The Effect of Gray Balance and Tone Reproduction on Consistent Color Appearance

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Keywords

Consistent color appearance, gray balance, tone reproduction, color difference, 95th percentile ΔE_{00}, reference printing conditions

Abstract

CMYK pictorial color images, when output to ISO 15339-2 CRPC1~CRPC7 reference printing conditions, are said to have consistent or common color appearance despite their colorimetric differences in white point and gamut volume. However, the concept of consistent color appearance and its enablement through CRPCs have not been experimentally validated. This research, as a part of the CIE TC8-16 on Consistent Color Appearance, explores the effects of gray balance and tone reproduction as underlying criteria of this attribute.

The experiment involves altering the chosen CRPC reference dataset with known colorimetric differences, generating ICC profiles and preparing pictorial color images in the altered printing conditions and conducting psychometric evaluations. In the experiment, we used the CRPC4 dataset as the reference printing condition to print eight CMYK SCID images and their alterations. For each scene, two alterations of gamut volume are created as control datasets resulting in small and large gamut volume conditions that differ from the CRPC4 reference by 4-5 ΔE_{00} at the 95th percentile, used as the measure of colorimetric differences between datasets. In addition to the gamut volume alterations, two additional alterations are created by modifying either gray balance or tone reproduction, whereby those alterations differ by 4-5 ΔE_{00} at the 95th percentile with the primaries held constant. The research question was formulated as follows: "Will color images with similar colorimetric changes in gamut volume without alterations of GB and TR be perceived as more consistent than similar colorimetric changes due to alterations of GB and TR?" During psychometric evaluations observers were presented two images with gamut alterations as end points. From a pair of images of the same scene randomly chosen among three alternatives: reference CRPC4, GB and TR altered images, they had to select one that yields more consistent color appearance for the entire triplet. In the second experiment, observers were asked to identify one image from the set of three test images: CRPC4 reference, GB and TR altered, to produce the highest color consistency among eight images of different scenes wherein seven of them were produced using CRPC4 reference printing conditions.

The results show that consistent color appearance of images of the same scenes, reproduced in multiple printing conditions, depends on gray balance and tone reproduction. In addition, consistent color appearance of multiple scenes, reproduced in one printing condition, also depends on similar gray balance and tone reproduction.

Introduction

Color characterization datasets are resulted from color characterization targets, e.g., ISO 12642-2, IT8.7/4, TC1617, etc. Color reproduction is tied to color characterization dataset. CMYK image files, when output to ISO 15339-2 Characterized Reference Printing Conditions (CRPCs), appear to have consistent or common color appearance (CCA) despite their differences in gamut volume and white point. Figure 1 is a visual simulation of pictorial color image reproduction in CRPC1~CRPC7 printing conditions.

CRPC1 CRPC2 CRPC3 CRPC4 CRPC5 CRPC6 CRPC7

Figure 1. Visual simulation of CRPC1~CRPC7

CIE Division 8 (Image Technology) proposed the study of "Consistent Color Appearance (CCA)" in 2016. Three definitions of "Consistent Color Appearance" were cited: (a) an image attribute which gives a sense of identity among a set of images which have different tone and color; (b) maintaining the color consistency of a document or image rendered on different printing systems or displays where one rendering serves as the reference; and (c) when color reproductions show the highest similarity between the display reference and each print, and across the set of prints, when viewed under a common viewing condition" (CIE DR8-13, Draft 5, 2016).

This research explores the effects of gray balance and tone reproduction as underlying criteria of consistent color appearance, i.e., a measure of visual consistency among multiple images (a) of the same scene reproduced in different reference printing conditions or (b) of different scenes in one reference printing condition.

"Consistent color appearance" is different from "color image match." As depicted in Table 1, these two terms differ in their definitions, reference conditions, and applications, and should not be mixed.

Table 1. Consistent color appearance and color image match

	Consistent Color Appearance	Color Image Match
Definition	A measure of visual consistency among multiple images (1) of the same scene reproduced in different reference printing conditions or (2) of different scenes in one reference printing condition	A measure of visual match between a reference image and a sample image of the same scene in the same viewing conditions
Reference(s)	Multiple reference printing conditions with similar tone and color characteristics, but different color gamut, e.g., CRPC1~CRPC7	A specified reference printing conditions, e.g., CRPC6
Applications	Product campaign whereby different printing processes and substrates are used for packaging, labeling, advertising, etc.	Color proofs used in commercial and publication printing

Pros and cons of CRPCs

ISO 15339-2 (2015), in support of printing from digital data across multiple technologies, specifies seven characterized reference printing conditions (CRPC1~CRPC7). These seven CRPCs, although differ in their gamut volumes (see Figure 2), have something in common, i.e., (a) CRPCs, having similar hue angles in primaries and two-color overprints, and (b) color images, separated for one of the CRPCs, can be printed in other CRPC printing conditions and preserve color appearance.

CRPC	CRPC name
1	ColdsetNews
2	HeatsetNews
3	PremUncoated
4	SuperCal
5	PubCoated
6	PremCoated
7	Extra Large

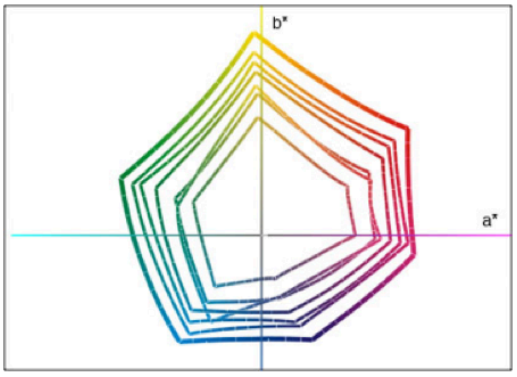

Figure 2. Naming and gamut size of CRPC1~CRPC7

In addition to similar CMYRGB hue angles, CRPC1~CRPC7 have similar gray balance. As shown in Figure 3, gray reproduction ramps of pre-defined CMY triplets are plotted with a* ramps (solid lines) and b* ramps (dotted lines) in the same color for each CRPC. Beginning with paper colors, all CRPCs show linear converging patterns toward the 100 CMY solid.

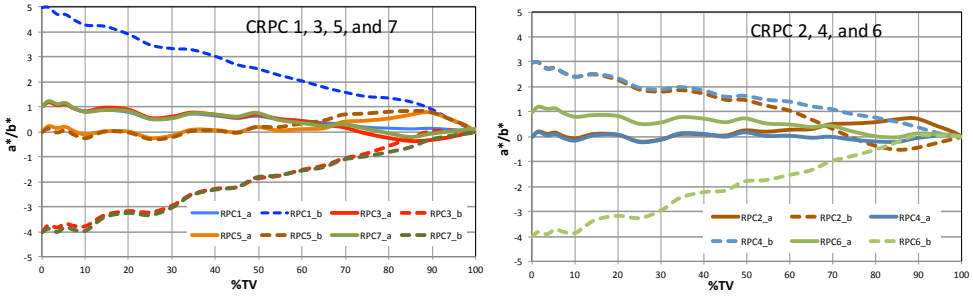

Figure 3. Gray balance characteristics of CRPC1~CRPC7

CRPC1~CRPC7 also have similar highlight-to-midtone tone reproduction. As shown in Figure 4, tone reproduction curves (TRCs) are expressed by plotting Darkness (100 - L*) vs. %TV (tone value) of the cyan. All CRPCs show similar highlight-to-midtone TRCs.

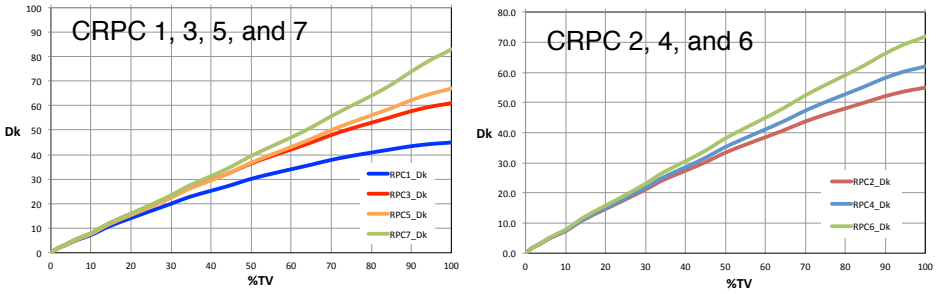

Figure 4. Tone reproduction characteristics of CRPC1~CRPC7

While there are many advantages to use CRPCs to study consistent color appearance, there is a disadvantage, i.e., the color differences between adjacent CRPC datasets are unequal. As shown in Table 2, the gamut volume difference between CRPC3 and CRPC4 (53%) is far greater than that of CRPC5 and CRPC6 (17%). As such, it has an adverse effect on consistent color appearance, as shown in Figure 1.

Table 2. Color differences between adjacent CRPC datasets

CRPC	Paper			C100			M100			Y100			K100			Gamut Volume	Gamut Volume Diff.
	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*	L*	a*	b*		
CRPC1	85	1	5	59	-24	-26	56	48	0	80	-2	60	37	1	4	84,280	80%
CRPC2	87	0	3	57	-28	-34	52	58	-2	82	-2	72	30	1	2	151,311	
ΔE00	2.5			3.7			4.9			3.3			5.9				
CRPC2	87	0	3	57	-28	-34	52	58	-2	82	-2	72	30	1	2	151,311	10%
CRPC3	95	1	-4	60	-26	-44	56	61	-2	89	-3	76	32	1	1	165,764	
ΔE00	8.4			4.8			3.9			4.7			1.8				
CRPC3	95	1	-4	60	-26	-44	56	61	-2	89	-3	76	32	1	1	165,764	53%
CRPC4	89	0	3	55	-36	-38	47	66	-3	83	-3	83	23	1	2	253,711	
ΔE00	7.7			7.0			9.0			4.2			6.8				
CRPC4	89	0	3	55	-36	-38	47	66	-3	83	-3	83	23	1	2	253,711	31%
CRPC5	92	0	0	57	-37	-44	48	71	-4	87	-4	88	19	0	1	331,416	
ΔE00	3.4			2.8			1.6			2.9			3.3				
CRPC5	92	0	0	57	-37	-44	48	71	-4	87	-4	88	19	0	1	331,416	17%
CRPC6	95	1	-4	56	-37	-50	48	75	-4	89	-4	93	16	0	0	389,023	
ΔE00	4.3			2.2			0.9			1.6			2.2				
CRPC6	95	1	-4	56	-37	-50	48	75	-4	89	-4	93	16	0	0	389,023	35%
CRPC7	97	1	-4	54	-42	-54	47	78	-10	90	-4	103	14	0	0	525,551	
ΔE00	1.2			2.6			2.5			2.0			1.3				

The 95th percentile ΔE_{00}, based on the cumulative relative frequency of ΔE_{00} and adopted by CGATS TR016 (2014), is a metric used to assess colorimetrical color difference and print conformance. As shown in Figure 5, CRF (Cumulative Relative Frequency of ΔE_{00}) and the 95th percentile ΔE_{00} between adjacent CRPCs are unequal. This suggests that test images should be prepared to have similar color differences, in terms of the 95th percentile ΔE_{00}, prior to psychometric experiments.

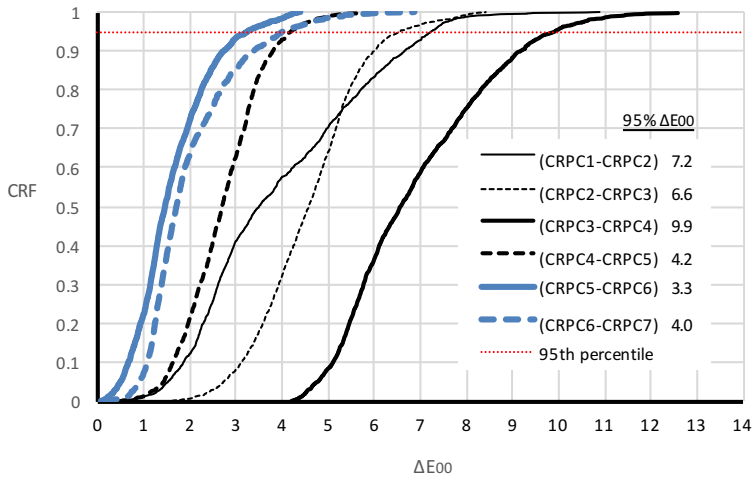

Figure 5. CRF and 95th percentile ΔE_{00} between adjacent CRPCs

Research Questions and Hypotheses

The research questions are (a) Does Consistent Color Appearance, CCA, of the same scene, reproduced in different printing conditions, depend on gray balance (GB) and tone reproduction (TR)? (b) Does CCA of multiple scenes, reproduced in one printing conditions, depend on TR and GB?

The research objectives are to devise a methodology, by using standard CMYK test images, multiple datasets, and psychometric experiments, to test that gray balance and tone reproduction are underlying criteria of consistent color appearance.

Specifically, the control datasets vary in gamut volume, but have similar hue angle, gray balance, and tone reproduction, thus simulating the concept behind CRPCs. The test datasets have the same gamut volume, but vary in gray balance and tone reproduction. We hypothesize that changes in gray balance and tone reproduction decrease consistency of color appearance of printed images.

Methodology

To investigate if consistent color appearance depends on gray balance (GB) and tone reproduction (TR), the following image preparation procedures were used and are summarized in Figure 6.

Scene	CRPC4 Alteration	95th Percentile ΔE_{00}
1~8 Plus TC1617	Varying gamut in control datasets; Varying GB or TR in test datasets	4.5 ± 0.5

Figure 6. A summary of the test stimuli preparation method

1) Select eight CMYK pictorial images.
2) Select CRPC4 as the reference and create two altered datasets, varying in gamut volume (Small and Large), without changing hue angle, GB and TR.
3) Create two more datasets from CRPC4 varying in TR and GB, without changing gamut volume.
4) The color difference between any dataset and CRPC4 is 4.5 +/- ΔE_{00} at the 95th percentile.
5) Create the test form (Figure 7) and output to Epson 4900 inkjet proofer.

Figure 7. Test form consisting of eight pictorial test images and TC1617

Subsequently, psychometric tests were conducted to evaluate consistency of color appearance of printed images, where observers were asked to select one image among several pairs to yield the best consistency of color appearance for a group of three images of the same scene in the first experiment, and a group of eight images of different scenes in the second experiment. The psychometric experiments are described in more detail in the sections below.

Results

Verification of test images

This section verifies how control datasets and test datasets are prepared according to the methodology. Figure 8 shows that the color gamuts of the control dataset (second left – Small and third left - Large) are varied and the color gamuts of test datasets are not altered.

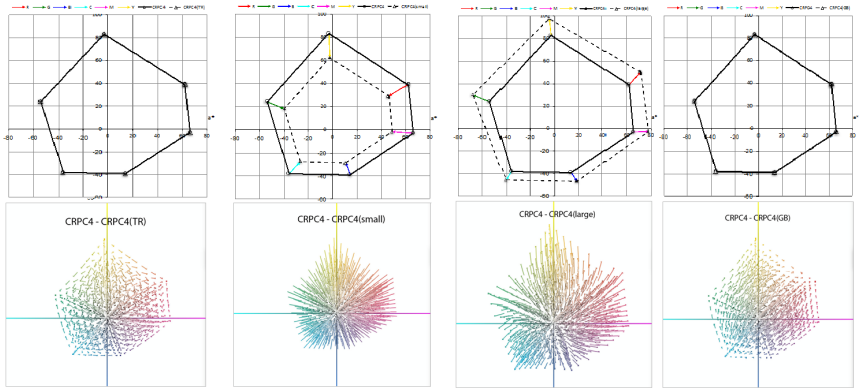

Figure 8. Color gamut of control datasets and test datasets

Figure 9 shows that the tone reproduction is varied for only the test dataset (leftmost TR) compared to others.

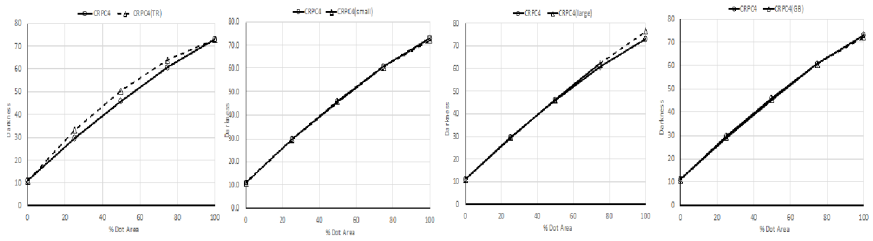

Figure 9. Tone reproduction of control datasets and test datasets

Figure 10 shows that the gray balance of only the test dataset (lower right - GB) is varied.

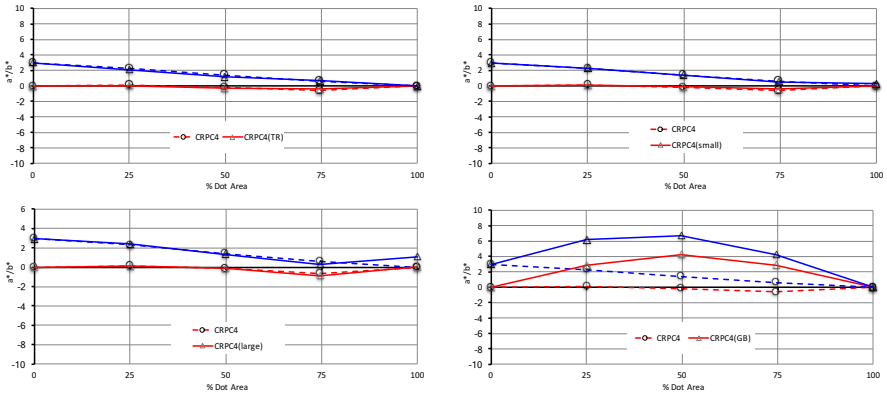

Figure 10. Gray balance of control datasets and test datasets

Figure 11 shows that the CRF and the 95th percentile ΔE_{00} of the four altered datasets. All four altered datasets meet the design criteria, i.e., 4.5 +/- 0.5 ΔE_{00} at the 95th percentile.

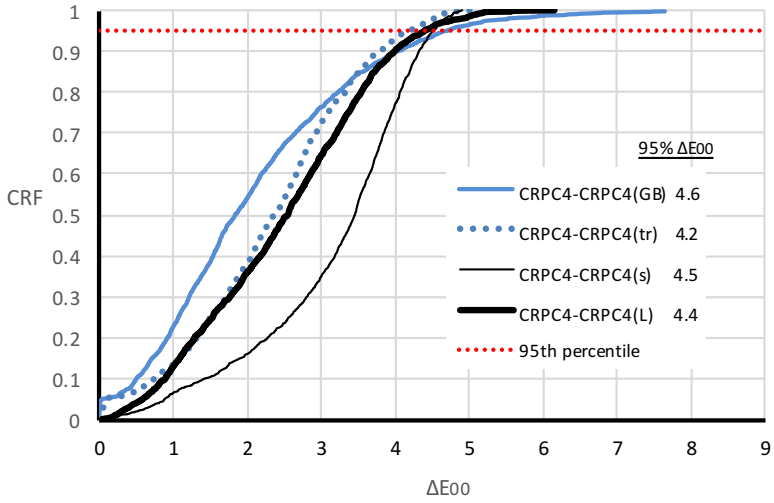

Figure 11. CRF and 95th percentile ΔE_{00} between CRPC4 and test datasets

Psychometric testing of CCA of the same scene

Figure 12 (left) depicts the scheme to test CCA for the images of the same scene. Observers are presented with two control images (blue), and a random selection of two out of 3 test images (yellow) differing in TR, GB or None (CRPC4), of the same scene. Observers are asked to select a test image that appears to yield more color consistency in the triplet. There are three pairs per scene. Eight scenes are tested. Figure 12 (right) shows how the test was conducted in standard viewing conditions. Paired comparison was used to analyze the psychometric data.

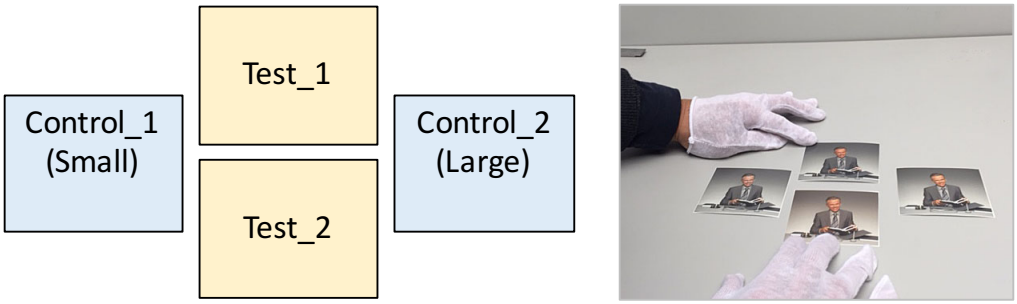

Figure 12. Psychometric testing of CCA of the same scene

Psychometric testing of CCA of multiple scenes

Figure 13 (left) depicts the scheme to test CCA of multiple scenes. Observers are presented with seven control images (blue) of different scenes. Observers are asked to select one of the three test images (yellow) that appears to yield more color consistency. Eight scenes are tested.

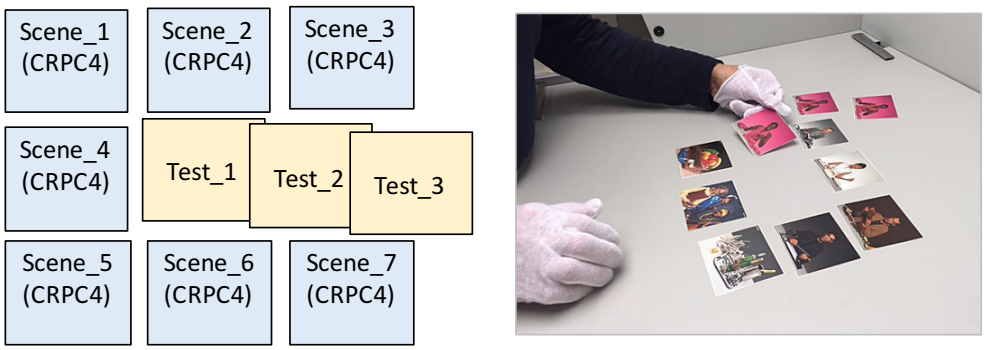

Figure 13. Psychometric testing CCA of multiple scenes

Twelve observers with normal color vision tested using Farnsworth-Munsell 100 hue test and normal visual acuity participated in both experiments. The tests were conducted under the standard lighting conditions using the ISO 3664 (2009) compliant viewing booth.

Color Consistency for Single Scene

For every scene, paired comparison data were collected as a 3x3 matrix across participants. Each location is the number of times the image in the jth column was chosen over the image in the ith row. For example, the CRPC4 image is chosen over the GB-altered image 34 times where the GB-altered image is chosen only twice over the CRPC4 image (see Figure 14).

Roman16_02_midtone

	GRAY BALANCE	TONE REPRODUCTION	CRPC4
GRAY BALANCE		29	34
TONE REPRODUCTION	7		33
CRPC4	2	3	

Figure 14. An example of paired comparison data

The choice frequency data were aggregated across all 8 scenes and the average rank was calculated for the three datasets representing an ordinal scale for the CCA for the three datasets: Gray Balance Altered, Tone Reproduction Altered and the CRPC4. The result, as shown in Figure 15, indicates that the CRPC4 image, GB- and TR-altered images have different ranks.

SCENE-BASED PAIRED COMPARISON

CHOICE FREQUENCIES COMBINED ACROSS SCENES

	GRAY BALANCE	TONE REPRODUCTION	CRPC4
GRAY BALANCE		190	264
TONE REPRODUCTION	98		255
CRPC4	24	33	
AVERAGE RANK	***0***	***1***	***2***

Figure 15. Average rank for ordinal CCA scale

Thurstone's Law of Comparative Judgment, Case V (Thurstone, 1927) was used to convert color consistency data from ordinal scale into interval scale. This involves (a) dividing frequencies by the number of observations and convert to proportions, (b) converting proportions to z-scores, and (c) calculating columns' mean to get scale values (Figure 16).

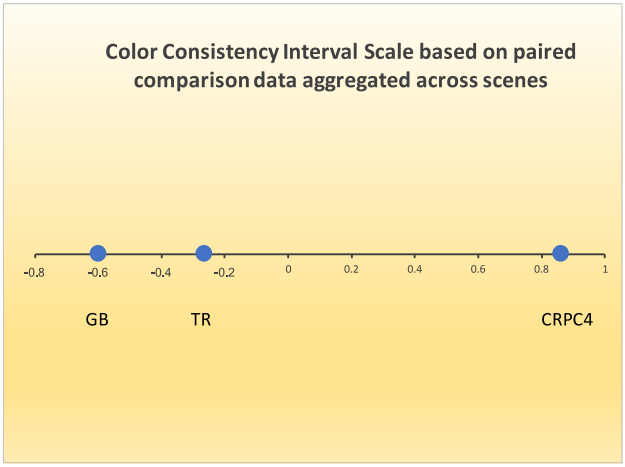

Figure 16. Color consistency scale

Now that color consistency data has been converted from ordinal scale into interval scale, we can study the relationship between color consistency data and the 95th percentile ΔE_{00}. As shown in Figure 17, color consistency lowers as the 95th percentile ΔE_{00} increases due to gray balance or tone reproduction alteration. Moreover, a nearly perfect linear relationship between the actual measured 95th percentile ΔE_{00} and consistency of color appearance among the tested images and corresponding printing conditions can be observed. Although the target 95th percentile ΔE_{00} was accomplished and verified to be within the desired range of 4.5 +/- 0.5 ΔE_{00}, small variations in this colorimetrically derived measure were reflected in the observed linearity. This result underscores the usefulness and the practical significance of the 95th percentile ΔE_{00} as a colorimetrically based measure of the print reproduction accuracy (conformance) adopted by CGATS TR016.

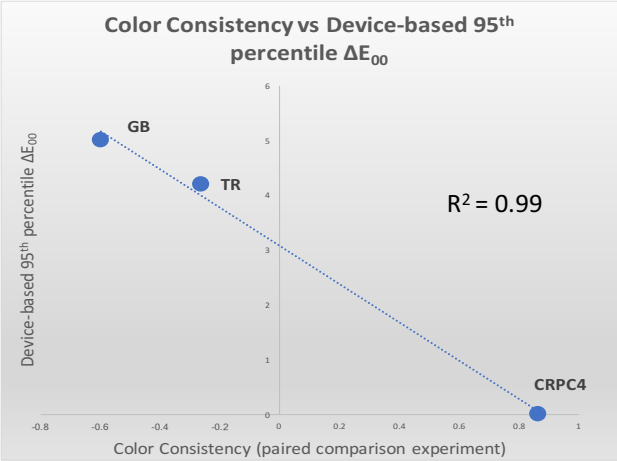

Figure 17. Color Consistency for single scene vs. the 95th percentile ΔE_{00}

Color Consistency for Multiple Scenes

The same data analysis technique was applied to color consistency for multiple scenes. As shown in Figure 18, color consistency decreases as the 95th percentile ΔE_{00} increases due to gray balance or tone reproduction alteration. Similar to the previous results, there is a linear relationship between the scaled color consistency and the 95th percentile ΔE_{00}.

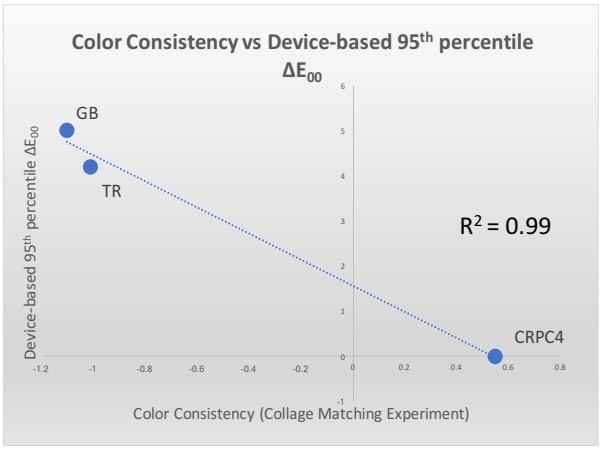

Figure 18. Color Consistency for multiple scenes vs. device-based 95th percentile ΔE_{00}

In both experiments images printed using the CRPC4 reference printing condition were chosen as providing a more consistent color appearance impression compared to the images produced with the gray balance or tone reproduction alterations, supporting our original hypothesis.

Conclusions

Consistent color appearance of images of the same scenes, reproduced in multiple printing conditions, depends on gray balance and tone reproduction. If tone reproduction and gray balance deviate from the reference (CRPC4), CCA significantly decreases. In addition, consistent

color appearance of multiple scenes, reproduced in one printing condition, also depends on similar gray balance and tone reproduction. Observers were able to group different scenes based on the uniformity of gray balance and tone reproduction.

Further Research

The 95th percentile ΔE_{00}, derived from the color characterization target is device dependent. Although the device-based 95th percentile ΔE_{00} is shown to be a good predictor for consistent color appearance in the present experiment, the device-based 95th percentile ΔE_{00} is scene independent. At the same time images with color distributions significantly different from the datasets can be differently affected by printing conditions. This may not be captured in the present study. Additionally, the psychometric testing that is done separately for each scene, as in the first experiment, can be prone to contextual effects. That is, it may reveal relationships within each scene, but not between the scenes. To overcome the limitation of two alterations for each reproduction parameter, multiple gradations of gamut volume and gray balance and tone reproduction changes using reference CRPCs and comparisons between difference scenes must be used. Our further research should explore image-based metric, for example, a scene-dependent 95th percentile ΔE_{00} as a predictor of consistent color appearance.

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