

Performance Of Five Chromatic Adaptation Transforms Using Large Number Of Color Patches

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Abstract:

Input devices in general use light sources with different color temperatures. As a consequence, in color acquisition, display and rendering processes a number of chromatic adaptations transforms (CATs) are being used. In our study, color transformations between three illuminant source pairs (D50-A, D50-D65 and D65-A) were investigated using five CATs (Bradford, von Kries, XYZ Scaling, CMCCAT97 and CMCCAT00). Research was made on 8190 color patches that were printed with inkjet printer. Results showed that color differences obtained with the Bradford method were the lowest regardless of the implemented illuminant source pair. The same ranking of CATs was observed in all combinations of illuminant source pairs, however the smallest color differences were generated with D50-D65 CATs and the biggest with D65-A models.

Key words:

Chromatic adaptation, CAT, color differences, principal components analysis

1. Introduction

Input devices in general use light sources with different color temperatures. Scanners usually use fluorescent light sources with color temperature between 4200 and 4800 K (Süsstrunk et al, 2001). White point of monitor displays is usually set to either CIE standard illuminant D50 (5000 K), which is warmer white, or to D65 (6500 K), which is cooler (i.e. more blue) white.

D50 is appropriate for displays that are used for professional corrections of images prepared for printing process, according to standard ISO 12646 (ISO 12646 : 2004). D65 is suitable for preparing photos intended to be published on Internet according to standard ISO 3664 (ISO 3664 : 2000). D50 is also used for evaluation of prints (hardcopy) (ISO 3664 : 2000). White point (D50) of Profile Connection Space (PCS) is defined by ICC specification.

1.1 Chromatic Adaptation Models

This 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).

The majority of present CATs are based on a modified form of the von Kries model (Süsstrunk et al, 2001; Von Kries, 1970; Luo and Hunt, 1998), which is a simple linear transform between CIE tristimulus values (XYZ) of colors observed under different light sources. The model is based on independent gain regulation of three sensors in human visual system (Fairchild, 2005). XYZ Scaling is generally considered to be an inferior chromatic adaptation model that is used for transforming the source color XYZ values to Lab values using the source reference white (xws, yws, zws) followed by a conversion back to XYZ using the destination reference white (xwd, ywd, zwd) (Lindbloom). Bradford CAT was developed and published by Lam (1985) (Spectral Sharpening) and is based on empirical data. Model enables transformation from a source to a destination reference illuminant where color appearance is preserved. Bradford method is the newest of the three methods and considered by most experts as the best one (Lindbloom). This method is also implemented in Adobe Photoshop.

CMCCAT97 is based on a modified Bradford model and is used in CIECAM97s color appearance model (CAM) (Luo and Hunt, 1998; ISO 12647-7: 2007). The model contains a degree of adaptation term that includes parameter F for a surface observed under typical, dim or dark viewing conditions and luminance LA (cd/m²) of adapting test field. The degree of adaptation is then used with ratios of illuminant white points to convert RGB values of the sample to the RGB values of the corresponding color. It was found out that reversibility of CMCCAT97 is unreliable because of the power function in the blue (B) channel. This problem was solved by a small revision but then the next weakness of CMCCAT97 was exposed: the model was derived by fitting

only small data sets. As a result, Color Measurement Committee accepted CMCCAT2000 model (Westland and Ripamonti, 2004; Li et al, 2000) 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 LAR, i.e. the luminance of the reference adapting fields. CMCCAT2000 and the related color appearance model CMCCAM2000 were found to be the most reliable models so far.

Generic CAT consists of the following consecutive steps (Fairchild, 2005):

1. Calculation of CIE tristimulus values X₁Y₁Z₁ for the first viewing conditions (VC₁),
2. conversion of X₁Y₁Z₁ to L₁M₁S₁ (cone excitations),
3. incorporation of information about VC₁ using the chromatic adaptation model to predict adapted cone signals (LaMaSa) and
4. reversal of the process for the second viewing conditions VC₂ to determine L₂M₂S₂ and conversion to CIE X₂Y₂Z₂ values.

Eq. 1 shows an example of transformation from CIE tristimulus values XYZ to LMS cones responsivities using linear matrix multiplication (Fairchild, 2005). This transformation or a similar one is common to all chromatic adaptation and color appearance models that are compatible with CIE colorimetry.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (1)$$

In the literature many researchers described different CATs based on non-linear transformations such as Sharp CAT, CMCCAT97 and CMCCAT2000 (Süsstrunk et al, 2001). Fairchild and Johnson observed prints under standard illuminants D₅₀ and D₆₅ in dark environment (Fairchild and Johnson, 1999). They investigated various CATs and color appearance models. Results have shown good matching on samples that were observed under two illuminants.

CIECAM97s produced the best results. Color appearance models were derived from the results of psychophysical experiments using samples on different backgrounds and under different illuminants (Sueprasan et al, 2001). Applicability of these models in real color reproduction was confirmed by experiments on complex images. Thus, in 1990 the CIE Technical Committee (TC) 1-27 published Specification of Color Appearance for Reflective Media in Self-Luminous Display Comparison. Its purpose was to collect as much data as possible from different sources for evaluation of colorimetric and color appearance models used for visual matching of samples on a self-luminous display and reflective printed samples.

Sueprasan et al. investigated two CATs (CMC-CAT97 and von Kries) and eight color appearance models (CIELAB, LLAB, RLAB, ATD, Hunt96, Nayatani97, CIECAM97s and CIECAM97s2) using complex images [12]. They concluded that CIECAM97s and CIECAM97s2 performed better than the other examined models. CIELAB and von Kries are simple models that include only a shift in chromaticity from one white point to another, while complex color appearance models require more input data to account for various color appearance phenomena.

1.2 Principal Components Analysis

The main goal of our research was to evaluate performance of five CATs (Bradford, XYZ Scalling, von Kries, CMCCAT97 and CMCCAT2000 transform) based on three illuminant pairs (combinations of A, D50 and D65) by calculating color differences on prints using two delta E calculation equations and assisted by Principal Components Analysis (PCA). PCA is one of the most frequently used exploratory multivariate techniques and is often implemented to identify general trends in the original data set by reducing its dimensionality. It is based on a construction of new variables, so called principal components (PCs), which are defined as orthogonal linear combinations of original variables. Extraction of individual PCs proceeds successively

so that each new PC captures as much as possible of the variables' variance, which has not been explained by the former PC. Mathematical details of this procedure can be found elsewhere (Massart et al, 1997).

The number of extracted PCs equals the number of variables, but generally the first few – two or three – PCs already account for most of the variability in the data since higher ones mainly represent data noise and can therefore be neglected. By examining plots of the first few PCs one can detect similarities and dissimilarities among the samples as well as visualize linear relationships that exist among the original variables.

2. Experimental

Test chart with 8190 color patches was prepared in Argyll, an open source, ICC-compatible color management system. Full spread patches were 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. Test chart was printed with inkjet printer Canon w8400pg on Heavy Weight Semi Glossy Photo Paper. Maximum ink limits were: cyan 80%, magenta 80%, yellow 60% and black 85%, total area coverage was 370 %. After a few days of color stabilization on test chart, measurements with instrument GretagMacbeth Spectrolino Spectroscan were performed. CIE standard tristimulus values (XYZ) were then calculated from spectral data from Eqs. (2) to (4):

$$X = k \sum_{340}^{780} S(\lambda)R(\lambda)\bar{x}(\lambda) \quad (2)$$

$$Y = k \sum_{340}^{780} S(\lambda)R(\lambda)\bar{y}(\lambda) \quad (3)$$

$$Z = k \sum_{340}^{780} S(\lambda)R(\lambda)\bar{z}(\lambda) \quad (4)$$

$S(\lambda)$ - relative spectral power distribution for illuminants:

- a. illuminant A, tungsten-filament bulb with color temperature 2856 K,
- b. illuminant D50, standard illuminant with color temperature 5000 K and
- c. illuminant D65, standard daylight illuminant with color temperature 6500 K.

Those three different CIE standard illuminants (A, D50 and D65) are represented in Fig. 2.

$R(\lambda)$ - spectral reflectance (measurements of spectral data)

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ - red, green and blue color-matching functions for CIE standard colorimetric observer (2°) (Fig. 3)

k - normalizing factor; for a perfect white reflector ($\gamma = 100$) k can be calculated from Eq. 5:

$$k = \frac{100}{\sum_{340}^{780} S(\lambda) \bar{y}(\lambda)} \quad (5)$$

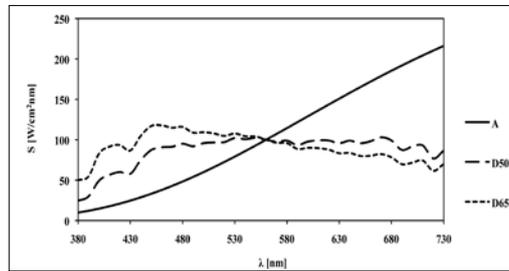


Figure 1: Spectral power distribution of A, D50 and D65

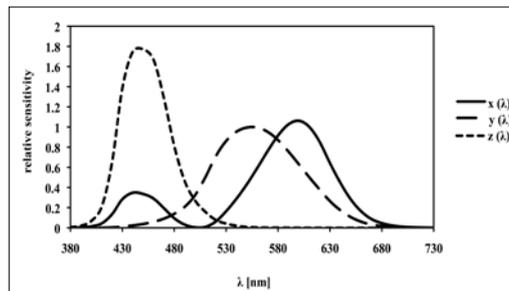


Figure 2: The CIE standard observer (2°) color-matching functions

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 Eq. (6):

$$[X_d Y_d Z_d] = [M] \cdot [X_s Y_s Z_s] \quad (6)$$

$[X_d Y_d Z_d]$ - destination color

$[X_s Y_s Z_s]$ - source color

$[M]$ - transformation matrix

In the study color transformations were made from illuminant D50 to A, from illuminant D65 to A and from illuminant D50 to D65. In addition, five CATs were used: Bradford (BFD), von Kries (VK), XYZ Scaling (SC), CMCCAT97 (CAT97) and CMCCAT2000 (CAT00). Matrix $[M]$ coefficients depend on the implemented CAT. Matrices for five studied transforms are displayed in Table 1. Note that $[M]$ for CMCCAT97 and Bradford models are identical, however CMCCAT97, in addition to $[M]$, also includes some nonlinear transformation factors, such as degree of adaptation that also includes LAR, i.e. the luminance of the reference adapting field.

Table 1: Matrices for the five chromatic adaptations transforms used in the study

CAT	$[M_A]$
XYZ Scaling	$\begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}$
	$\begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & 0.0685 & 1.0296 \end{bmatrix}$
	$\begin{bmatrix} 0.4002 & 0.7076 & -0.0808 \\ -0.2263 & 1.1653 & 0.0457 \\ 0.0000 & 0.0000 & 0.9182 \end{bmatrix}$
CMCCAT97	$\begin{bmatrix} 0.8951 & -0.7502 & 0.0389 \\ 0.2664 & 1.7135 & 0.0685 \\ -0.1614 & 0.0367 & 1.0296 \end{bmatrix}$
CMCCAT2000	$\begin{bmatrix} 0.7982 & 0.3389 & -0.1371 \\ -0.5918 & 1.5512 & 0.0406 \\ 0.0008 & 0.0239 & 0.9753 \end{bmatrix}$

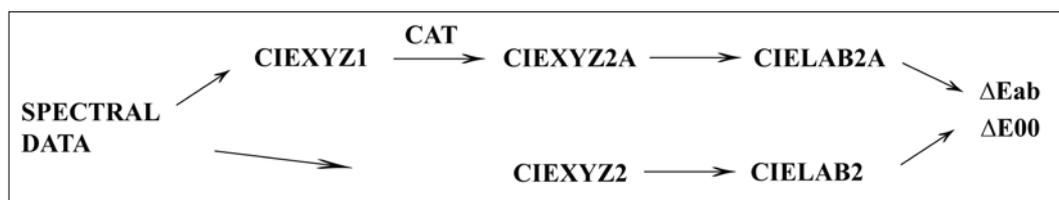


Figure 3. Scheme of work (CIE XYZ1 – source XYZ, CIE XYZ2 – calculated XYZ, CIE XYZ2A – adapted XYZ)

Scheme of work is outlined in Fig. 3. To calculate color differences (delta E) between the reference (XYZ values generated directly from the measured spectral data) and the chromatic adaptation-transformed values (adapted XYZ values), the established ΔEab (Golob and Golob, 2001) as well as newest ΔE00 (Golob and Golob, 2001; Gurav et al, 2004) formulas were implemented. All calculations were performed using program Octave 3.0 (Schlöpfer, 2002).

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) (Schlöpfer, 2002), 1-3 (small color difference between two patches) (ISO 12647-7 : 2007), 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.

3. Results And Discussion

To visualize relationships that exist in a large results database consisting of color differences (delta E) values for 8190 samples – color patches – and 15 variables – combinations of five CATs and three illuminant pairs – PCA was implemented.

PCA results are displayed in Figs. 4 and 5. As much as 97% (PC1: 69%, PC2: 28%) of original data variance can be accounted for by the first two PCs. Fig. 4 shows a clock-wise pattern of increased delta E values of investigated samples according to ΔEab formula.

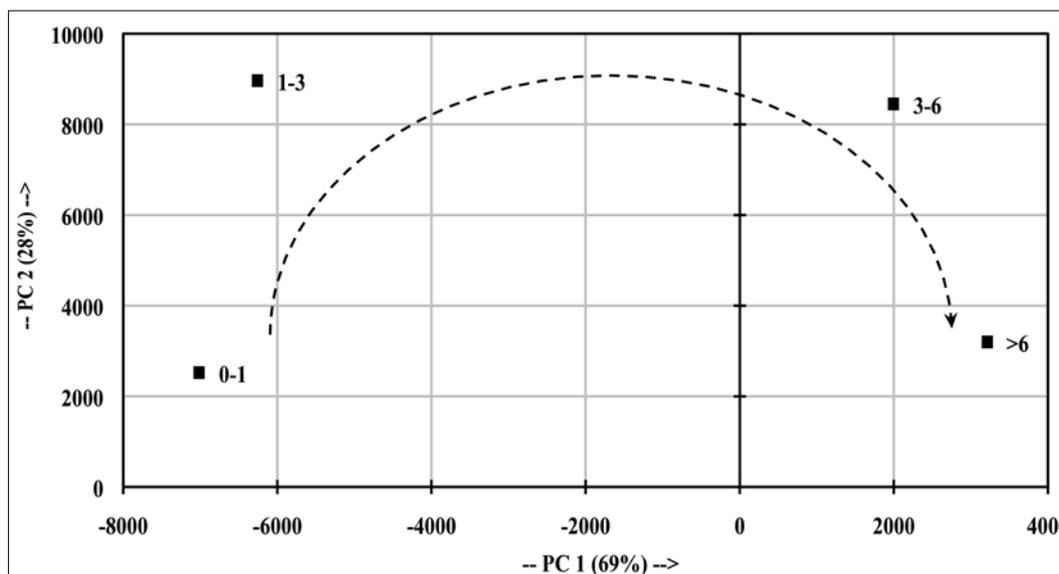


Figure 4: Groups of ΔEab values in PC1- PC2 coordinate system

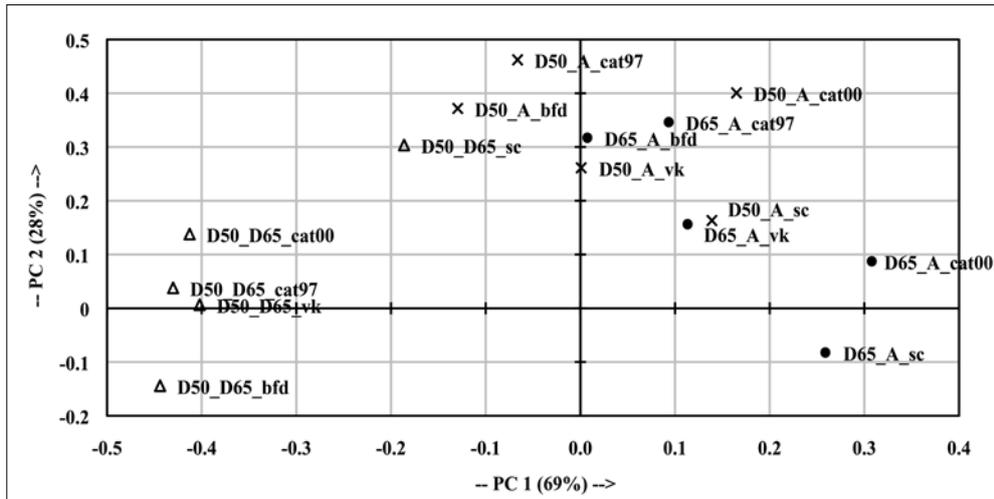


Figure 5: CAT/illuminant pair combinations for ΔE_{ab} formula in PC1-PC2 coordinate system

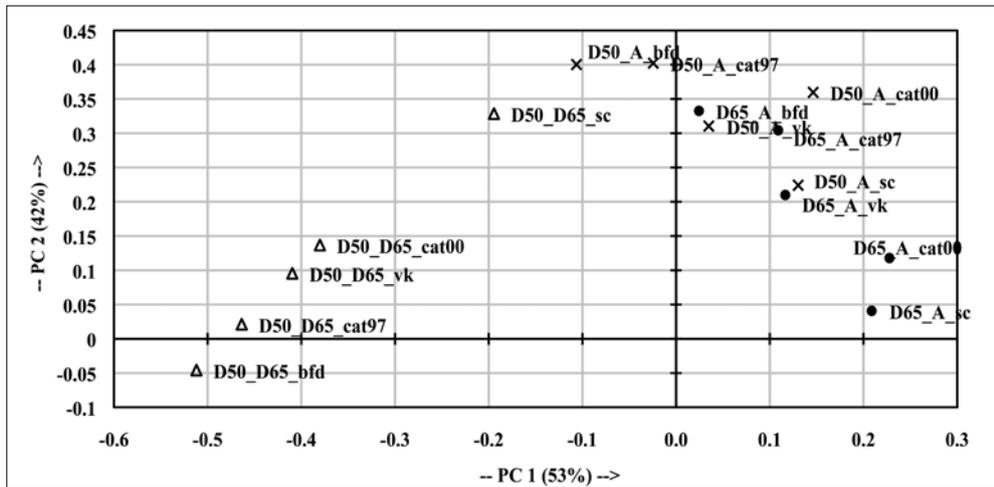


Figure 6: Groups of ΔE_{00} values in PC1-PC2 coordinate system

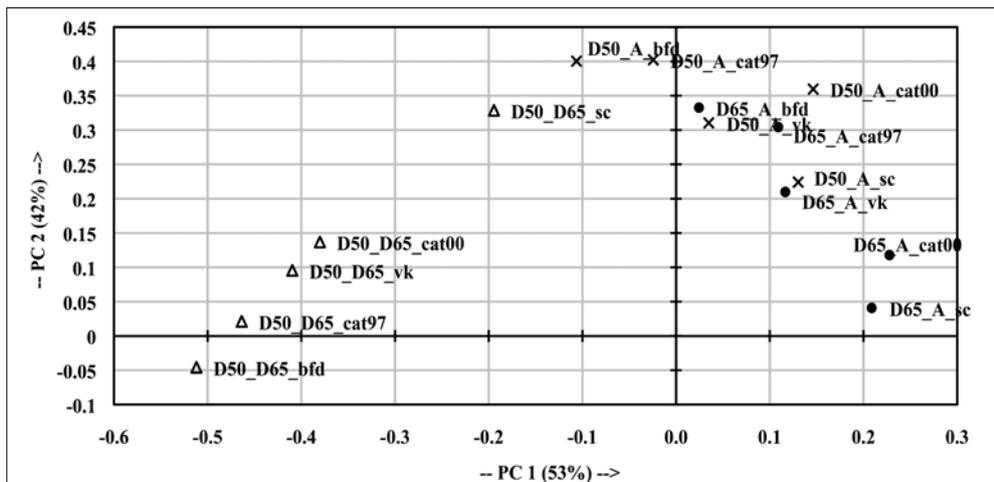


Figure 7: CAT/illuminant pair combinations for ΔE_{00} formula in PC1-PC2 coordinate system

reveals that D50-D65 illuminant pair generates by far the smallest color differences as all five corresponding CATs models in Fig. 5 – Bradford (D50_D65_bfd), von Kries (D50_D65_vk), CMCCAT97 (D50_D65_cat97) CMCCAT00 (D50_D65_cat00) and XYZ Scaling (D50_D65_sc) – are located in the same (i.e. bottom-left) relative position with respect to the delta E point 0-1 location in Fig. 4. Larger color differences – typically within 1-3 or 3-6 delta E classes – were found in case of D50-A models while samples that underwent one of the D65-A illuminant pair transforms were generally characterized by the largest (>6) differences. For instance, with D65_A_sc transform combination, as much as 20 patches exhibited delta E values larger than 30 units, while with D65_A_cat00 combination, 2 samples were found to have delta E values between 22 and 23 units.

PCA treatment of ΔE_{00} results (Figs. 6 and 7) leads to conclusions similar to those described above. Again, most of the relevant information (95%) is represented by the first two PCs. Although positions of individual data points are somewhat different when compared to those located in Figs. 4 and 5, the same clock-wise pattern of samples (0-1 followed by 1-3, 3-6 and >6) and ranking of variables (D50_D65_xx model followed by D50_A_xx and D65_A_xx) is evident.

In addition, in order to assess the performance of each individual CAT, the three implemented illuminant pairs – D50-D65, D50-A and D65-A – were studied separately.

3.1. TRANSFORMATIONS WITHIN ILLUMINANT PAIR D50-A

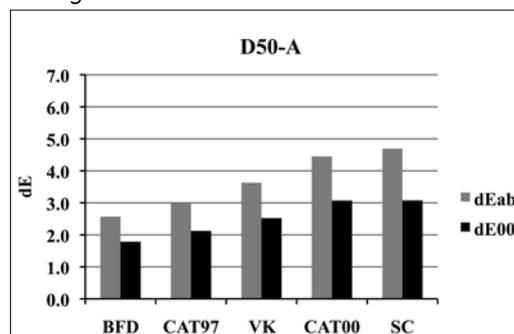


Figure 8: Average color differences obtained with D50-A illumination pair and various CATs

Fig. 8 shows average color differences ΔE_{ab} and ΔE_{00} obtained with D50-A illumination pair and various CATs. Bradford CAT produces the smallest color differences, followed by CMCCAT97, von Kries, CMCCAT00 and XYZ Scaling model, which generates the biggest ones.

3.2. TRANSFORMATIONS WITHIN ILLUMINANT PAIR D50-D65

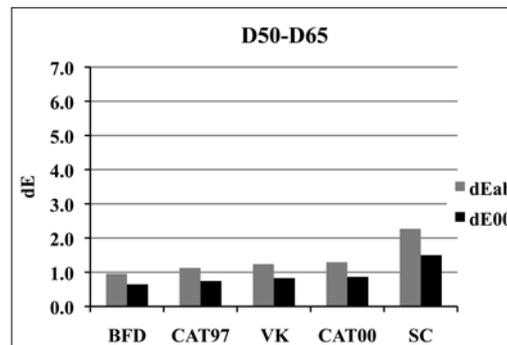


Figure 9: Average color differences obtained with D50-D65 illumination pair and various CATs

Fig. 9 shows average color differences ΔE_{ab} and ΔE_{00} obtained with D50-D65 illumination pair and various CATs. Color differences are much smaller than in the previous case, however the biggest delta E value for D50-D65 pair (XYZ Scaling) is approximately the same as the smallest delta E for D50-A pair (Bradford - ΔE_{ab} is 2.57 and ΔE_{00} is 1.78). Note that the performance ranking of individual CATs is the same as with D50-A.

3.3. TRANSFORMATIONS WITHIN ILLUMINANT PAIR D65-A

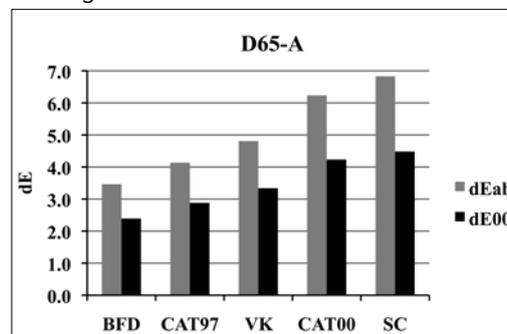


Figure 10: Average color differences obtained with D65-A illumination pair and various CATs

Fig. 10 shows average color differences ΔE_{ab} and ΔE_{00} obtained with D65-A illumination pair and various CATs. In this case color differences are the biggest of all three examined illuminant pairs, but ranking of the implemented CATs remains unchanged.

tions of colors were compared. We noticed that saturated cyan patches had large color differences (Fig. 13(b)) and neutral colors are well predicted by XYZ Scaling CAT (Fig. 13(a)). With CATs colors are shifted from illuminant D65 to A, therefore saturation of cyan decreased (from ΔE 60-90 to 40-70).

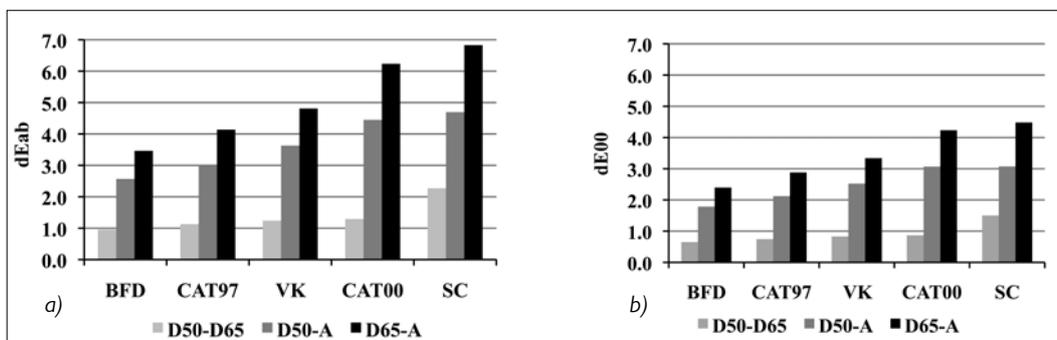


Figure 11: Average color differences ΔE_{ab} (a) and ΔE_{00} (b) obtained with different illumination pair and CATs

Fig. 11 shows comparison of color differences obtained with three illumination pairs and different CATs. Equation ΔE_{ab} is based on a distance between two colors without using any correction factors, while ΔE_{00} includes lightness, chroma and hue correction terms. Consequently, all obtained ΔE_{00} values are bigger than ΔE_{ab} values. The same performance ranking of CATs appears in all combinations of illuminant pairs (D50-A, D50-D65 and D65-A) (Fig. 11): the smallest color differences are generated with D50-D65 CATs and the biggest with D65-A models (see also Figs. 5 and 7). Illuminants D50 and D65 are both very close to each other in the CIE chromaticity diagram (Fig. 12) and also have a similar spectral power distribution (Fig. 1), which explains the obtained smallest ΔE values. Illuminant A is closer to D50 than to D65, therefore ΔE values for pair D50-A are smaller than in the case of D65-A illuminant pair.

Patches of yellow shades also moved to illuminant A, their saturation increased and ΔE was smaller in comparison with cyan and blue shades, however yellow shades reached the boundary of chromaticity (or spectral locus).

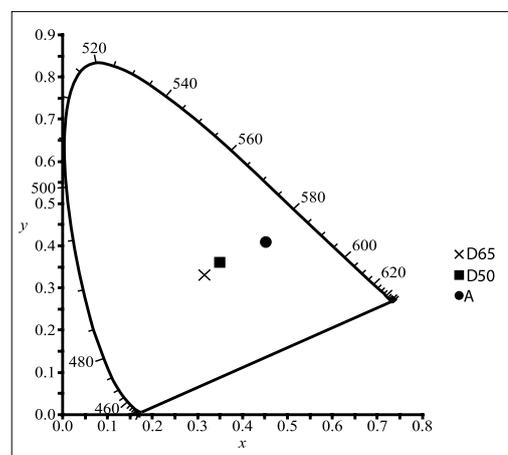


Figure 12: CIE x, y 1931 diagram (CIE Chromaticity diagram)

It was already mentioned that the largest ΔE values appeared at transformations from D65 to A, so we wanted to examine how many patches have large ΔE values and how many patch colors are well predicted by a particular CAT. Colors of patches were sorted according to color difference and presented in CIE chromaticity diagram. Two methods that give the worst (XYZ Scaling) and the best (Bradford) predic-

In case of magenta patches using illuminant A, a shift towards red color took place. XYZ Scaling method caused colors to move downwards to the diagram borders increasing at the same time their saturation.

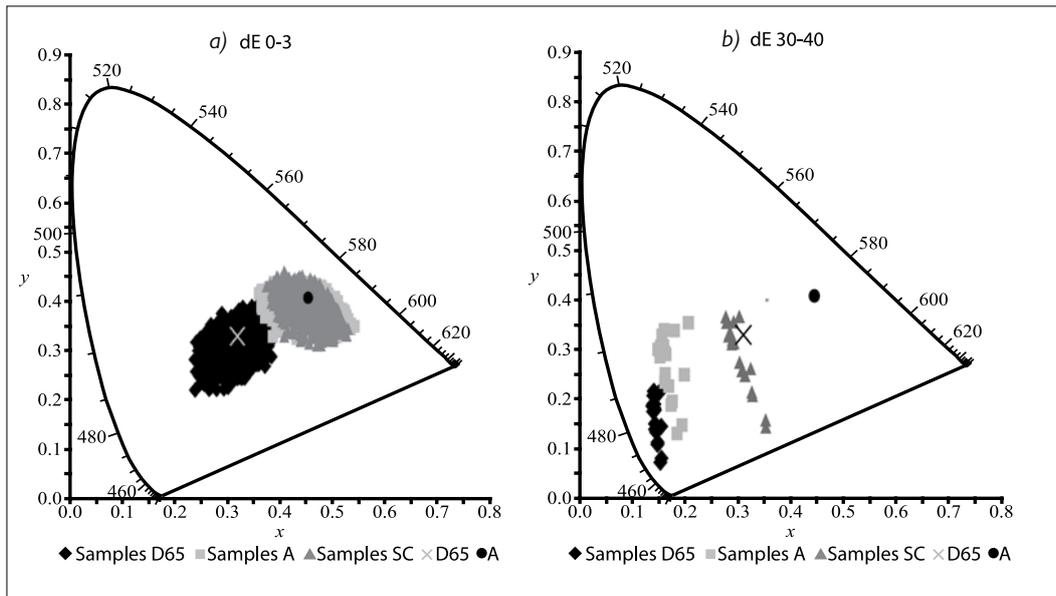


Figure 13: Source and destination colors (adapted with *xyz Scaling CAT*) in *cie* chromaticity diagram (*dE* 0-3 (a) and *dE* 30-40 (b)). Samples: chromatic coordinates of adapted colors (Samples *sc*) and colors under illuminant *D65* (Samples *D65*) and *A* (Samples *A*)

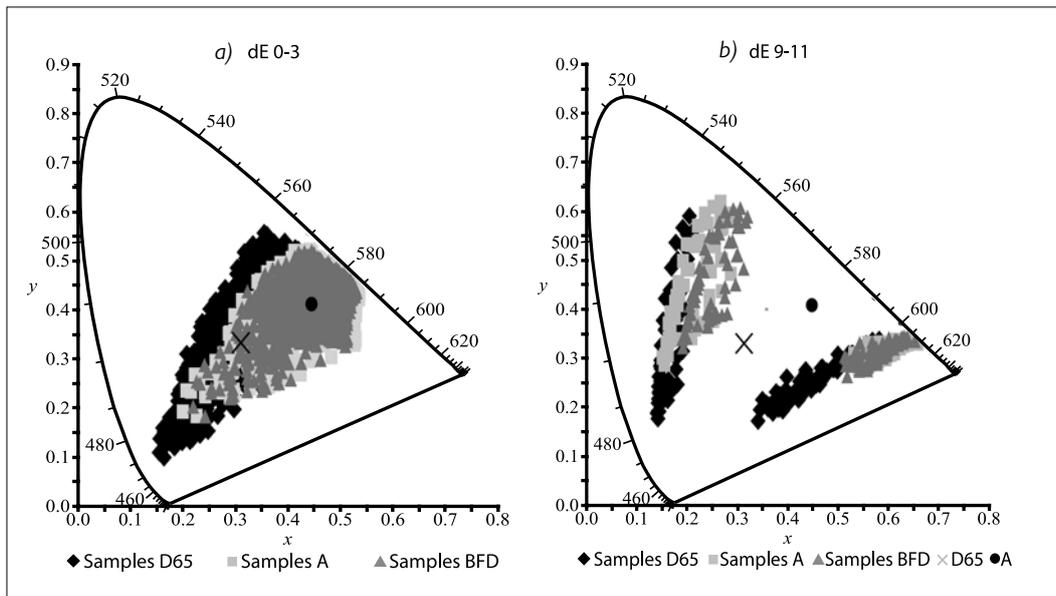


Figure 14: Source and destination colors (adapted with *Bradford CAT*) in *cie* chromaticity diagram (*dE* 0-3 (a) and *dE* 9-11 (b)). Samples: chromatic coordinates of adapted colors (Samples *BFD*) and colors under illuminant *D65* (Samples *D65*) and *A* (Samples *A*)

The smallest color differences ($\Delta E_{ab} < 3$) were observed with neutral colors of all shades, i.e. color patches with lower saturation (chroma ranging from 0 to 25); saturation of these colors remained practically unchanged. From this we can conclude that XYZ Scaling method is suitable only for approx. 1800 patches with lower saturation.

Bradford cat showed the best performance, since 4000 patches have $\Delta E < 3$ and saturated colors are also well predicted (Fig. 14 (a)-(b)). With this method colors move from point D65 to point A in the same manner as in the case of XYZ Scaling method.

4. Conclusions

Raw spectral data make it possible to calculate CIE tristimulus values (XYZ) under various illumination sources. 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 all five examined models, Bradford CAT exhibited the best performance since the observed color differences were found to be the lowest regardless of the illumination pair used. The same performance ranking of CATs appears in all combinations of illuminant pairs (D50-A, D50-D65 and D65-A): the smallest color differences are generated with D50-D65 CATs and the biggest ones with D65-A models. It seems that newer methods are more complex and more suitable for larger data sets. PCA proved useful in evaluating performance of different CATs.

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