' recommendation for high quality color printing –on the resolution of 720x1440 dpi. Thirteen patches were printed for each color and each lightness/hue variation, whereas each color patch was measured nine times (as depicted in Figure 1) and L*a*b* values were recorded accordingly. They were used for color difference (averaged) and MCDM calculation (L*, a* and b* value of 117 measurements per each color lightness/hue variation). The colorimetric measurements were performed using Techon SpectroDens Advanced spectrophotometer (measurement geometry: $0^0/45^0$ with respect to CIE D50 standard illuminant and standard 2° observer). Measurement is performed on black, matte backing.

For accurate quantification of produced color difference on ink-jet imprints, we used ΔE^*_{ab} (Eqn.1) and ΔE_{00} ($\Delta E2000$) [33,35-36]:

$$\Delta E_{00} = [(\Delta L'/K_L S_L)^2 + (\Delta C'/K_C S_C)^2 + (\Delta H'/K_H S_H)^2 + R_T(\Delta C'/K_C S_C)(\Delta H'/K_H S_H)]^{1/2} \quad (8)$$

where

$\Delta L' = L'_1 - L'_2$

$\Delta C' = C'_1 - C'_2$

$\Delta H' = 2(C'_1 C'_2)^{1/2} \sin(\Delta h'/2)$

$\Delta h' = h'_1 - h'_2$

$$S_L = 1 + \frac{0.015(\bar{L}' - 50)^2}{\sqrt{20 + (\bar{L}' - 50)^2}}$$

$$S_c = 1 + 0.045\bar{C}'$$

$$S_H = 1 + 0.015\bar{C}'T$$

$$T = 1 - 0.17\cos(\bar{h}' - 30^0) + 0.24\cos(2\bar{h}') + 0.32\cos(3\bar{h}' + 6^0) + 0.20\cos(4\bar{h}' + 63^0)$$

$$R_T = -\sin(2\Delta\theta)\, R_C$$

$$\Delta\theta = 30 exp\left\{-\left[(\bar{h}' - 275^0)/25\right]^2\right\}$$

$$R_C = 2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}$$

$$L' = L^*$$
$$a' = (1 + G)a^*$$
$$b' = b^*$$
$$C' = (a'^2 + b'^2)^{1/2}$$
$$h' = tan^{-1}(b'/a')$$
$$G = 0.5\left(1 - \sqrt{\frac{\overline{C^*_{ab}}^7}{\overline{C^*_{ab}}^7 + 25^7}}\right)$$

$K_L=1$; $K_C=1$; $K_H=1$ (default values).

Mean Color Difference from the Mean (MCDM) was computed across all repetitions (measuring areas, Fig.1), for each color and each variation in order to give better insight in color variability caused by printing process itself. MCDM value was calculated based on ΔE^*_{ab} and ΔE_{00}, as well [37-38]:

$$MCDM = \sum_{i=1}^{n} E^*_{abi} \quad (9)$$

where:

$\Delta E^*_{ab}= [(L_i^*-L^*_{mean})^2+ (a_i^*-a^*_{mean})^2+ (b_i^*-b^*_{mean})^2]^{1/2}$

$L^*_{mean}=\sum_{i=1}^{n} L_i^*/n$;

$a^*_{mean}=\sum_{i=1}^{n} a_i^*/n$;

$b^*_{mean}=\sum_{i=1}^{n} b_i^*/n$;

n =117 (the number of samples);

$$MCDM = \sum_{i=1}^{n} E^*_{00i} \quad (10)$$

where:

$\Delta E_{00}= [((L_i'-L'_{mean})/K_LS_L)^2 + ((C_i'-C'_{mean})/K_CS_C)^2+ + (2(C'_iC'_{mean})^{1/2} \sin((h'_i - h'_{mean})/2)/K_HS_H)^2+ + R_T((C_i'-C'_{mean})/K_CS_C) (2(C'_iC'_{mean})^{1/2} \sin((h'_i - h'_{mean})/2)/K_HS_H)]^{1/2}$

$L'_{mean}=\sum_{i=1}^{n} L'_i/n$;

$C'_{mean}=\sum_{i=1}^{n} C'_i/n$;

$h'_{mean}=\sum_{i=1}^{n} h'_i/n$;

n =117 (the number of samples).

RESULTS AND DISCUSSION

On Fig. 2 and Fig. 3 are depicted calculated color differences in contrast to expected ones. Figure 2 represent the results where the color difference was obtained by lightness variation, while Figure 3 shows those obtained by hue variations. The gray line represents the ideal color reproduction, thus theoretically achievable targeted/ reproduced color difference ratio.

According to the results presented on Fig. 2, the achieved color differences exhibited moderate to large discrepancies from targeted values. The highest deviations were observed in case of green color by lowering the L^* value of the color centre. In case of gray, red, blue and yellow CIE color centre, similar trend can be observed: if the targeted color difference value were smaller, the deviations were higher and the

a) b) c) d) e)

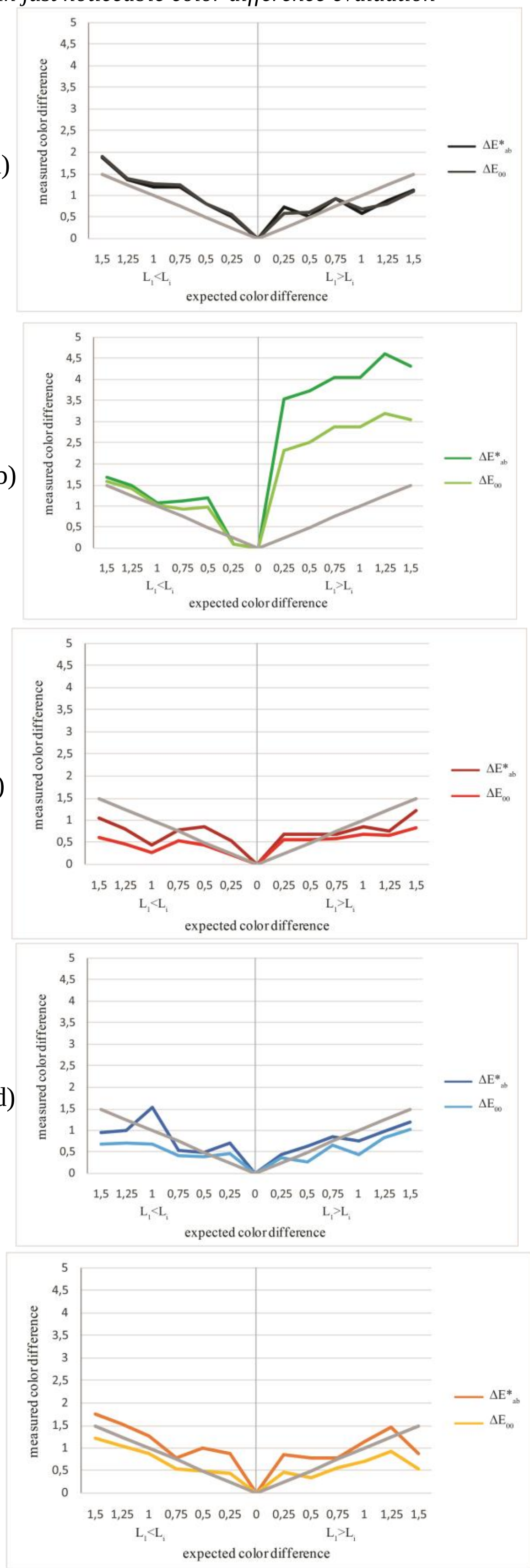

Figure 2. ΔE^*_{ab} and ΔE_{00} color difference values (lightness scale variations): a) gray, b) green; c) red; d) blue; e) yellow.

reproduced values were above the targeted ones; if the targeted ΔE values were bigger, the discrepancies were of lower value, while the reproduced ΔE values are below the targeted ones. In the case of the smallest initially defined ΔE values, the color differences were doubled, or even tripled from the expected ones. The highest discrepancies were reached for color differences ranging from 0.25 to 0.75, for all the colors encompassed in the analysis. The defined trends were observed regardless of the color difference formulae used. The use of ΔE_{00} color difference formula resulted in lower ΔE values in comparison to ΔE^*_{ab}. The exception is achromatic, gray color, where both equations led to almost the same values. Taking into account the way of obtaining the color difference values, this result was expected (see Eqns. 1 and 8).

Overall, if the L value was changed, ΔE^*_{ab} presented slightly better performances when evaluating the reproduction closest to target one, but restricted to range of color difference above 0.75. Otherwise, the minor advantage is given to ΔE_{00} formula. Comparing the results presented on Fig. 3 with those shown on Fig. 2 it is evident that higher reproduction accuracy was achieved when color difference was obtained by the change in chromacity. Better agreement between targeted ΔE values and reproduced ones was obviously achieved in case of green and yellow color. On the other side, quite huge discrepancies were outlined in case of blue and red color. Expressed in ΔE^*_{00}, color differences certainly have shown lower deviation range, especially in case of green, yellow and blue. Thus, if the hue value was changed, ΔE_{00} is expected to slightly outperform ΔE^*_{ab} when evaluating the color reproduction closer to target one.

In order to get better insight in given results, we performed the MCDM calculations based on both used formulae (Eqns. 9 and 10). Mean Color Difference from the Mean was used to express the color variation over each measuring area (see Fig. 1), regardless of predefined ΔE values. MCDM, as a pure measure of repeatability, should be able to give an overall overview about expected discrepancies in color difference. The results are presented on Fig. 4 and Fig. 5.

As it can be seen from the presented graphs, MCDM value was ranging from 0.15 to 0.7. This can be easily correlated to poorer reproduction of targeted color differences lower than 0.75 ΔE, indicating that expected variations in color reproduction could be up to 0.75 ΔE.

This is not likely to be credited to measuring procedure or measuring device, since the manufacturers guarantees of high measuring precision and repeatability [34] and low coefficient of variation for each measuring field and all three

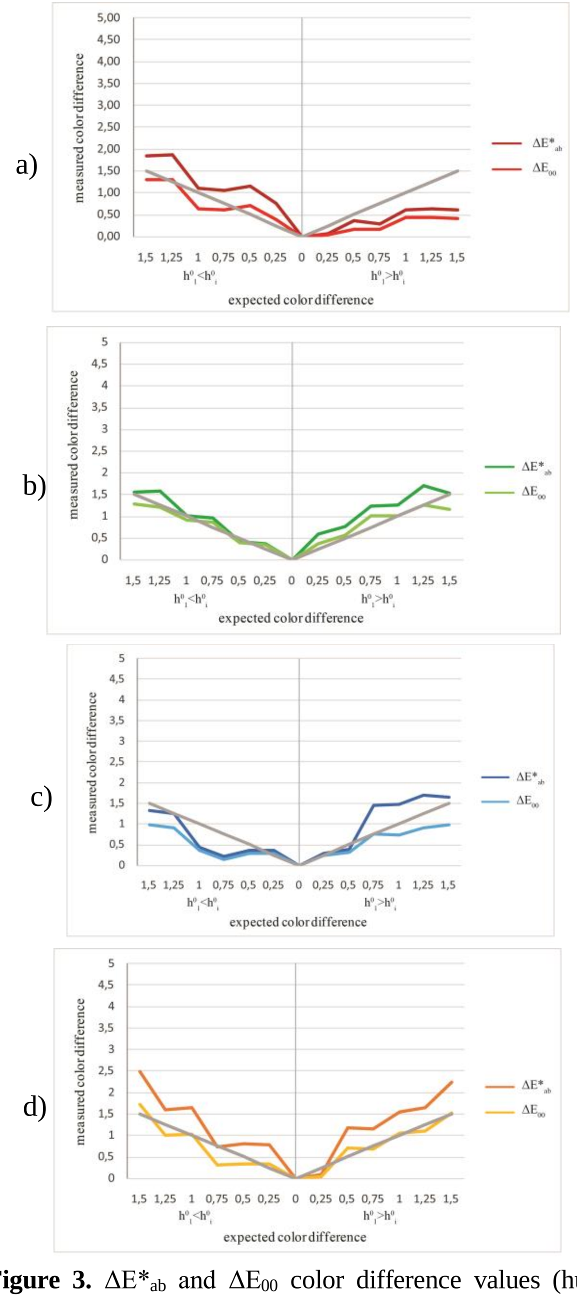

Figure 3. ΔE^*_{ab} and ΔE_{00} color difference values (hue scale variations): a) green; b) red; c) blue; d) yellow

colorimetric values, L*, a* and b* (bellow 3%, with the exception of green - below 7%). The results showed that if MCDM calculation is based on ΔE^*_{ab} rather than ΔE_{00} color difference formula, the color reproduction repeatability will be estimated of lower range (higher MCDM values), and vice versa.

As it was expected, almost the same MCDM values were calculated in case of achromatic gray color. According to MCDM, the lowest color variation was achieved for blue color, whereas the smallest differences between MCDM ΔE^*_{ab} and MCDM ΔE_{00} were achieved, as well. On the contrary, obtained results for yellow color centre, followed by green ones, pointed on higher impact of color difference calculation method on MCDM values.

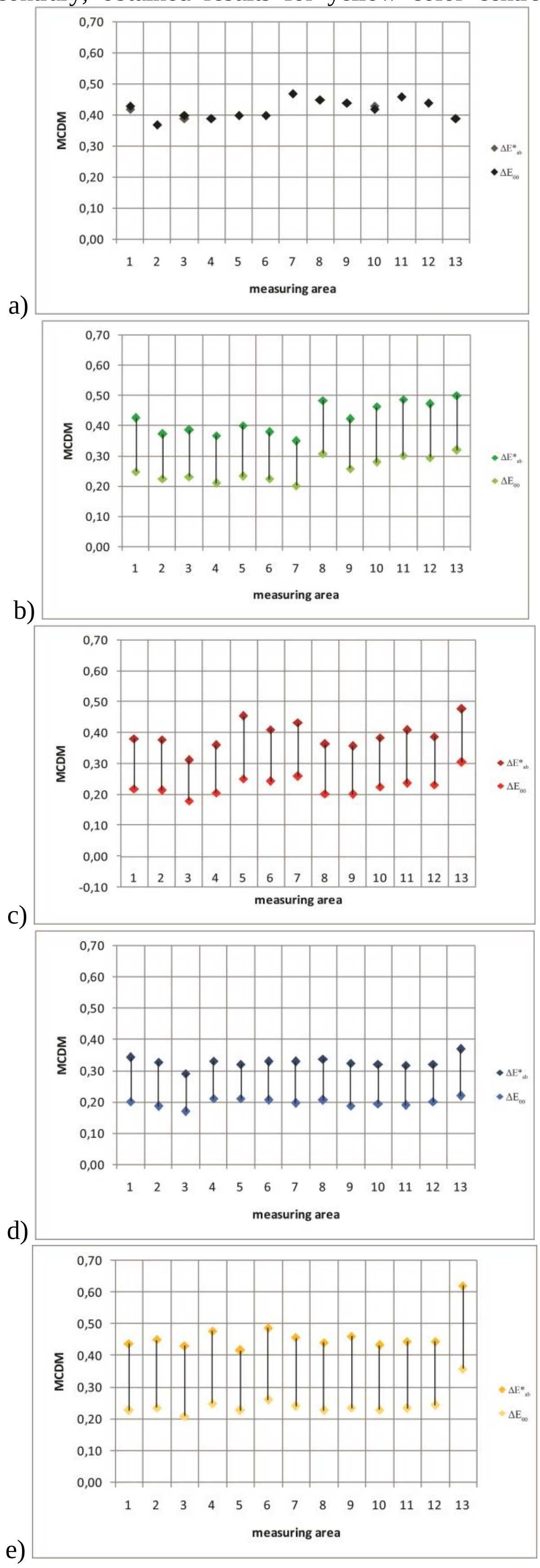

Figure 4. MCDM values / ΔE^*_{ab} and ΔE_{00} (lightness scale variations): a) gray, b) green; c) red; d) blue; e) yellow.

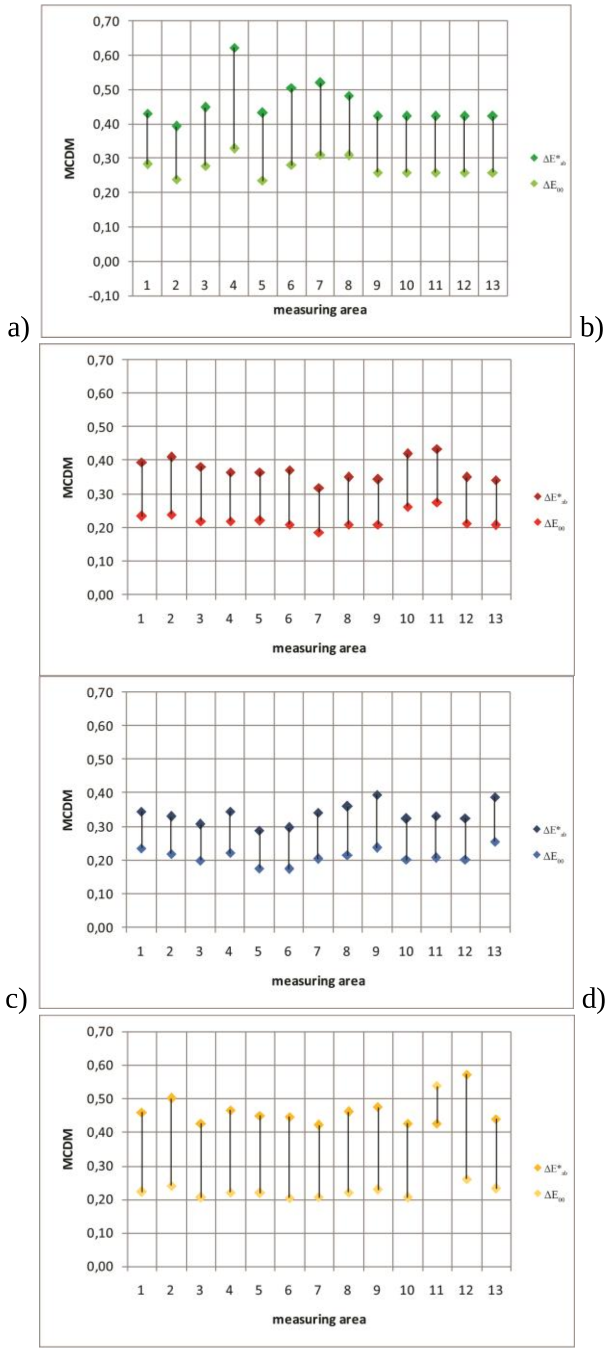

Figure 5. MCDM values / ΔE^*_{ab} and ΔE_{00} (hue scale variations): a) green; b) red; c) blue; d) yellow.

CONCLUSIONS

This research aimed to investigate the possibilities of using ink - jet printing technique for the purpose of just noticeable color difference evaluation (JND). We started from the premise that the printing technique used may significantly influence the color reproduction, thus alter the targeted color difference. In order to evaluate the level of discrepancies, we chose five initial color centers and independently varied their lightness and hue. For color difference calculation we used ΔE^*_{ab} and ΔE_{00} color difference formulae. The conclusions derived were as follows:

- Results shown that the expected color differences were not obtained in all cases and for all colors used.
- The variability is dependent on whether the color difference was effected by initial variations in color lightness or hue, color itself as well as calculation method used.
- If the controlled color difference change is aimed to be achieved using ink-jet printing technique, the one can expect that the printing process itself will contribute to color shift up to 0.75 ΔE.
- The larger the initially defined color difference, the more precise reproduction is achieved.
- Slightly higher reproduction accuracy was achieved when color difference was obtained by change in hue, comparing to the case when lightness was altered.
- Although the ΔE_{00} formula gave slightly more accurate results than ΔE^*_{ab}, their performances are quite similar: if the L value was changed, ΔE^*_{ab} presented slightly better performances, but restricted to range of color difference above 0.75. Otherwise, the minor advantage is given to ΔE_{00} formula; if the hue value was changed, ΔE_{00} slightly outperformed ΔE^*_{ab}.
- Both formulas performed better in case of green and yellow color centre when hue was changed, and blue color center, when lightness was changed.
- The obtained results are considered to be attributable to the size of the color difference used, as well.

In the future, we plan to extended this research with the assessment of medium and large color differences and the performance of other color difference formulae, as well.

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ОЦЕНКА И АНАЛИЗ НА СЛАБО ЗАБЕЛЕЖИМИ ЦВЕТОВИ РАЗЛИКИ ПРИ СТРУЕН ПЕЧАТ

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(Резюме)

В настоящата статия са изследвани възможностите за използване на дигитални струйни печатни системи за оценка на слабо различимите цветови разлики, които са особено важни от гледна точка на зрителния анализатор за получаване на вярна и коректна репродукция на тоновете и цветовете. При оценката на цветовите разлики спрямо зададен еталон се очаква да има коректно зададени референтни стойности още в процеса на предпечат и репродуциране. Равномерността и еднородността на получените печатни изображения е изключително важна и зависи от вида на печатната технология. В настоящия експеримент е направено изследване за дигиталния струен печат като най-качествен и перспективен. Избрани са пет дефинирани еталонни точки с вариране на светлотата и цветовия тон с цел постигане на диапазон от контролни скали и полета с цветови разлики започващи от 0,25 и достигащи до 1,5 единици. Цветовата разлика между 2 съседни полета има стойност 0,25. Използвана е 120 г/кв.м хартия и дигитална струйна система Epson Stylus Pro 7800. Използвани са две от формулите за изчисляване на цветовите разлики - CIELAB и MCDM. От направения анализ на резултатите е установено в кои от случаите се получават коректно зададените цветови разлики от 0,25 единици и репродукцията е вярна. Установено влиянието на свелотата и наситеността на изследваните полета върху получените резултати.