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Primerjava CMCCAT2000 in bradfordskega modela kromatične prilagoditve

Izvirni znanstveni članek

Poslano *april 2009* • Sprejeto *junij 2009*

Izvleček

Medtem ko se človek lahko prilagodi svetlobnemu viru, večina naprav tega ni sposobna. Zato se v procesu zajemanja, prikaza in upodabljanja barv uporabljajo modeli kromatičnih prilagoditev (CAT). V raziskavi smo primerjali dva modela kromatičnih prilagoditev, in sicer bradfordskega in CMCCAT2000, pri dveh kombinacijah svetlobnih virov, D50-D65 in D65-A, na 8190 vzorcih. Ugotovili smo, da so barvne razlike po bradfordski metodi pri obeh kombinacijah svetlobnih virov manjše kot pri CMCCAT2000 in da je bradfordska metoda tudi primernejša za največje število vzorcev.

Ključne besede: modeli kromatičnih prilagoditev, bradfordska CAT, CMCCAT2000, barvne razlike.

1 Uvod

Sodobni trendi tiskanja manjših kolekcij in unikatnih izdelkov zahtevajo večjo prilagodljivost tiskarjev in s tem hitro pripravo barvnih vzorcev ter potiskanje izdelka. Z uporabo grafičnih programov so tudi pričakovanja tako oblikovalcev tekstilij in oblačil kot tudi malih podjetnikov vse večja. V večini primerov naročniki zahtevajo, da je točno določeni barvni vzorec oziroma barvni odtenek na papirju (t. i. hard proof) ali zaslonu (soft proof) upodobljen na tekstilnem substratu. Vendar je pot od vzorca, upodobljenega na papirju ali prikazanega na zaslonu, pa do končnega izdelka, odtisnjenega na substratu, precej kompleksna. Težave se pojavijo zaradi razlik med barvami vzorcev na papirju, računalniškem zaslonu in substratu. Pri tem si lahko uspešno poma-

Comparison of CMCCAT2000 and Bradford chromatic adaptation transforms

Original Scientific Paper

Received *April 2009* • Accepted *June 2009*

Abstract

Unlike the human visual system, image-capturing devices, e.g. scanners and digital cameras, are unable to accommodate to different light sources. In consequence, a number of chromatic adaptation transforms (CATs) are used in color acquisition, display and rendering processes. In this research, a comparison between two models – Bradford and CMCCAT2000 – and two illumination source pairs – D50-D65 and D65-A – was conducted using 8190 color patches. The results showed that the color differences obtained with the Bradford method were lower than with CMCCAT2000 for both implemented illumination source pairs. The Bradford method also proved to be more suitable for most patches.

Keywords: chromatic adaptation, CAT, Bradford CAT, CMCCAT2000, color differences.

1 Introduction

Modern trends of printing smaller collections and unique products require from print shops a higher degree of adaptability and speed in color

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gamo z modeli kromatičnih prilagoditev, kot je opisano v nadaljevanju.
Barva je rezultat človeškega zaznavanja vidnega dela spektra v območju od 380 do 780 nm. Naš vizualni sistem je zmožen prilagoditve pri zaznavanju barv v širokem spektru svetlobnih pogojev. Vendar pa večina naprav, s katerimi zajemamo barve, kot so skenerji, digitalne kamere in fotoaparati, prilagoditve na svetlobni vir ni sposobna. Preslikava med barvami, zajetimi pod eno vrsto osvetlitve (vhodnimi barvami), in barvami, prikazanimi pod drugo vrsto osvetlitve (ciljnimi barvami), je pri modelih barvnega zaznavanja in na splošno v barvni reprodukciji pomembna. Preslikavo med vhodnimi in ciljnimi barvami imenujemo kromatična prilagoditev (chromatic adaptation transform – CAT).

2 Teoretični del

Večina današnjih modelov kromatičnih prilagoditev izhaja iz von Kriesovega modela [1, 2, 3], ki predvideva preprosto linearno pretvorbo med standardiziranimi barvnimi vrednostmi XYZ barve, opazovane pod različnimi svetlobnimi viri. Temelji na posamezni prilagoditvi prirastka ali primanjkljaja pri treh senzorjih v človeškem vizualnem sistemu (v kratkem (S – short), srednjem (M – medium) in dolgem (L – long) valovnem območju) [4].
Bradfordsko kromatično prilagoditev je razvil in leta 1985 objavil Lam [5], temelji pa na empiričnih podatkih. Ta model omogoča preslikavo vrednosti XYZ iz referenčnega svetlobnega vira v ciljni, pri čemer se barvna zaznava ohranja. Po mnenju večine strokovnjakov je bradfordska kromatična prilagoditev, ki se uporablja tudi v Adobe Photoshopu, ena najnatančnejših [6].

2.1 Izračun bradfordske kromatične prilagoditve

Preračun bradfordske kromatične prilagoditve je podan v enačbah od (1) do (6) [5].
Prvi korak: transformacija vrednosti XYZ v bradfordske izostrene senzorje RGB:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_B \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix} \tag{1}$$

Matrika za Bradfordsko metodo je:

$$M_B = \begin{bmatrix} 0.8951 & -0.7502 & 0.0389 \\ 0.2664 & 1.7135 & 0.0685 \\ -0.1614 & 0.0367 & 1.0296 \end{bmatrix} \tag{2}$$

Drugi korak: preslikava referenčnih vrednosti RGB v R'G'B', ki predstavljajo ciljne vrednosti:

$$R' = R'_w \frac{R}{R_w} \tag{3}$$

sample preparation and final product printing. A widespread use of graphical software has also increased expectations of textile designers and small companies. Customers almost always require the very same color sample, i.e. its hue, be printed both on paper (hard proof) and viewed on computer monitor (soft proof) before rendered on a textile substrate. This task, however, requires mastering a complex set of operations, since discrepancies among sample colors on paper, computer screen and substrate frequently occur. The use of chromatic adaptation models can be of great help in dealing with such problems, as described below.
Color is a result of human perception of light reflected from the surface in visible spectrum between 380 nm and 780 nm. Unlike the human visual system, which is capable of color adaptation to a wide range of lighting conditions, image-capturing devices, e.g. scanners or digital cameras, in general do not have the ability to adapt to the light source.
The latter suggests that transforms between colors captured under certain lighting conditions (source colors) and colors displayed under different viewing conditions (destination colors) play a crucial role in color appearance models as well as in color reproduction. Such transformations from source to destination colors are called chromatic adaptation transforms (CATs).

2 Theoretical part

The majority of present CATs are based on a modified form of the von Kries model [1, 2, 3], which is a simple linear transform between the CIE tristimulus values (XYZ) of colors observed under different light sources. The model is based on an independent gain regulation of three sensors in the human visual system (S-short, M-medium and L-long) [4].
Bradford CAT was developed and published by Lam (1985) [5] and is based on empirical data. The model enables transformation from a source to a destination reference illuminant, where color appearance is preserved. The Bradford method that is also implemented in Adobe Photoshop is considered by many experts as one of the best methods [6].

2.1 Bradford CAT computation procedure

Equations (1)–(6) show computation procedure for Bradford CAT [5].

Step 1: Transformation from XYZ to Bradford sharpened cone functions RGB (Equation 1).

The matrix for the Bradford method is(Equation 2)

Step 2: Transformation from reference RGB to destination R'G'B' values(Equations 3–5)

$R_wG_wB_w$ and $R_w'G_w'B_w'$ are values computed from XYZ of the reference and test illuminant.

Step 3: Transformation from adapted R'G'B' to destination X'Y'Z' values (Equation 6) where (Equation 7).

It was found out that the reversibility of CMCCAT97 (based on a modified Bradford model used in CIECAM97s color appearance model (CAM)) is unreliable and that the model was derived by fitting only small data sets. As a result, Color Measurement Committee accepted CMCCAT2000 model [7, 8], where the power function was removed, yet the model was still completely reversible and fitted all available data sets. In comparison with CMCCAT97, the degree of adaptation term of this model also includes L_{AR}, i.e. the luminance of the reference adapting fields.

2.2 CMCCAT2000 computation procedure

The computation procedure for CMCCAT2000 follows below.

Input data [9]:

- *tristimulus values under the reference illuminant: XYZ (obtained for each pixel of the processed image);*
- *tristimulus values of the white point under the reference illuminant: $X_{wr}Y_{wr}Z_{wr}$;*
- *tristimulus values of the white point under the adapting illuminant: $X_wY_wZ_w$;*
- *luminance of the reference and adapting illuminant (cd/m²): L_{A1}, L_{A2}.*

Output data:

corresponding tristimulus values under the adapting illuminant: $X_cY_cZ_c$.

Step 1: Calculate the inner RGB values of each pixel of the reference image (Equations 8–11).

Step 2: Calculate the degree of adaptation (Equation 12), where parameter F is a response

$$G' = G'_w \frac{G}{G_w} \tag{4}$$

$$B' = B'_w \frac{B}{B_w} \tag{5}$$

$R_wG_wB_w$ predstavljajo izračunane vrednosti za belo svetlobo, $R_w'G_w'B_w'$ pa vrednosti bele svetlobe v ciljnih pogojih.

Tretji korak: preračun iz prilagojenih vrednosti R'G'B' v ciljne vrednosti X'Y'Z':

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = M_B^{-1} \begin{bmatrix} R'Y \\ G'Y \\ B'Y \end{bmatrix} \tag{6}$$

Inverzna matrika za bradfordsko metodo je:

$$M_B^{-1} = \begin{bmatrix} 0.98699 & -0.14705 & 0.15996 \\ 0.43231 & 0.51836 & 0.04929 \\ -0.00853 & 0.04004 & 0.96840 \end{bmatrix} \tag{7}$$

Pri CMCCAT97 (modificirana verzija bradfordskega modela, ki se uporablja v modelu barvnega zaznavanja CIECAM97s) je bilo ugotovljeno, da je reverzibilnost modela nezanesljiva in da je bil dobljen na podlagi ujemanja relativno majhnega števila vzorcev. Zato je bil razvit model CMCCAT2000, ki ga je sprejel Colour Measurement Committee [7, 8]. V tem modelu je bila odstranjena potenčna funkcija, tako da je bil model v celoti reverzibilen in ustrezen za večino primernih oziroma razpoložljivih vzorcev. CMCCAT2000 v stopnji prilagoditve upošteva še L_{AR}, tj. osvetljenost referenčnega prilagojenega polja, ki pri CMCCAT97 ni upoštevana.

2.2 Izračun CMCCAT2000

Vhodni podatki [9]:

- standardizirane barvne vrednosti pod referenčno svetlobo: *XYZ* (za vsak piksel na sliki);
- standardizirane barvne vrednosti bele točke pod referenčno svetlobo: $X_{wr}Y_{wr}Z_{wr}$;
- standardizirane barvne vrednosti bele točke pod prilagojeno svetlobo: $X_wY_wZ_w$;
- osvetljenost referenčne in prilagojene svetlobe (cd/m²): L_{A1}, L_{A2}.
- Ciljne vrednosti:
- pripadajoče standardizirane barvne vrednosti pod prilagojeno svetlobo: $X_cY_cZ_c$.

Prvi korak: izračun vrednosti RGB za vsak piksel na referenčni sliki:

$$\begin{pmatrix} R_{wr} \\ G_{wr} \\ B_{wr} \end{pmatrix} = M \begin{pmatrix} X_{wr} \\ Y_{wr} \\ Z_{wr} \end{pmatrix} \tag{8}$$

$$\begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix} = M \begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} \tag{9}$$

for viewing conditions (F=1 for average surround, F=0.8 for dim- and dark-surround). If D >1 or < 0, set to 1 or 0, respectively [10]. For complete adaptation D=1 and for no adaptation D=0.

Step 3: Calculate the adapted RGB values [8] (Equations 13–15) where (Equation 16).

Step 4: Calculate the corresponding tristimulus values (Equation 17) where (Equation 18).

Generic CAT consists of the following consecutive steps [6]:

1. *Calculation of CIE tristimulus values $X_1Y_1Z_1$ for the first viewing conditions (VC_1),*
2. *conversion of $X_1Y_1Z_1$ to $L_1M_1S_1$ (cone excitations),*
3. *incorporation of information about VC_1 using the chromatic adaptation model to predict adapted cone signals ($L_aM_aS_a$) and*
4. *reversal of the process for the second viewing conditions VC_2 to determine $L_2M_2S_2$ and conversion to CIE $X_2Y_2Z_2$ values.*

Equation (19) shows an example of transformation from the CIE tristimulus values XYZ to LMS cones responsivities using linear matrix multiplication [6]. This transformation or a similar one is common to all chromatic adaptation and color appearance models that are compatible with the CIE colorimetry.

(Equation 19)

It therefore follows that individual matrix values include, apart from coefficients for each sensor type (LMS), also a conversion between the CIE tristimulus values XYZ and LMS (Equation 19). The main goal of this research was to evaluate the performance of the basic linear Bradford CAT and CMCCAT2000 by calculating the color differences of prints using two delta E calculation equations and to determine which method is more suitable for a larger number of patches. Illuminants D50, D65 and A were used. D50 is a standard illuminant for color measuring in graphic arts, while D65 is a standard illuminant used in textile, paper and color industry. Illuminant A is light emitted by still widely used tungsten bulbs.

3 Experimental

The test chart with 8190 color patches (Figure 1) was prepared in Argyll, an open source, ICC-

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{10}$$

$$M = \begin{bmatrix} 0.7982 & 0.3389 & -0.1371 \\ -0.5918 & 1.5512 & 0.0406 \\ 0.0008 & 0.0239 & 0.9753 \end{bmatrix} \tag{11}$$

Drugi korak: izračun stopnje prilagoditve:

$$D = F\left\{0.08 \log_{10}[0.5\,(L_{A1} + L_{A2})] + 0.76 - 0.45\,\frac{(L_{A1} - L_{A2})}{(L_{A1} + L_{A2})}\right\} \tag{12}$$

Parameter F pomeni pogoje opazovanja (F = 1 za povprečno okolje, F = 0,8 za srednje temno in temno okolje). Če je D večji od 1 ali manjši od 0, jih lahko nastavimo na 1 ali 0 [10]. Pri popolno prilagojenem opazovalcu je D = 1, pri neprilagojenem pa D = 0.

Tretji korak: izračun prilagojenih vrednosti RGB [8]:

$$R_c = R\left[\alpha\left(\frac{R_{wr}}{R_w}\right) + 1 - D\right] \tag{13}$$

$$G_c = G\left[\alpha\left(\frac{G_{wr}}{G_w}\right) + 1 - D\right] \tag{14}$$

$$B_c = B\left[\alpha\left(\frac{B_{wr}}{B_w}\right) + 1 - D\right] \tag{15}$$

$$\text{Pri tem je } \alpha = D\,\frac{Y_w}{Y_{wr}} \tag{16}$$

Četrti korak: izračun pripadajočih standardiziranih barvnih vrednosti:

$$\begin{pmatrix} X_c \\ Y_c \\ Z_c \end{pmatrix} = M^{-1} \begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} \tag{17}$$

Pri tem je inverzna matrika

$$M^{-1} = \begin{bmatrix} 1.076450 & -0.237662 & 0.161212 \\ 0.410964 & 0.554342 & 0.034694 \\ -0.010954 & 0.013389 & 1.024343 \end{bmatrix} \tag{18}$$

Na splošno kromatična prilagoditev poteka po naslednjih korakih [4]:

1. vrednosti vzorca CIE $X_1Y_1Z_1$, opazovane pod pogoji opazovanja 1,
2. pretvorba $X_1Y_1Z_1$ v $L_1M_1S_1$ (long, medium, short),
3. upoštevanje informacij o pogojih opazovanja 1 z uporabo modela kromatične prilagoditve za določitev prilagojenih (adapted – a) signalov $L_aM_aS_a$ in
4. obratni proces za pogoje opazovanja 2 za določitev $L_2M_2S_2$ in preslikava v vrednosti CIE $X_2Y_2Z_2$.

V enačbi (19) je prikazan primer linearne preslikave med LMS signali in standardiziranimi barvnimi vrednostmi XYZ, ki je znači-

compatible color management system. Prints were made using an inkjet printer Canon W8400pg and Heavy Weight Semi Glossy Photo Paper. Full spread patches are distributed according to the default or chosen algorithm. The default algorithm (Optimized Farthest Point Sampling – OFPS) optimizes the point locations to minimize the distance from any point in device space to the nearest sample point.

After a few days of color stabilization, measurements with the instrument GretagMacbeth Spectrolino Spectroscan were performed. The CIE standard tristimulus values (XYZ) were calculated from Equations (20)–(22).

$S(\lambda)$ … relative spectral power distribution

$R(\lambda)$ … spectral reflectance

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ … red, green and blue color-matching functions

k … normalizing factor; for a perfect white reflector (Y = 100) k can be calculated from Equation (23).

Moreover, three different CIE standard illuminants – A, D50 and D65 (Figure 2) – and a CIE standard colorimetric observer (2°) (Figure 3) were used in XYZ calculations.

The transformation from an XYZ source color $[X_S\ Y_S\ Z_S]$ to a destination color $[X_D\ Y_D\ Z_D]$ was accomplished according to Equation (24) where:

$X_D\ Y_D\ Z_D$ destination color

$X_S\ Y_S\ Z_S$ source color

$[M]$ transformation matrix

In the study, two CATs were compared: Bradford (BFD) and CMCCAT2000 (CAT00). CMCCAT2000, in addition to the basic matrix, also includes some nonlinear transformation factors and a degree of adaptation. Parameter F was 1 (average surround), luminance of reference and adapting illuminant (cd/m²): L_{A1} and L_{A2} were 100; therefore, the computed D was 0.94.

The scheme of work is outlined in Figure 4. To calculate the color differences (delta E) between the reference (XYZ values generated directly from the measured spectral data) and the chromatic adaptation-transformed values, the established ΔE^*_{ab} [11] as well as the newest ΔE_{00} [12] formulas were implemented. All calculations were performed using the program Octave 3.0.0 [13].

len za vse kromatične prilagoditve in modele barvnega zaznavanja, ki so v skladu s CIE-kolorimetrijo.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{19}$$

Iz tega sledi, da posamezne vrednosti v matriki zajemajo poleg koeficientov za posamezni tip senzorjev (LMS) tudi pretvorbo med standardiziranimi vrednostmi CIE XYZ in LMS (enačba (19)). Namen naše raziskave je bil preučiti osnovni linearni bradfordski model CAT in model CMCCAT2000 ter ugotoviti, kateri CAT je primernejši za večje število vzorcev. Uporabili smo svetlobe D50, D65 in A. D50 je standardna svetloba za merjenje barv v grafiki, D65 je standardna svetloba, ki se uporablja v tekstilstvu, papirništvu in industriji barv. Svetloba A pa je svetloba, ki jo oddajajo še vedno precej pogoste žarnice z volframovo nitko.

3 Eksperimentalni del

V odprtokodnem programu Argyll CMS smo pripravili testno tablico z 8190 barvnimi polji (slika 1) in jo odtisnili na kapljičnem tiskalniku Canon W8400PG, in sicer na sijajno premazani papir. Pri izdelavi testne tablice je bil uporabljen algoritem (Optimized Farthest Point Sampling – OFPS), ki definira točke v prostoru naprave na tak način, da jih razporeja z minimalno medsebojno razdaljo.

Figure 1: Sample of test chart made by Argyll.

Po nekajdnevnem stabiliziranju smo barvna polja na tablici spektrofotometrično izmerili z instrumentom GretagMacbeth Spectrolino Spectroscan. Iz spektralnih podatkov smo računali vrednosti XYZ po enačbah od (20) do (22):

4 Results and discussion

The equation ΔE^*_{ab} is based on the distance between two colors without using any correction factors, while ΔE_{00} includes lightness, chroma and hue correction terms. Consequently, all the obtained ΔE_{00} values are higher than the ΔE^*_{ab} values. Prior to the analysis, each sample was categorized according to the magnitude of its delta E value into one of the four groups: 0–1 (color difference undetectable by a human eye), 1–3 (small color difference between two patches) [14], 3–6 (perceivable difference) or >6 (large difference). The number of patches belonging to each group was a direct indication of the quality of the corresponding CAT/illuminant pair combination: the higher the number of low delta E (0–1, 1–3) patches, the better the performance of that model.

Figure 5 shows the average color differences ΔE^*_{ab} and ΔE_{00} when using two CATs – Bradford CAT and CMCCAT2000 – and two illumination source combinations – D65-A and D50-D65. The mean values of obtained color differences calculated with ΔE^*_{ab} are, as discussed above, higher than when applying the ΔE_{00} formula.

The smallest average color differences are generated with both of the D50-D65 CATs, followed by D65-A. Illuminants D50 and D65 are both very close to each other in the CIE chromaticity diagram (Figure 6) and also have a similar spectral power distribution (Figure 2), which explains the obtained lowest delta E values.

Since Bradford CAT exhibited the best performance, its appropriateness was to be tested for predicting a larger number of colors.

Figure 7 shows that the Bradford method transform from D65 to A predicts better a larger number of samples compared with the CMCCAT2000 with the average $\Delta E^*_{ab} < 4$. The color differences < 3 were obtained with approximately 4,000 samples in case of the Bradford method and only 1,304 in case of CMCCAT2000. There were more than 1,000 samples characterized by having extremely low color differences ($\Delta E^*_{ab} < 1$) when applying the Bradford method.

When computing color differences using the D50-D65 illumination source pair (Figure 8), the Bradford method proved more successful

$$X = k \sum_{340}^{780} S(\lambda)\, R(\lambda)\, \bar{x}(\lambda) \tag{20}$$

$$Y = k \sum_{340}^{780} S(\lambda)\, R(\lambda)\, \bar{y}(\lambda) \tag{21}$$

$$Z = k \sum_{340}^{780} S(\lambda)\, R(\lambda)\, \bar{z}(\lambda) \tag{22}$$

$S(\lambda)$ … relativna spektralna porazdelitev energijskega toka svetlobe
$R(\lambda)$ … spektralna stopnja remisije
$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ … funkcije spektralnih vrednosti (vizualni sistem s spektralno občutljivostjo očesa za svetlobo daljših, srednjih in krajših valovnih dolžin)
k … koeficient; za idealno belo telo velja Y = 100, zato lahko vrednost k določimo iz enačbe:

$$k = \frac{100}{\sum_{340}^{780} S(\lambda)\, \bar{y}(\lambda)} \tag{23}$$

Za izračun vrednosti XYZ smo uporabili tri vrste osvetlitve (s spektralno porazdelitvijo, prikazano na sliki 2) in standardnega opazovalca 2° (slika 3):

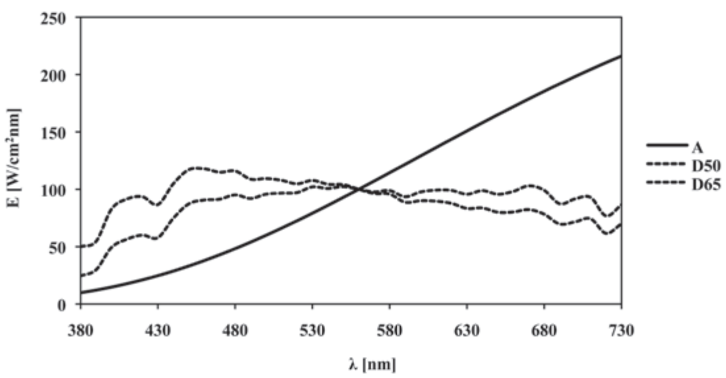

Figure 2: Spectral power distribution of A, D50 and D65.

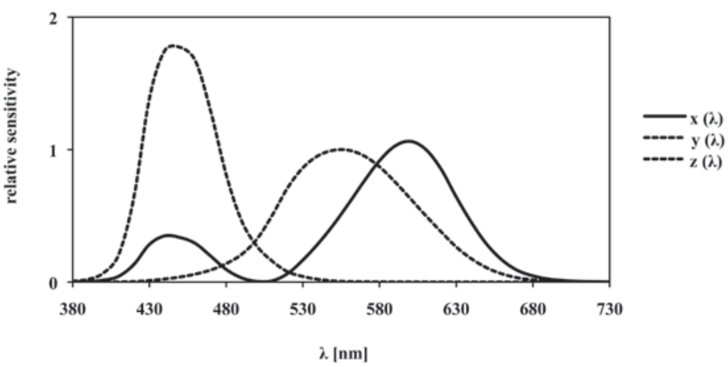

Figure 3: The CIE standard observer (2°) color-matching functions.

for $\Delta E^*_{ab} < 1$, while CMCCAT2000 was slightly better for $1 < \Delta E^*_{ab} < 2$. The color of a large number of samples was predicted quite accurately in both cases, since the calculated average color differences were here much smaller than with the D65-A transforms (Figure 7).

5 Conclusion

Raw spectral data make it possible to calculate the CIE tristimulus values (XYZ) under various illumination sources. One of the major advantages of using CATs is their ability to transform the CIE tristimulus values obtained under one illumination source into the XYZ values related to a different illumination source in cases when spectral data are unavailable. The best method is the one giving the smallest color differences between the calculated XYZ values from spectral data and the adapted XYZ values. When compared to CMCCAT2000, Bradford CAT exhibited better performance, since the observed color differences were found to be lower regardless of the illumination source pair used. The Bradford method is also more appropriate for describing a greater number of color patches than CMCCAT2000.

The research demonstrated the importance of chromatic adaptation models and color management in general for graphical designers as well as for printers who print on paper, textile and other materials, since correct implementation of a particular chromatic adaptation model can significantly improve the final product color quality and consequently, customer satisfaction.

Pretvorba iz vhodnih standardiziranih barvnih vrednosti XYZ v ciljne je potekala po enačbi:

$$[X_D\ Y_D\ Z_D] = [X_S\ Y_S\ Z_S] \cdot [M] \qquad (24)$$

$X_D\ Y_D\ Z_D$ ciljne XYZ (destination color)
$X_S\ Y_S\ Z_S$ vhodne XYZ (source color)
$[M]$ matrična linearna preslikava

Uporabili smo dva modela kromatičnih prilagoditev, in sicer bradfordskega in CMCCAT2000. CMCCAT2000 poleg osnovne matrike, ki se razlikuje od bradfordske, vsebuje še dodatne korekcijske faktorje in upošteva stopnjo prilagoditve. Pri izračunu stopnje prilagoditve je bil parameter F = 1 (povprečno osvetljeno okolje), osvetljenosti referenčne in prilagojene svetlobe (cd/m^2) L_{A1} in L_{A2} sta bili 100, iz tega sledi, da je bila stopnja prilagoditve D = 0,94.

Potek dela je prikazan na sliki 4. Za izračun barvnih razlik smo uporabili najpreprostejšo enačbo za izračun barvnih razlik ΔE^*_{ab} [11] in novejšo enačbo ΔE_{00} [12]. Izračuni so potekali v programu Octave 3.0.0 [13].

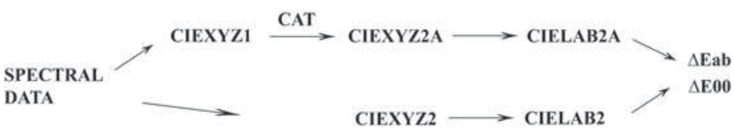

Figure 4: Scheme of work (CIEXYZ1 – source XYZ, CIEXYZ2 – calculated XYZ, CIEXYZ2A – adapted XYZ).

4 Rezultati in razprava

Enačba ΔE^*_{ab} temelji zgolj na razdalji med dvema točkama v prostoru in ne upošteva dodatnih korekcijskih faktorjev, zato so vrednosti barvnih razlik v vseh primerih nekoliko višje kot pri enačbi ΔE_{00}, ki upošteva korekcijo svetlosti, krome in barvnega tona. Barvne razlike pod vrednostjo 1 so še sprejemljive in jih s prostim očesom ne zaznamo. Barvne razlike med 1 in 3 pomenijo majhne razlike med vzorcem in standardom [14]. Barvna razlika med 3 in 6 je zmerna in jo naše oko že zazna. Zato smo primernost metod podkrepili tudi z določitvijo števila vzorcev, pri katerih smo dobili barvne razlike od 0 do 1 in od 0 do 3.

Na sliki 5 so grafično prikazani rezultati povprečnih barvnih razlik ΔE^*_{ab} in ΔE_{00} barvnih polj (slika 1) ob uporabi bradfordske CAT in CMCCAT2000 pri preslikavi iz svetlobnega vira D50 v D65 in D65 v A. Povprečne vrednosti barvnih razlik po enačbi ΔE^*_{ab} so v obeh primerih preslikav višje kot po enačbi ΔE_{00}.

Najmanjše povprečne barvne razlike se pojavijo pri pretvorbi med svetlobnima viroma D50-D65, sledi D65-A. Rezultat lahko utemeljimo z dejstvom, da sta svetlobi D50 in D65 po spektralnem odzivu dokaj podobni (slika 2), v kromatičnem diagramu pa ležita dokaj blizu, medtem ko je svetloba A od svetlobnega vira D65 precej oddaljena (slika 6).

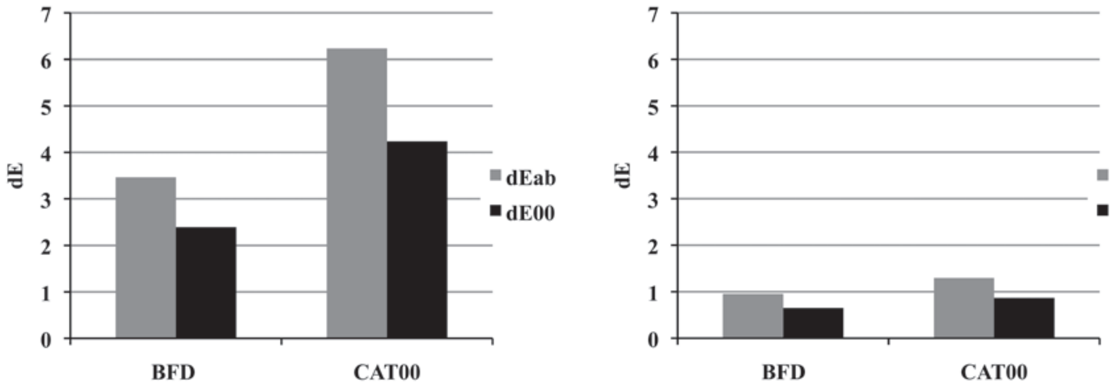

Figure 5: The average color differences obtained with two different illumination source pairs and CATs; BFD-Bradford, CAT00-CMCCAT2000, dEab-ΔE^*_{ab}, dE00-ΔE_{00}.

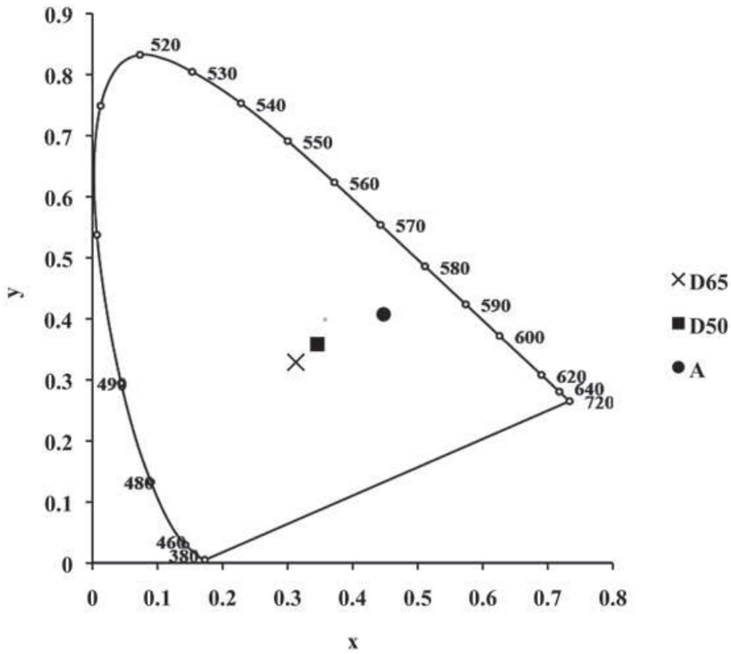

Figure 6: CIE x, y 1931 diagram (CIE Chromaticity diagram).

Glede na to, da smo manjše povprečne barvne razlike dobili pri bradfordski metodi, je bilo treba ugotoviti, ali ta metoda dovolj dobro opiše tudi večje število vzorcev.

Na sliki 7 je prikazano, da bradfordska metoda pri preslikavi iz D65 v A opiše večje število vzorcev kot CMCCAT2000 pri povprečni $\Delta E^*_{ab} < 4$. Barvne razlike, manjše od 3, smo pri bradfordski metodi dobili pri približno 4000 vzorcih, pri CMCCAT2000 pa le pri 1304 vzorcih.

Bradfordska metoda prav tako zelo dobro opiše ($\Delta E^*_{ab} < 1$) več kot 1000 vzorcev.

V primeru preslikave med D50 in D65 je pri povprečni $\Delta E^*_{ab} < 1$ za opis vzorcev nekoliko boljša bradfordska CAT, pri $1 < \Delta E^*_{ab} < 2$ pa CAT00. V obeh primerih je zelo dobro opisano večje število vzor-

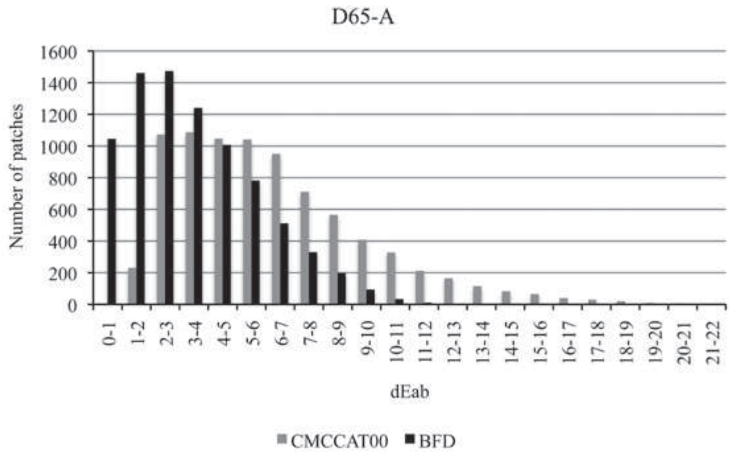

Figure 7: The number of color patches according to ΔE^*_{ab}, predicted with Bradford CAT and CMCCAT2000 obtained with the illumination source pair D65-A; BFD-Bradford, CAT00-CMCCAT2000, dEab-ΔE^*_{ab}.

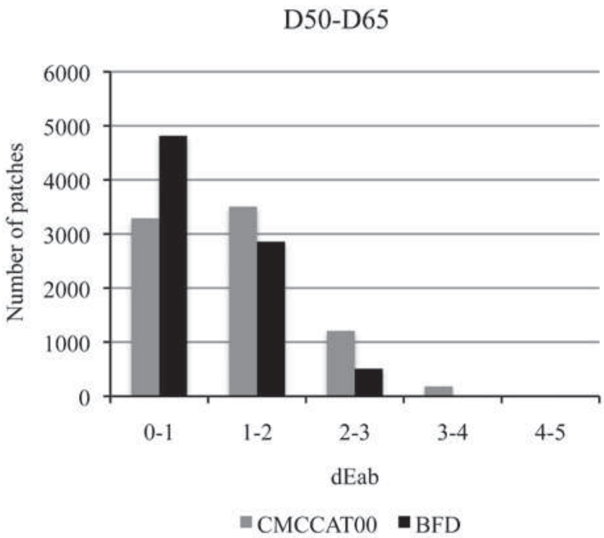

Figure 8: Number of color patches according to ΔE^*_{ab}, predicted with Bradford CAT and CMCCAT2000 obtained with the illumination source pair D50-D65; BFD-Bradford, CAT00-CMCCAT2000, dEab-ΔE^*_{ab}.

cev, saj so tudi povprečne barvne razlike veliko manjše kot pri preslikavi iz D65 v A.

5 Zaključek

Iz spektralnih podatkov je mogoče izračunati standardizirane barvne vrednosti CIE (XYZ) pod različnimi svetlobnimi viri, medtem ko kromatična prilagoditev omogoča pretvorbo standardiziranih barvnih vrednosti, dobljenih pod enim svetlobnim virom, v vrednosti XYZ pod drugim svetlobnim virom v primeru, ko spektralnih podatkov nimamo na razpolago. Najboljša metoda kromatične prilagoditve je tista, pri kateri bo barvna razlika med vrednostmi XYZ, izračunanimi direktno iz spektra, in vrednostmi XYZ, dobljenimi s pomočjo kromatične prilagoditve, najmanjša. Preprosta bradfordska metoda, čeprav ni najnovejša, je dala boljše rezultate in opisala večje število vzorcev kot CMCCAT2000.

Raziskava je pokazala, da je poznavanje modelov kromatičnih prilagoditev in celotnega barvnega upravljanja pomembno tako za grafične oblikovalce kot za tiskarje, ki tiskajo na papir, tekstil in druge materiale, saj lahko uporaba ustreznega modela kromatične prilagoditve pomembno prispeva k večji barvni kakovosti izdelka in s tem k večjemu zadovoljstvu končnega uporabnika oziroma kupca.

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