Influence of Background and Surround on Image Color Matching

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ABSTRACT: In this article, the corresponding-color data for complex images reproduced on different media were obtained by simultaneous matching using an adjustment method. In our experiment printed color images and images displayed on a monitor were compared in different viewing conditions. The viewing condition varied in surround relative luminance and background. The experimental data show that surround relative luminance has little influence on color matching between printed and monitor images while changes in background modify color appearance. These results were used to evaluate different chromatic adaptation transforms (CAT). We found that for the same viewing conditions the SHARP transform shows the best agreement between the experimental and predicted data. SHARP transform can not predict accurately corresponding colors for blue and black regions. Therefore, we proposed new CAT that shows better characteristics than other transforms for cyan, green, and black colors and similar characteristics for other colors. Int J Imaging Syst Technol, 17, 244–251, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ima.20117

Key words: color appearance; chromatic adaptation transform; color matching experiment; color difference

I. INTRODUCTION

The exponential growth of affordable digital imaging technologies has created a huge demand for digital color reproduction and color management (Stokes et al., 1992). The goal of color management is to reproduce the desired color appearance of an original in a way that is consistently pleasing and acceptable. With so many different media and devices used in image processing it becomes hard to achieve the desired color quality (Luo and Morovic, 1996). In a typical natural scene, the reflected spectral radiance at each surface elements of an object is determined by the spectral reflectance factor of the surface and the spectral power distribution of the illumination (Lee, 2005). There are very reach varieties of spectral distributions that produce colorful images in our visual perception. Because of the trichromatic nature of our color vision, most colors can be reproduced by using mixtures of three primary colors. Colors can be reproduced either by using self-emitting light (e.g. in CRT monitors), or by using reflected light (e.g. in painting and prints).

In a reproduced image, in a monitor or in a printer, colors cannot be created in such rich varieties of spectral compositions. If a simple colorimetric match is made between a printed image and a monitor display, the perceived colors in the images typically do not match. This is due to differences in viewing conditions between the two displays. Such differences include changes in luminance level, in white point chromaticity and in surround relative luminance (Braun and Fairchild, 1997). The results of color measurement can be the same but an observer may not think they are identical because there is a difference in the way we perceive monitor colors and printed colors. Metamerism occurs between surface color and monitor outputs. Monitors make use of the luminescence of phosphors and produce different color mode compared with that of surface colors.

Conventional CIE XYZ colorimetry is useful for specifying color appearance under a given set of viewing conditions and for determining whether two colors will match in a viewing configuration (CIE 15.2-1986). It incorporates none of the information necessary for specifying the color appearance of those matching stimuli. If viewing condition is changed the color match will no longer hold. Therefore, in recent years, researchers have tried to develop more comprehensive color appearance models (CAM), which are able to predict color appearance accurately across a range of viewing conditions. CAMs were derived from the results of psychophysical experiments using simple scenes (e.g. single colors against a variety of different viewing environment).

The human visual system has the ability to maintain the color appearance of an object despite quite large changes in the quality and intensity of the illumination. This adaptation is chromatic adaptation that relies on sensory and cognitive mechanisms. When a monitor image output is being viewed only sensory mechanisms are active. When a printed image is being viewed both mechanisms are active: sensory mechanisms which respond to the spectral energy

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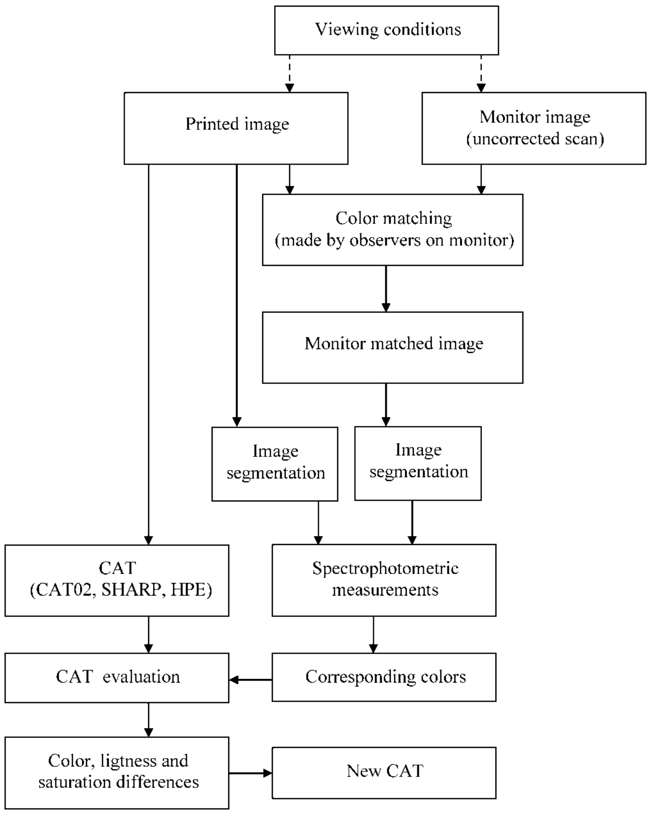

Figure 1. The workflow of experiment.

distribution, and cognitive mechanisms, which discount the ''known'' color of the light source. Most CAMs include a CAT, as a method for computing the corresponding data. Corresponding-colors data are two stimuli, viewed under different viewing conditions that match in color appearance. Corresponding data have been obtained through a wide variety of experimental techniques (Luo and Hunt, 1998). Fairchild and Johnson (1999) obtained corresponding data for complex images using an adjustment method, which were used to evaluate CAM and CAT. It was shown that a simple linear transformation of tristimulus values provide a good description of data. Komatsubara et al. (2002) obtained corresponding-colors data using the method of constant stimuli. They found that optimizing the input parameters and introducing incomplete adaptation allow to have the mean color difference ΔE^* less than 10 CIELAB units. Fez et al. (2001) obtained corresponding-color data by simultaneous matching and by memory matching. Matching methods may be classified as simultaneous and memory matching, according to the time elapsed between the presentation of the reference and matching stimuli. In simultaneous matching, reference and matching stimuli are viewed simultaneously side-by-side. In memory matching experiments, observers match the reference stimulus they remember under the same or different viewing conditions. They found that the best matching colors lie along the red–green axis. Sueeprasan et al. (2001) obtained corresponding-color data by employing the memory matching methods and found that the input parameters for each model had a distinct impact on model performance.

Corresponding-color data have been obtained through a wide variety of experimental techniques and viewing conditions. The results of different experiments cannot be compared directly because of different data sets and matching methods. Usually, color experiments are performed using color patches (Finlayson et al., 1994; de Fez et al., 2001; Sueeprasan et al., 2001; Komatsubara et al., 2002). When dealing with color patches on a uniform background, the viewing conditions are well specified and understood but are less understood when dealing with spatially complex stimuli such as images. Additional problems arise from changes in viewing conditions that are caused by reproducing images in different media. The perceived colors of the same image printed on the paper or displayed on a monitor typically do not match. Additionally, two colors, which are a colorimetric match, can appear quite different if viewed under different viewing conditions. The research presented in this article concentrates on color appearance for complex images through examination of color matching data for different media and different viewing conditions.

In Section II, the workflow of experiment is given. The viewing conditions are described. In Section III, the results are given in term of color differences (ΔE_{94} and ΔE_{00}), and differences in lightness (ΔL) and chroma (ΔC). Next, in Section IV, we discuss several CAT. We introduce a new transform that is based on SHARP adaptation transform. In Section V, we compare corresponding colors obtained from visual matching with the corresponding colors computed using different transform matrix.

II. EXPERIMENT

The workflow of experiment is given in Figure 1. The experiment was taken in dark and dim room that is close to the actual environment in practical viewing conditions (Mandic and Grgic, 2005; Mandic et al., 2005). The viewing conditions are described in Table I. The illumination was measured by radiometer, and the results are shown in Table II. Printed hard copies were illuminated and viewed under viewing booth that simulated CIE Standard Illuminants D50. Additionally, images were displayed on Mitsubishi monitor. A cathode ray tube and the light boot with a gray background of luminance factor 0.2 were placed on the table with the same center height. The CRT white point was set to the chromaticity coordinates close to 6500K (CIE Illuminant D65). Each printed and each monitor image had a 5-mm white border, which was the reference white for chromatic adaptation purposes. The printed originals and monitor reproduction were used so as to correspond to simultaneous binocular viewing. The layout of experiment is shown in Figure 2.

Six printed images containing pictorial information were used as the originals (Fig. 3). The images contain memory, neutral and saturated colors. Memory color refers to the phenomenon that observers remember prototypical color for familiar object (green grass, blue

Table I. Viewing conditions.

Viewing Condition	White Point (Monitor)	Background (Monitor)	Light Box D50	Room
A	D65	black	+	dark
B	D65	gray	+	dark
C	D65	gray	+	dim

Table II. Radiometric measurements.

	Luminance (cd/m^2)
White point D65 monitor	138
Light boot D50	389
Room	32.5

Figure 2. Layout of experiment. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

sky, skin). Neutral colors are desaturated colors: black, white and a range of grays in between. The preservation of neutral colors is one of the most important requirements in color reproduction. Humans are able to notice even a small color cast in neutral areas. Image 1 contains a house, snow and sky. Image 2 contains skin tone. Image 3 contains black and white parts. Image 4 contains grass and sky. Image 5 contains different hues and image 6 gold color. These images were continuous tone images printed on mat papers using a large format printer at 254 dpi. The original hardcopies were captured by an Agfa scanner at 305 dpi to provide RGB data for processing the CRT reproduction. The scanner and CRT display were calibrated and characterized using Macbeth software ProfileMakerPro 4.

A total of five observers, all experienced in using Adobe Photoshop, took part in the entire experiment. The observers were skilled operators, who have been worked in graphic industry for a long time (more than five years). All the observers had normal color vision. Color vision of observers was evaluated for each observer before experiment using Ishihara plates and a Farnsworth–Munsell 100-hue test. Observers sat approximately 25 in. from the printed originals and monitor screen. All experiments were carried out first in a darkened room, so that only the printed or monitor images occupied observers' field of view. The images on monitor were placed on black background. Observers adjusted the colors on monitor images to match the color appearance of the printed images. The monitor images adjustments were accomplished using Adobe Photoshop. Observers were allowed to use any of the color adjustment tools in Photoshop, but were not allowed to perform spatial manipulation of the images. The length of each experimental session was left to the discretion of the observers. Each experiment began with the same starting-point image, uncorrected scans. The same trial was done for second viewing condition, when the images displayed on monitor were placed on gray background of luminance factor 0.2. The third part of experiment was taken in dim room, similar to practice environment. The images were placed on the gray background of luminance factor 0.2.

After observers completed the various matching tasks, the resulting images were saved for later processing. Both printed and monitor images, were segmented into several number of object region, depending on the image context (Fig. 4).

After segmentation, the same fields were measured on printed and monitor images using a GretagMacbeth Spectrolino 45/0 spectrophotometer (X-Rite/GretagMacbeth). Measurements were made by systematically sampling the same image regions and then averaging the tristimulus values. The pairs of corresponding colors obtained from visual experiments were compared. The color differences, differences in lightness and chroma were found. The results of experiment were used to evaluate three different CAT. These transforms were applied to *XYZ* tristimulus values of printed images to predict *XYZ* tristimulus values of monitor images. Predicted data were compared with data obtained from visual matching

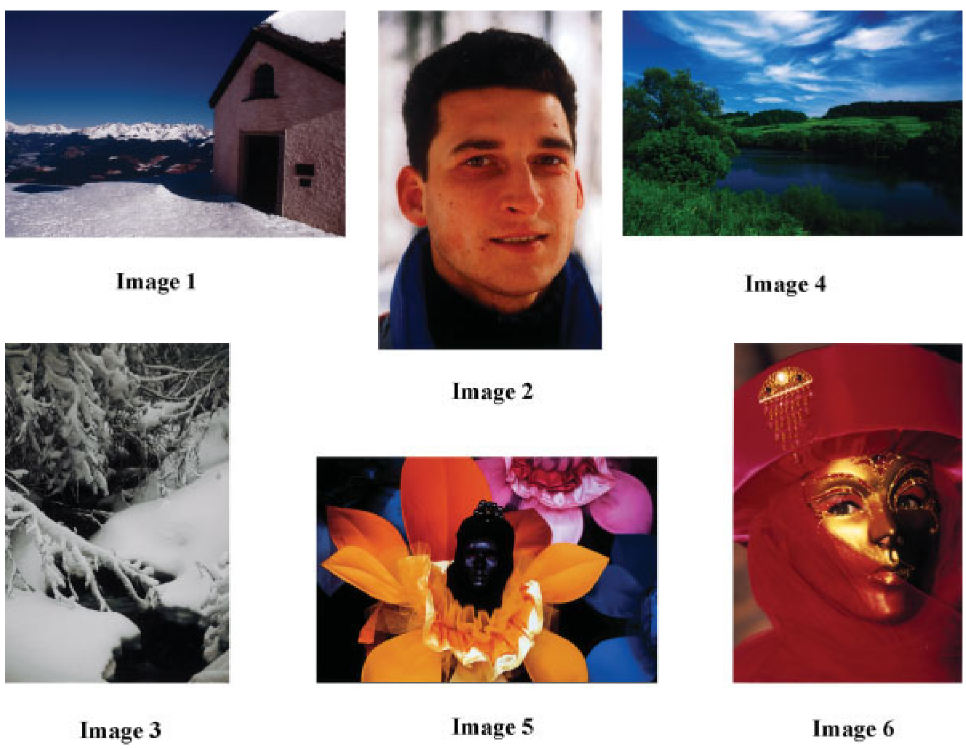

Figure 3. Test images. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

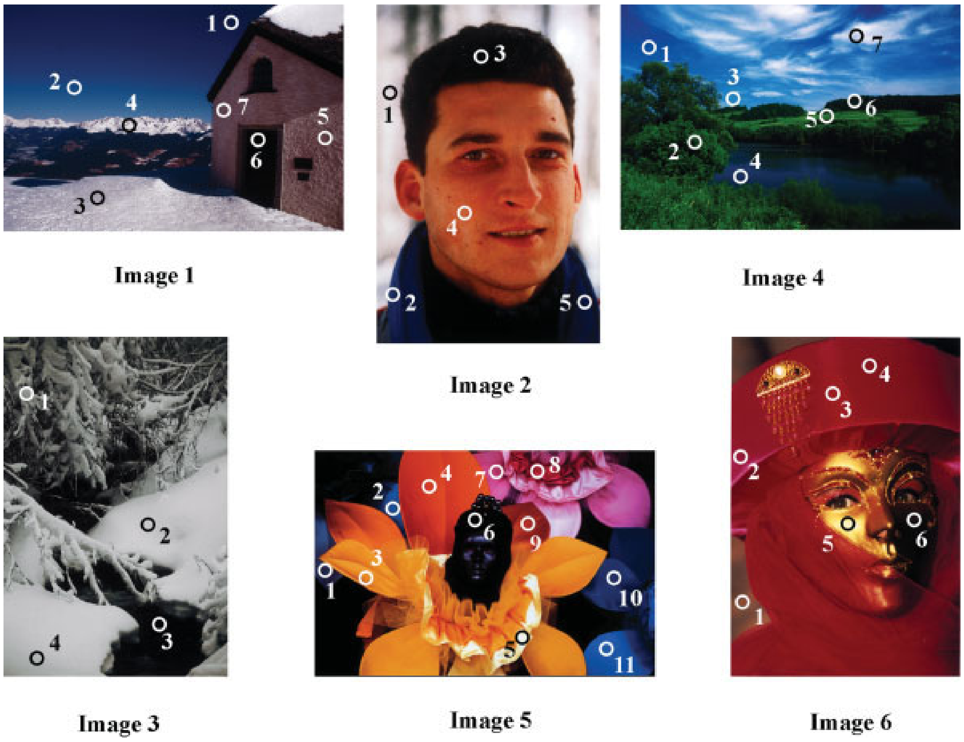

Figure 4. Image segmentation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

experiment and results were used to build up new chromatic adaptation transform.

III. RESULTS OF SPECTROPHOTOMETRIC MEASUREMENT

For each segmented field and all conditions the mean values of tristimulus XYZ and $L^*a^*b^*$ were found. Those data were used for calculating color-differences between monitor and printed images. There are many ways to describe the differences between two colors: ΔL, Δa, Δb, ΔC, and ΔE (CIE 15.2-1986). In (Berns, 2000) the use ΔL and ΔC was recommended for chromatic samples and the use of Δa and Δb was recommended for neutral samples. The CIE, through its technical committees, has periodically established recommended practices for color-difference evaluation to promote uniformity of industrial practice. CIE 1976 ($L^*a^*b^*$) color-difference model ΔE^*_{ab} between two color stimuli is calculated as the Euclidean distance between the points representing them in the CIELAB color space (Robertson, 1990). After that new models with improved agreement with visual color-difference judgments have been developed such as color-difference model ΔE_{94} (CIE 116-1995) and color-difference model ΔE_{00} (CIE 142-2001; Luo et al., 2001) that improves the prediction of color differences in blue and near-neutral regions. In our research we evaluated color differences using ΔL, ΔC, ΔE_{94}, and ΔE_{00}.

Table III. Differences in lightness (ΔL), chroma (ΔC), and color differences (ΔE_{94} and ΔE_{00}) for image 1.

Image 1	Cond.	ΔL	ΔC	ΔE_{94}	ΔE_{00}
1	A	−0.10	0.17	7.35	1.28
	B	4.10	−1.05	5.62	0.85
	C	1.30	3.80	5.08	0.65
2	A	−0.72	−0.04	8.05	2.32
	B	2.70	1.27	6.54	1.57
	C	−0.20	3.20	6.43	1.45
3	A	−11.80	13.90	15.05	3.45
	B	−2.10	14.74	10.08	3.02
	C	−5.40	17.50	12.30	3.16
4	A	1.90	15.10	11.39	9.70
	B	7.60	13.08	13.19	11.06
	C	5.80	15.80	13.44	11.92
5	A	−3.70	0.17	11.68	0.88
	B	−3.30	0.62	9.09	0.71
	C	−3.90	0.49	11.19	0.85
6	A	6.00	8.94	11.74	1.24
	B	6.00	8.44	11.39	1.20
	C	2.70	6.35	8.37	0.92
7	A	3.90	−20.3	13.4	1.6
	B	−0.20	−20.42	12.88	1.60
	C	5.90	−19.76	12.55	1.51

Table IV. Differences in lightness (ΔL), chroma (ΔC), and color differences (ΔE_{94} and ΔE_{00}) for image 2.

Image 2	Cond.	ΔL	ΔC	ΔE_{94}	ΔE_{00}
1	A	−1.9	12.7	11.3	2.1
	B	1.9	12.8	11.7	2.2
	C	−2.6	10.9	11	2.1
2	A	4.4	−2.3	8.7	0.8
	B	8	0.4	10.9	0.8
	C	3	0.5	7	0.5
3	A	8.4	8.1	13.3	1.2
	B	8.7	8.7	13.8	1.2
	C	4.9	7.6	10.9	1.1
4	A	−4.8	−18.1	11.4	0.5
	B	−1.8	−15.6	10.1	0.4
	C	−5	−18.3	11.8	0.5
5	A	5	4	9	0.5
	B	6.3	4.4	9.4	0.5
	C	3.7	5.6	7.1	0.3

Table V. Differences in lightness (ΔL), chroma (ΔC), and color differences (ΔE_{94} and ΔE_{00}) for image 3.

Image 3	Cond.	ΔL	ΔC	ΔE_{94}	ΔE_{00}
1	A	−4	8.2	7.8	22.5
	B	−0.3	11.8	8.9	27.6
	C	−3.3	7.6	6.8	20.4
2	A	8.7	10.2	12.7	68.1
	B	3.2	11.7	11.1	76.5
	C	10.7	11.3	14.4	73.9
3	A	−4.2	12.1	13.6	23.4
	B	−3	13.8	14.5	25.7
	C	4.2	7.9	10.5	16.7
4	A	3.9	13.2	10.7	86.5
	B	3.5	15.3	11.3	96.3
	C	4.4	11.9	9.4	77.8

The results for image 1 are shown in Table III. The results for image 1 show that the neutral colors on monitor (fields 4 and 6) are lighter and have higher chroma values, while color of sky (fields 1 and 2) does not differ a lot between monitor and printed image. The color difference ΔE_{00} is small, except for white (field 4) that is not correspond with visual sensation. The color that belongs to the house (shadow) is less chromatic. The results for image 2 (Table IV) show that the dark colors (fields 3 and 5) are lighter when displayed on the monitor. The color close to neutral is more chromatic, while the skin is less. The neutrals colors for image 3 (Table V) are more saturated and the color difference ΔE_{00} is large and not acceptable. The results for image 4 (Table VI) show that the differences in lightness are small, except for field 5 (grass). Green colors (fields 2 and 5) are less chromatic. Color difference ΔE_{00} varies a lot in values. The results for image 5 (Table VII) show that the yellow (field 3), orange (field 4), and brown (field 9) have lower chroma values. All other colors are more saturated. Most of the colors are darker. Larger differences in lightness can be noticed for violet (field 1) and brown (field 9). We notice that most of the colors on monitor are darker and less chromatic for image 6 (Table VIII) that contains red, gold, and black colors. Results of our experiment show large deviation between color difference ΔE_{00} and observers judgment so we excluded ΔE_{00} from further discussion.

Table VI. Differences in lightness (ΔL), chroma (ΔC), and color differences (ΔE_{94} and ΔE_{00}) for image 4.

Image 4	Cond.	ΔL	ΔC	ΔE_{94}	ΔE_{00}
1	A	−1.4	2.4	5.5	11.2
	B	−1.1	5.8	7.6	16.1
	C	0.8	−1.9	6	12.4
2	A	−2.4	−18.5	14	0.6
	B	0.8	−17.4	12.5	0.6
	C	3.1	−23.8	14.7	0.6
3	A	−1.9	9.6	7.3	2.6
	B	−1	12.1	8.6	3.1
	C	−0.3	8	7.3	2.9
4	A	−3	1.3	5.3	43.4
	B	−3.1	3.4	6.2	53
	C	0.3	−1.3	5.6	57.4
5	A	7.9	−7.3	11.1	0.5
	B	7.8	−6.8	10.7	0.45
	C	7	−11.8	11.5	0.4
6	A	−4	3.94	14.9	1.8
	B	−1.5	2.90	13.3	1.2
	C	1.6	−1.21	13.6	1.3
7	A	2.1	16	9.5	4.5
	B	3.5	16.9	10.5	4.9
	C	2	16.5	9.9	4.9

Table VII. Differences in lightness (ΔL), chroma (ΔC), and color differences (ΔE_{94} and ΔE_{00}) for image 5.

Image 5	Cond.	ΔL	ΔC	ΔE_{94}	ΔE_{00}
1	A	−7.8	8.9	9.1	3.9
	B	−4	13.4	7.9	3.2
	C	−5.5	8.9	7.9	2.9
2	A	−3.6	6.8	9.5	10.1
	B	2.6	10	9.1	13.5
	C	−0.4	6.3	9.3	9.5
3	A	0.4	−31.9	9.9	4.5
	B	3.6	−31.2	10.1	4.4
	C	1.2	−30.9	9.5	4.3
4	A	−7.1	−17.6	12.7	0.3
	B	−0.9	−15.7	9.3	0.2
	C	−3.4	−17.6	11.1	0.3
5	A	0.1	17.7	14.8	16.6
	B	1.0	17.7	14.8	16.6
	C	0.3	17.1	14.4	16.2
6	A	−1.3	9.8	8.7	0.5
	B	1.3	12.7	10.8	0.7
	C	4.6	8.2	9.2	0.7
7	A	−5.5	3.7	9.7	0.3
	B	−1.1	5.7	6.5	0.2
	C	−6.2	1.8	8.4	0.3
8	A	−2.4	−2.8	5.6	0.1
	B	1.3	1.7	4.4	0.1
	C	0.2	−2.4	4.1	0.1
9	A	−11.2	−26.1	17	0.7
	B	−5.7	−18.2	13.1	0.5
	C	−8.2	−24.9	15	0.6
10	A	−3	−2	9.4	1
	B	−1.7	2.7	10.4	0.8
	C	0.1	−4.6	9.7	1.2
11	A	−5.9	4.9	13.9	3.6
	B	−0.9	7.3	12.1	1.9
	C	−3.8	3.6	13.1	2.9

Table VIII. Differences in lightness (ΔL), chroma (ΔC), and color differences (ΔE_{94} and ΔE_{00}) for image 6.

Image 6	Cond.	ΔL	ΔC	ΔE_{94}	ΔE_{00}
1	A	−12.7	−16.6	19.4	1.9
	B	−3.4	−16	11.6	1.1
	C	−8.4	−15.9	17.1	1.8
2	A	−6.6	−10.9	8.1	0.2
	B	−2.5	−7.3	3.9	0.1
	C	−1.8	−11.8	5.5	0.1
3	A	−7.1	−14.1	8.8	0.2
	B	−2.4	−8.7	4	0.1
	C	−2.7	−14.8	6.6	0.2
4	A	−5.3	−12.3	7.1	0.2
	B	−1.8	−7.7	3.2	0.1
	C	−1.5	−12.1	5.3	0.1
5	A	−0.2	−1.9	3.8	0.7
	B	2.9	−6.9	6.6	1.4
	C	2	−12.3	8.3	7.8
6	A	−3.8	11.2	11.8	1.9
	B	−3	9.5	10.3	1.8
	C	1.3	10.2	10.5	1.8

Table IX. Color differences (ΔE_{94}) between visual and computed corresponding data for blue and cyan colors.

		Blue					Cyan		
		1–1	2–2	4–1	4–4	5–1	3–1	3–3	5–11
Cond.	Matrix	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}
A	$\mathbf{M}_{CAT02}$	5.3	5.8	4.2	4.5	9.9	9.8	14.5	12.1
	$\mathbf{M}_{SHARP}$	5.3	6	4.1	5.6	9.7	9.8	14.5	12.3
	$\mathbf{M}_{HPE}$	1.1	4.3	5.2	6.3	12.8	16.6	14.6	7.6
	$\mathbf{M}_{NEW}$	5.3	6.2	4.4	4.5	10.2	9.9	14.5	11.8
B	$\mathbf{M}_{CAT02}$	4.3	8.6	6.1	5.5	8.8	11.3	15.4	10
	$\mathbf{M}_{SHARP}$	4.3	8.9	5.9	6.7	8.7	11.3	14.5	10.3
	$\mathbf{M}_{HPE}$	5.7	7.8	4.4	6.2	11.4	17.4	15.2	4.8
	$\mathbf{M}_{NEW}$	3.7	8.8	6.2	5.5	9.2	11.5	15.4	9.7
C	$\mathbf{M}_{CAT02}$	3.7	4.2	3.7	3.6	8.4	8.7	11.3	11.1
	$\mathbf{M}_{SHARP}$	3.7	4.4	3.7	4.7	8.3	8.7	11.3	11.3
	$\mathbf{M}_{HPE}$	4.3	3.5	3.5	3.5	10.2	14.9	9	5.7
	$\mathbf{M}_{NEW}$	3.8	4.6	3.6	3.6	8.7	9	11.3	10.7

IV. CHROMATIC ADAPTATION TRANSFORM

A number of CATs are currently in use and most of them transform the *RGB* space into tristimulus values *XYZ* (Drew and Finlayson, 1994; Finlayson, 1994; Fairchild, 2001):

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{4.1}$$

where $\mathbf{M}$ is the transform matrix. The implication of all these proposed CAT is that color correction for illumination takes place not in cone space but rather in a ''narrowed'' cone space. As a consequence, the CAT sensors have their sensitivity more narrowly concentrated than the cones. The RGB space differs slightly between the different transforms. The HPE cone fundamentals have been used by Hunt to develop color vision models (Hunt et al., 2003). The transform matrix of HPE is defined as

$$\mathbf{M}_{HPE} = \begin{vmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0 & 0 & 1 \end{vmatrix} \tag{4.2}$$

The transform matrix $\mathbf{M}$ is derived as a linear combination of the CIE 1931 *XYZ* color matching functions that most closely match a cone absorption and study of Estevez for 2 degree observers (Hunt and Pointer, 1985). Li et al. (2002) derived CAT based on minimizing perceptual error over a set of corresponding data. Their transform was adopted by the CIE as the CAT02 for a new color appearance model CIECAM02:

$$\mathbf{M}_{CAT02} = \begin{vmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6974 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{vmatrix} \tag{4.3}$$

The SHARP adaptation transform (Finlayson and Süsstrunk, 2000) was developed for solving the non-perceptual adaptation problems when treating *XYZ* as the important units:

$$\mathbf{M}_{SHARP} = \begin{vmatrix} 1.2694 & -0.0988 & -0.1706 \\ -0.8364 & 1.8006 & 0.0357 \\ 0.0297 & -0.0315 & 1.0018 \end{vmatrix} \tag{4.4}$$

These transform matrix were applied to *XYZ* tristimulus values of printed images ($X_1Y_1Z_1$) to predict *XYZ* tristimulus values of monitor images ($X_2Y_2Z_2$).

Table X. Color differences (ΔE_{94}) between visual and computed corresponding data for black and white colors.

		Black				White		
		1–6	3–3	5–6	6–6	1–4	1–2	5–5
Cond.	Matrix	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}
A	$\mathbf{M}_{CAT02}$	12.1	14.5	0.5	3.6	15.2	14.8	17.4
	$\mathbf{M}_{SHARP}$	12.1	14.5	0.5	3.8	15.2	14.7	17.4
	$\mathbf{M}_{HPE}$	9.3	14.7	3.8	14.5	20.1	20.1	22.1
	$\mathbf{M}_{NEW}$	12.7	14.5	2.4	3.8	15.6	14.7	17.4
B	$\mathbf{M}_{CAT02}$	11.8	15.4	3.6	6.9	16.2	13.7	17.5
	$\mathbf{M}_{SHARP}$	11.8	15.4	3.6	7.1	16.2	13.6	17.5
	$\mathbf{M}_{HPE}$	8.9	15.2	4.4	15.8	21.8	20.1	21.8
	$\mathbf{M}_{NEW}$	12	15.4	3.7	7.1	16.4	13.8	17.4
C	$\mathbf{M}_{CAT02}$	8.8	11.3	6.4	9.1	17.1	16.3	17
	$\mathbf{M}_{SHARP}$	8.8	11.3	6.4	9.2	17.1	16.2	17
	$\mathbf{M}_{HPE}$	5.6	9	7	16.3	22.5	20.8	21
	$\mathbf{M}_{NEW}$	9	11.2	6.2	9.1	17.3	16.3	17

Table XI. Color differences (ΔE_{94}) between visual and computed corresponding data for green, neutrals, red, yellow, and orange colors.

		Green		Neutral			Red		Yellow	Orange
		4–2	4–5	2–1	3–1	1–7	6–2	5–8	5–3	5–4
Cond.	Matrix	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}	ΔE_{94}
A	$\mathbf{M}_{\mathrm{CAT02}}$	14.3	11.6	0.5	9.8	8.3	8.1	5.9	10.2	12.8
	$\mathbf{M}_{\mathrm{SHARP}}$	14.6	11.7	0.5	9.8	9.3	7.9	5.8	10.3	12.7
	$\mathbf{M}_{\mathrm{HPE}}$	15.3	13.8	3.8	16.6	12.1	9.7	7.1	11.5	12.7
	$\mathbf{M}_{\mathrm{NEW}}$	13	12	2.4	9.9	9.2	9.3	9.5	10.3	15
B	$\mathbf{M}_{\mathrm{CAT02}}$	12.8	11.2	3.6	11.3	7.8	4.1	4.9	10.2	9.7
	$\mathbf{M}_{\mathrm{SHARP}}$	13.1	11.3	3.6	11.3	8.5	3.8	4.8	10.3	9.7
	$\mathbf{M}_{\mathrm{HPE}}$	13.9	13.3	4.4	17.4	11.2	5.7	4.9	12.4	8.9
	$\mathbf{M}_{\mathrm{NEW}}$	11.9	11.7	3.7	11.5	8.5	5.1	8.5	10.1	12.2
C	$\mathbf{M}_{\mathrm{CAT02}}$	15.1	12.2	6.4	8.7	10.7	5.8	4.5	9.7	11.4
	$\mathbf{M}_{\mathrm{SHARP}}$	15.2	12.2	6.4	8.7	11.5	5.6	4.4	9.9	11.3
	$\mathbf{M}_{\mathrm{HPE}}$	14.5	13.4	7	14.9	14.5	7.4	5.5	11.3	10.8
	$\mathbf{M}_{\mathrm{NEW}}$	13.5	12.1	6.2	9	11.5	5.3	7.5	9.8	13

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \mathbf{M}^{-1}\mathbf{M} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{4.5}$$

Predicted data using $\mathbf{M}_{\mathrm{SHARP}}$, $\mathbf{M}_{\mathrm{CAT02}}$, and $\mathbf{M}_{\mathrm{HPE}}$ were compared with data obtained from visual matching experiment. The difference between the experimental and predicted data was smallest for SHARP transform (Tables IX–XI) for the most colors and all viewing conditions. SHARP transform is able to predict accurately corresponding colors for almost all colors and shows better agreement with visual data than CAT02 and HPE transforms. Results of our experiment show that accuracy of SHARP transform should be improved for blue and black region. Therefore, we decided to modify SHARP transform to obtain improved agreement with corresponding data from visual experiment in blue and neutral color regions. Our modification includes scaling of SHARP transform by taking into consideration the influence of media and surround luminance white points. The resulting transform is:

$$\mathbf{M}_{\mathrm{NEW}} = \mathbf{M}_{\mathrm{SHARP}}\mathbf{D} \tag{4.6}$$

where $\mathbf{D}$ is the diagonal scaling matrix formed from the ratios of two white point vectors $[X_w^{65}\, Z_w^{65}][X_w^{50} Z_w^{50}]$ and different luminance $[L^{65}\, L^{50}]$ that are shown in Table II. Matrix $\mathbf{D}$ is defined as

$$\mathbf{D} = \begin{vmatrix} X_{\mathrm{R}}/X_{\mathrm{T}} & 0 & 0 \\ 0 & L_{\mathrm{R}}/L_{\mathrm{T}} & 0 \\ 0 & 0 & Z_{\mathrm{R}}/Z_{\mathrm{T}} \end{vmatrix} \tag{4.7}$$

where index R is referred on monitor viewing condition (D65 and L_{R}) and index T on print viewing condition (D65 and L_{T}). The new transform becomes:

$$\mathbf{M}_{\mathrm{NEW}} = \begin{vmatrix} 1.2694 & -0.0988 & -0.1706 \\ -0.8364 & 1.8006 & 0.0357 \\ 0.0297 & -0.0315 & 1.0018 \end{vmatrix} \times \begin{vmatrix} 0.9858 & 0 & 0 \\ 0 & 0.3547 & 0 \\ 0 & 0 & 1.3199 \end{vmatrix} \tag{4.8}$$

$$\mathbf{M}_{\mathrm{NEW}} = \begin{vmatrix} 1.2514 & -0.0353 & -0.2252 \\ -0.8245 & 0.6435 & 0.0471 \\ 0.0293 & -0.0113 & 1.3223 \end{vmatrix} \tag{4.9}$$

V. RESULTS

After transform evaluation, corresponding data were computed using $\mathbf{M}_{\mathrm{CAT02}}$, $\mathbf{M}_{\mathrm{SHARP}}$, $\mathbf{M}_{\mathrm{HPE}}$, and $\mathbf{M}_{\mathrm{NEW}}$. The results of transforms were compared with the corresponding-visual data obtained from visual matching. The colorimetric differences are presented in Tables IX–XI, where image and field numbers specified below color name locate this color in tested images.

The results show that proposed CAT predicts slightly different colors than $\mathbf{M}_{\mathrm{SHARP}}$ and $\mathbf{M}_{\mathrm{CAT02}}$. Using the new transform color differences are decreased for cyan, green, blue, and black colors. Green and blue colors are important for obtaining corresponding data for complex images because those colors belong to memory colors (colors of sky and grass). For other colors, the proposed transform show similar characteristics as $\mathbf{M}_{\mathrm{SHARP}}$ and $\mathbf{M}_{\mathrm{CAT02}}$. $\mathbf{M}_{\mathrm{HPE}}$ transform gives different corresponding data than other transforms in neutral colors and cyan. It results in larger color difference between calculated corresponding colors and those obtained from visual experiment.

VI. CONCLUSION

This article presents results of visual matching experiment between printed color images and images displayed on a monitor under different viewing conditions. To preserve the same color appearance on both media, observers adjusted image displayed on monitor as follows:

- black and white become more saturated and lighter,
- the light colors that are close to neutrals become more saturated,
- the dark colors that are close to neutrals become darker and less saturated,
- yellow, orange, and brown colors become less saturated.

Color appearance in blue, red, and cyan areas show small differences in lightness and chroma between the two media. We noticed that color difference ΔE_{00} is not appropriate for evaluation of corresponding colors obtained from matching between images displayed on different media. Our results show that the color difference ΔE_{94} is appropriate in experiments that include different media. For this type of experiment ΔE_{94} gives good result for the most colors and viewing conditions. The smallest ΔE_{94} was obtained for viewing condition B that incorporates matching in dim room and gray background on image display.

The results of the experiment were used to evaluate different CAT: SHARP, CAT02, and HPE. These transforms were applied to *XYZ* tristimulus values of printed images to predict *XYZ* tristimulus values of monitor images. Predicted data were compared with data obtained from visual matching experiment. The difference between the experimental and predicted data was smallest for SHARP transform for the most colors and all viewing conditions. But, for the same viewing conditions the SHARP transform can not predict accurately corresponding colors for blue and black regions. The proposed transform, based on the SHARP transform, includes influence of white point of both media and surround luminance in CAT equation. The proposed CAT shows better characteristics than other transforms for cyan, green, blue, and black colors and slightly differs from other CATs for the rest of the colors.

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