

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

RIT approach



Contributors

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Outline

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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.
 - CIE Division 8 (Image Technology) proposed the study of “Consistent Color Appearance (CCA)” in 2016.
 - CIE TC 8-16 Consistency of Colour Appearance within a Single Reproduction Medium
- This research explores the effects of gray balance and tone reproduction as underlying criteria of consistent color appearance.



Visual Simulation of CRPC1~CRPC7



Consistent (Common) Colour Appearance

- CCA Definitions (CIE DR8-13, Draft 5, 2016)
 - An image attribute which gives a sense of identity among a set of images which have different tone and color.
 - Maintaining the color consistency of a document or image rendered on different printing systems or displays where one rendering serves as the reference.
 - 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, they have, by definition, a "consistent color appearance". Similarity is judged by subjective assessment.

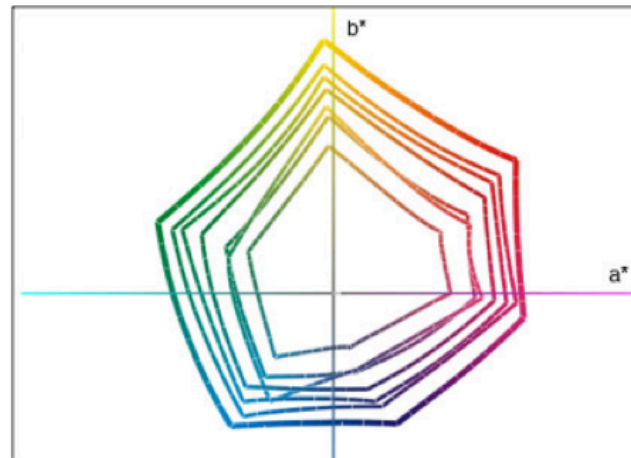
CCA vs. Color Image Match

	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 condition, 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

Theoretical Basis

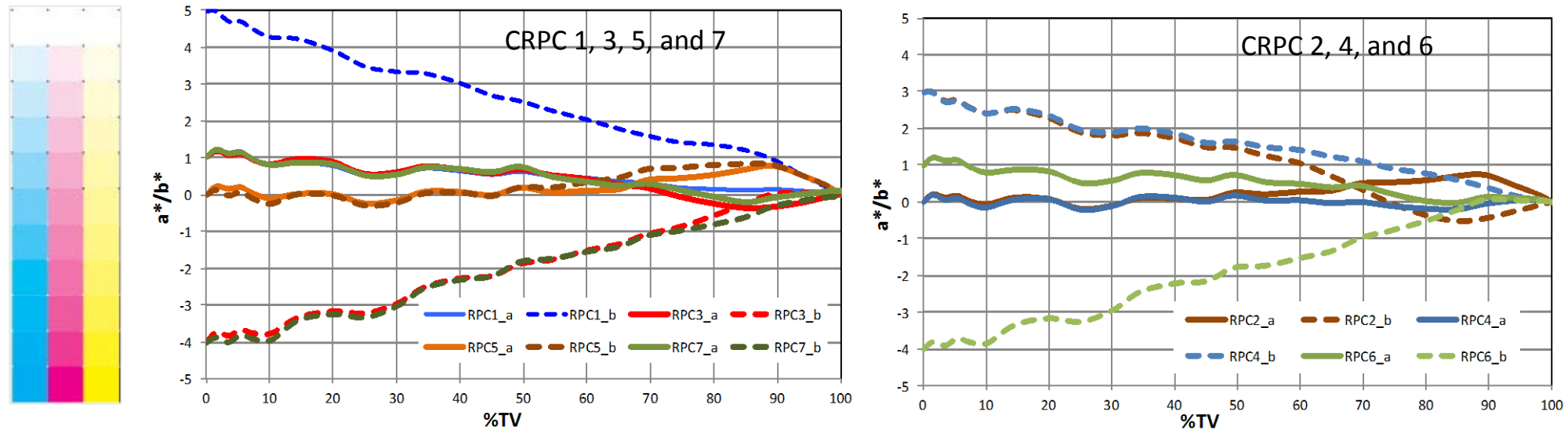
- ISO 15339-2 (2015), in support of printing from digital data across multiple technologies, specifies seven characterized reference printing conditions (CRPC1 ~ CRPC7).
 - CRPCs, having **similar hue angles** in primaries and two-color overprints, are suitable for calibrating CMYK output devices.
 - 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



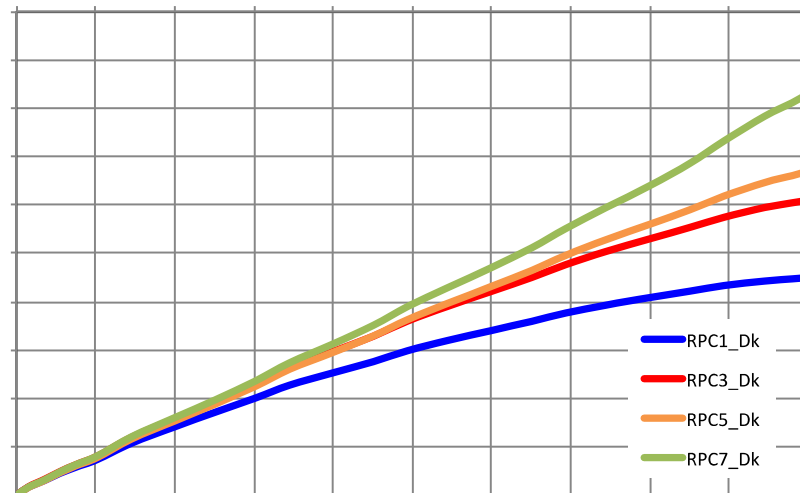
Theoretical Basis

- In addition to similar CMYRGB hue angles, CRPC1~CRPC7 have similar gray balance.
 - 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.



Theoretical Basis

- CRPC1~CRPC7 also have similar highlight-to-midtone tone reproduction.
 - Tone reproduction curves (TRCs) are expressed by plotting Darkness ($100 - L^*$) vs %TV of the cyan. These curves are known as NPDC according to G7 terminology.
 - All CRPCs show similar highlight-to-midtone TRCs.



CRPC 2, 4, and 6

4_Dk
RPC6_Dk

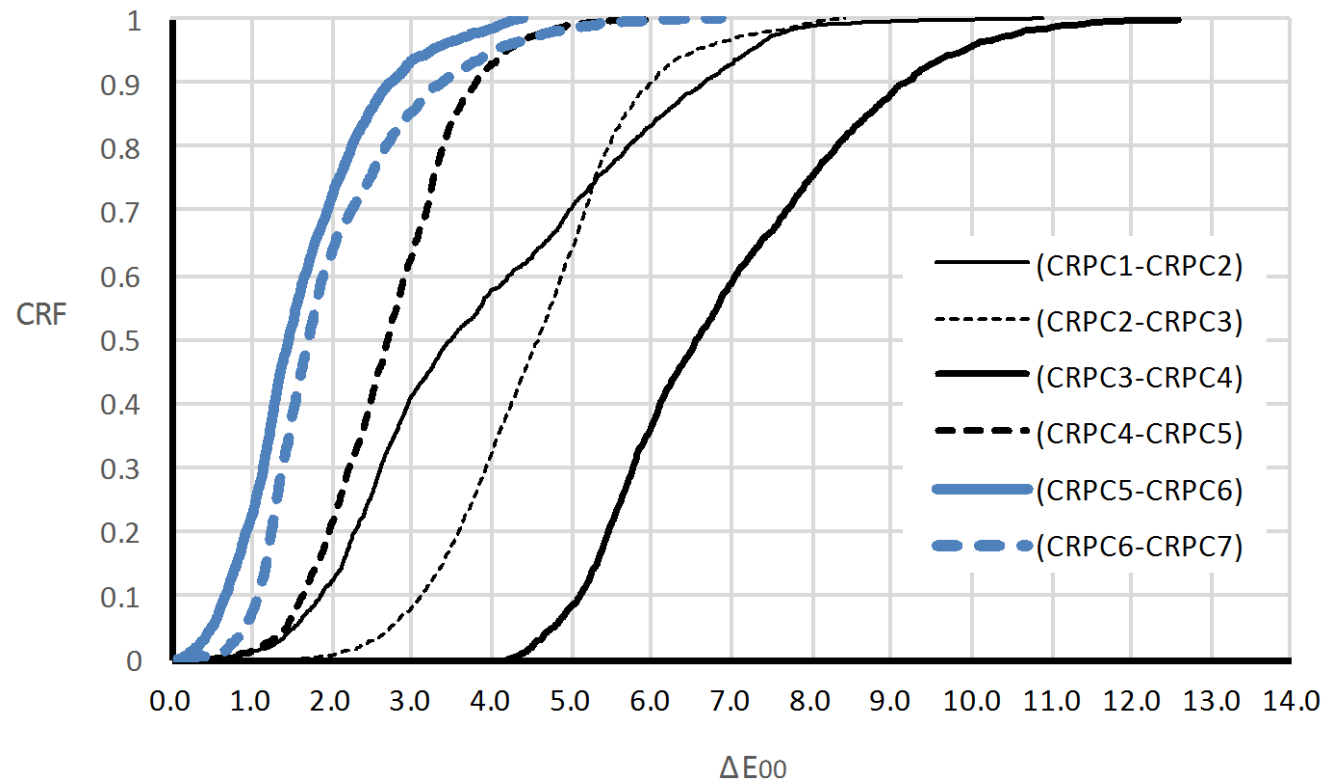
Theoretical Basis

- Adjacent CRPCs, in terms of paper, solids, and gamut volume, are unequal.

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	
ΔE_{ab}	3.0			9.2			11.0			12.2			7.3				
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	
ΔE_{ab}	10.7			10.6			5.0			8.1			2.2				
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	
ΔE_{ab}	9.3			12.7			10.3			9.2			9.1				
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	
ΔE_{ab}	4.2			6.4			5.2			6.5			4.2				
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	
ΔE_{ab}	5.1			6.1			4.0			5.4			3.2				
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	
ΔE_{ab}	2.0			6.7			6.8			10.0			2.0				

Theoretical Basis

- CRF (Cumulative Relative Frequency of ΔE_{00}) and the 95th percentile ΔE_{00}^{\ddagger} between adjacent CRPCs are unequal.



95th percentile ΔE_{00}	
CRPC1-CRPC2)	7.24
CRPC2-CRPC3)	6.56
CRPC3-CRPC4)	9.86
CRPC4-CRPC5)	4.18
CRPC5-CRPC6)	3.26
CRPC6-CRPC7)	4.03

\ddagger CRF and the 95th percentile ΔE_{00} are adopted by CGATS TR016 to assess colorimetric color difference and print conformance.

Pros and Cons of ISO 15339-2 CRPCs

- Pros of CRPC1~CRPC7
 - Have different color gamuts, but with similar hue angles of primaries and two-color overprints
 - Similar gray balance and tone reproduction characteristics
- Cons of CRPC1~CRPC7
 - The color difference between adjacent CRPC datasets, in terms of gamut volume and 95th percentile ΔE_{00} , are unequal.

Research Questions and Objectives

- Research Questions

- Does Consistent Color Appearance, CCA, of the same scene, reproduced in different reference printing conditions, depend on gray balance (GB) and tone reproduction (TR)?
- Does CCA of multiple scenes, reproduced in one reference printing conditions, depend on TR and GB?

- Research Objectives

- Devise a methodology, by using standard CMYK test images, multiple datasets, and psychometric experiments, to test that TR and GB are underlying criteria of CCA

Hypothesis

- Changes in gray balance and tone reproduction decrease consistency of color appearance of printed images
- There is significant difference in consistency of color appearance between the control datasets (images stemmed from datasets that vary in gamut volume) and the test datasets (images stemmed from datasets that vary in gray balance and tone reproduction).

Note 1: The control datasets vary in gamut volume, but have similar hue angle, gray balance, and tone reproduction.

Note 2: The test datasets have the same gamut volume, but vary in gray balance and tone reproduction, in relation to one of the control datasets.

First Experiments

Methodology

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 $4.5 \Delta E_{00}$ at the 95th percentile.
5. Output device: Epson 4900 inkjet proofer

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

Eight CMYK Pictorial Images

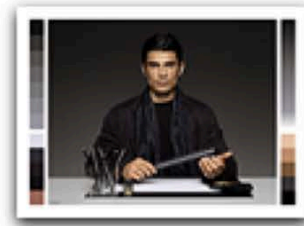
- Roman 16 CMYK



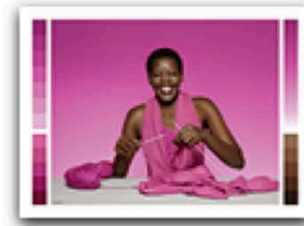
roman16_01_highkey.tif



roman16_02_midtone.tif



roman16_03_lowkey.tif



roman16_05_magenta.tif

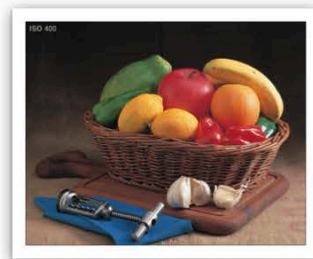


roman16_11_brown.tif

- ISO 12640 CMYK



N7.TIF



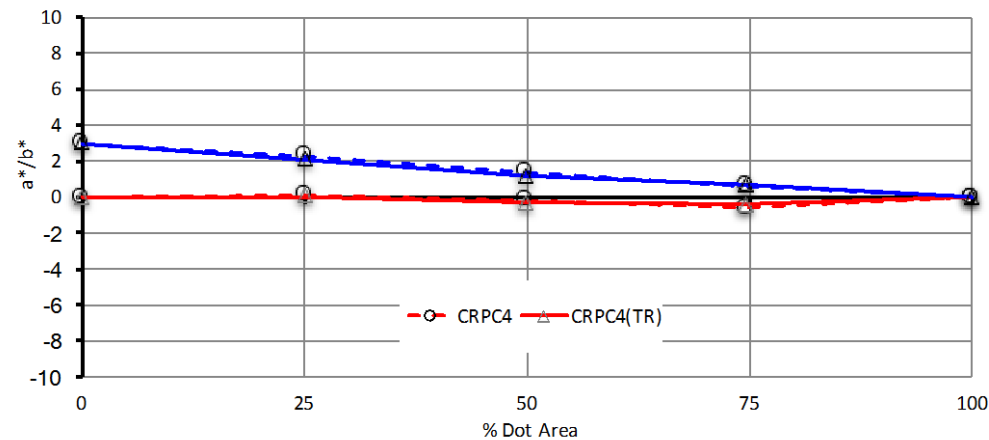
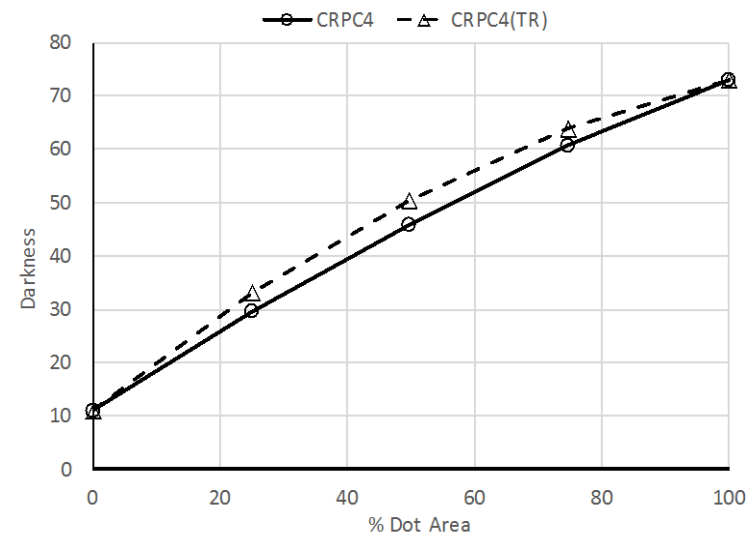
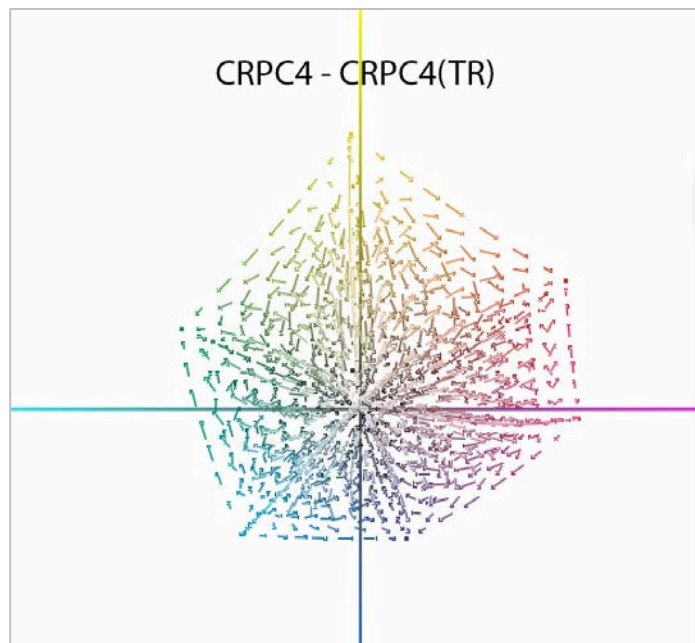
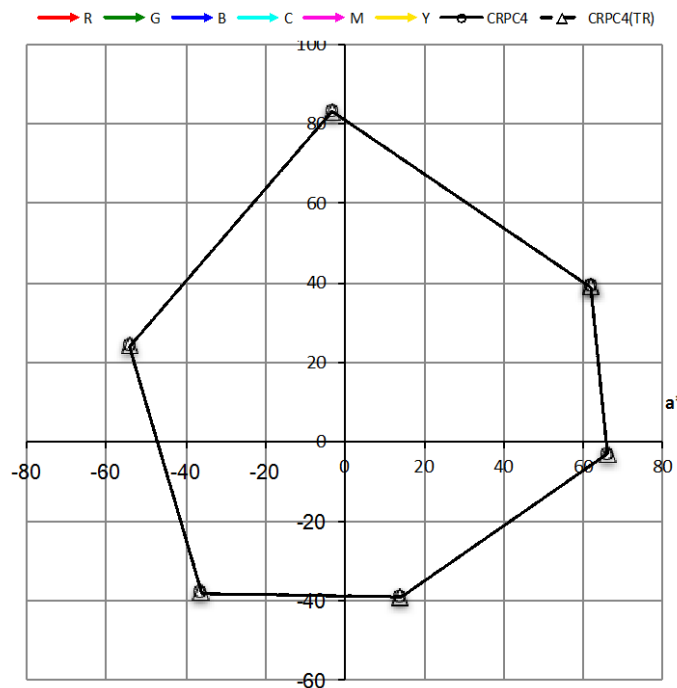
N3.TIF



N4A.TIF

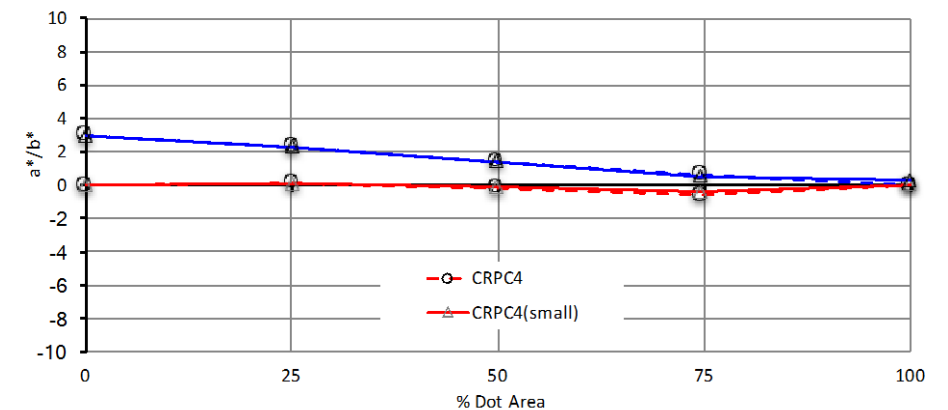
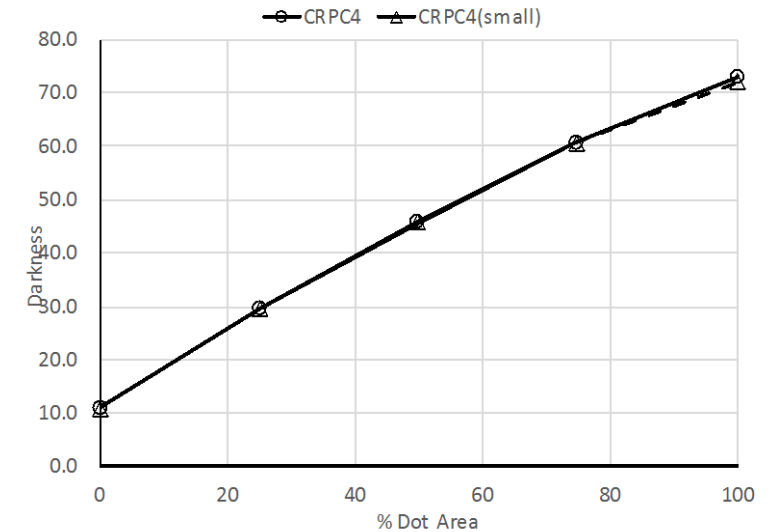
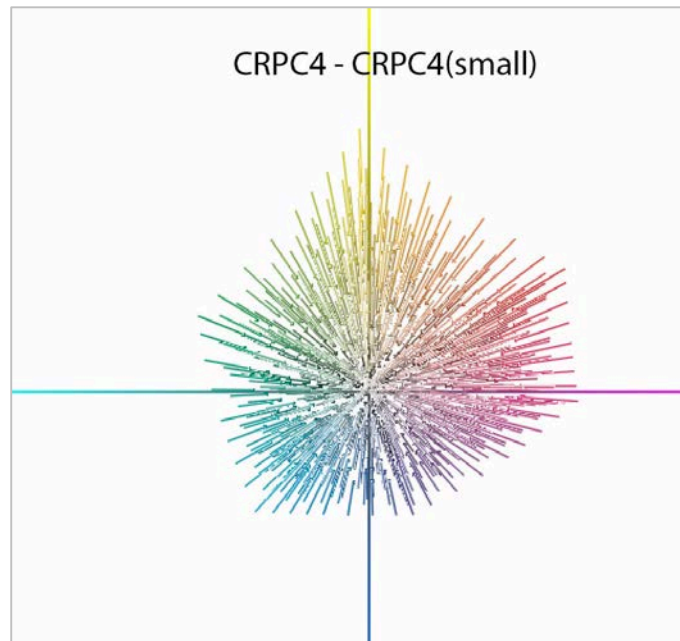
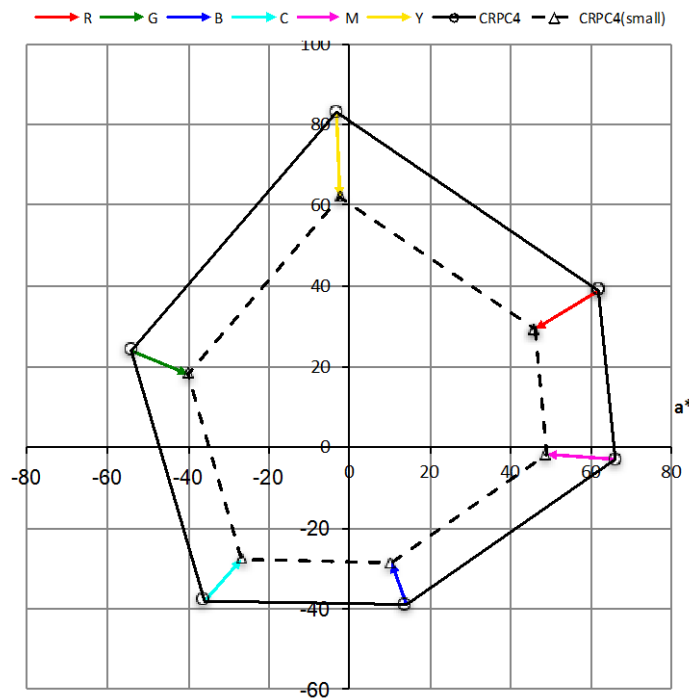
Verify the Altered Dataset to CRPC4

- CRPC4 vs. CRPC4 (Tone reproduction altered)
 - Different tone reproduction
 - Same gamut volume, 95th percentile ΔE_{00} , and gray balance



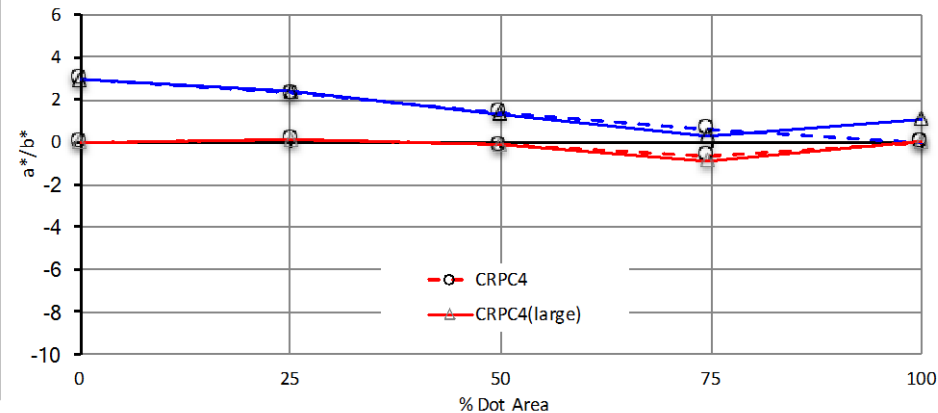
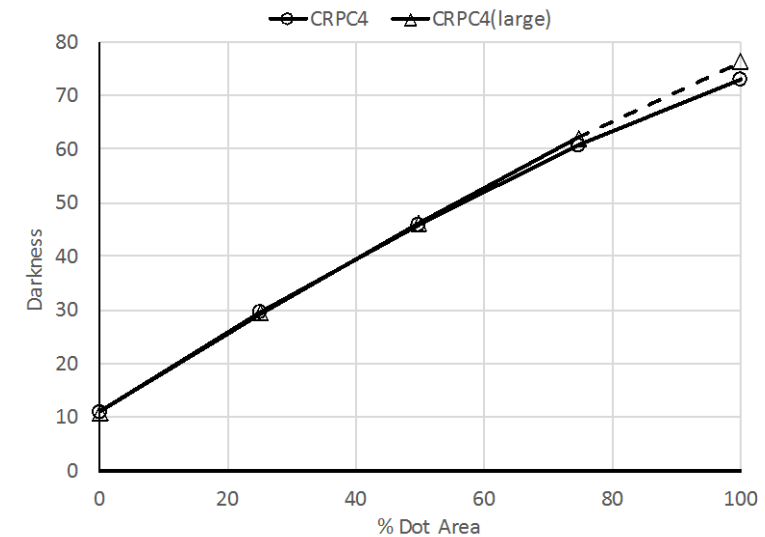
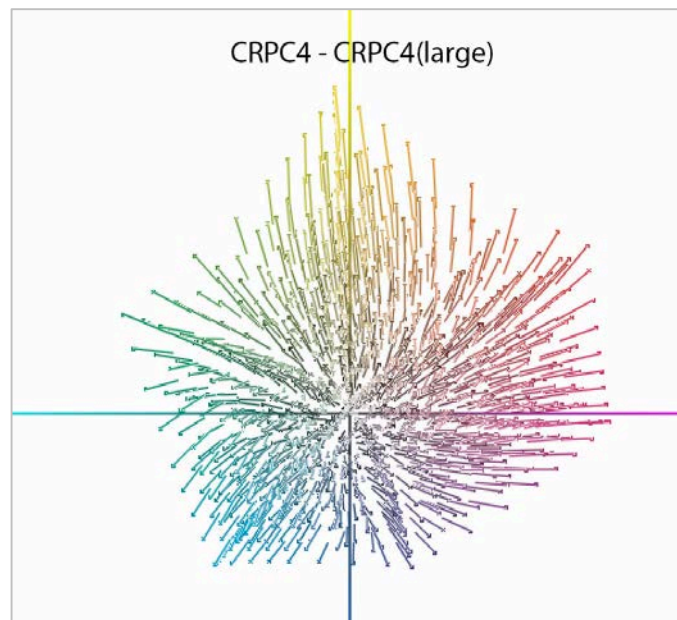
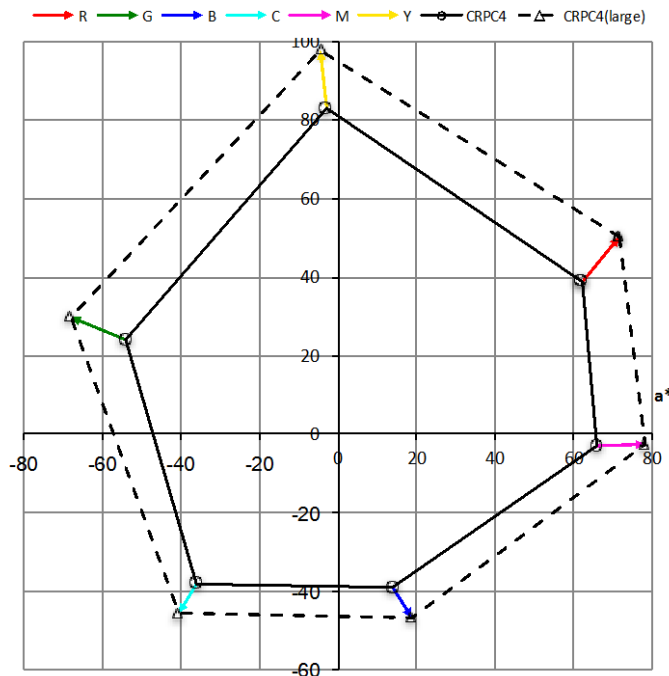
Verify the Altered Dataset to CRPC4

- CRPC4 vs. CRPC4 (Small)
 - Different gamut volume
 - Same 95th percentile ΔE_{00} , tone reproduction, and gray balance [Darkness = $100 - L^*$]



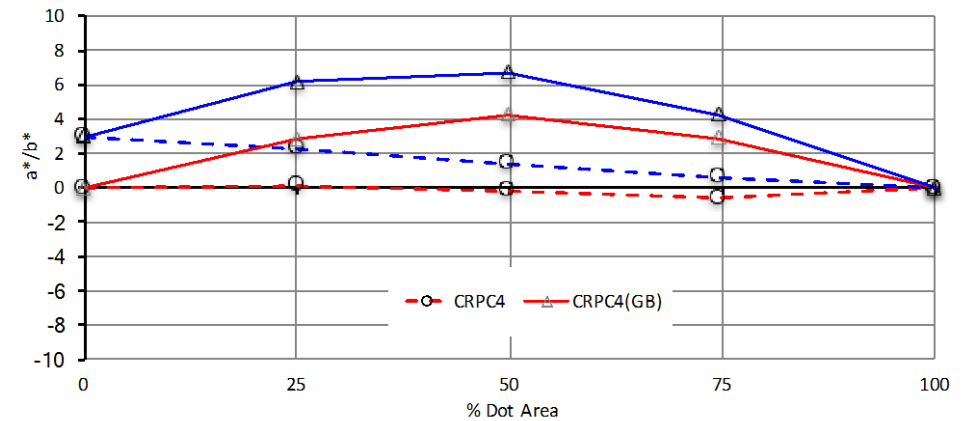
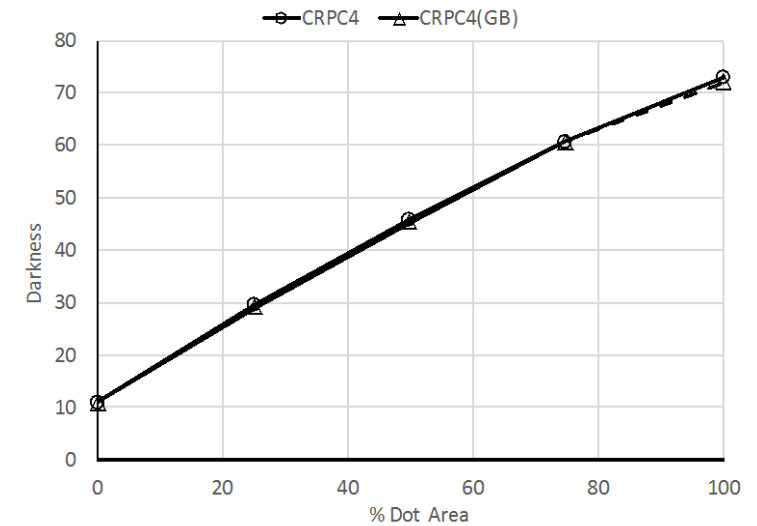
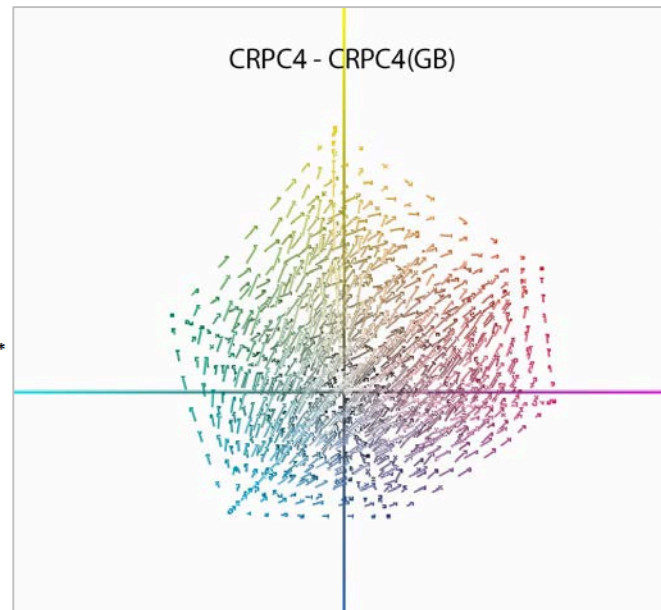
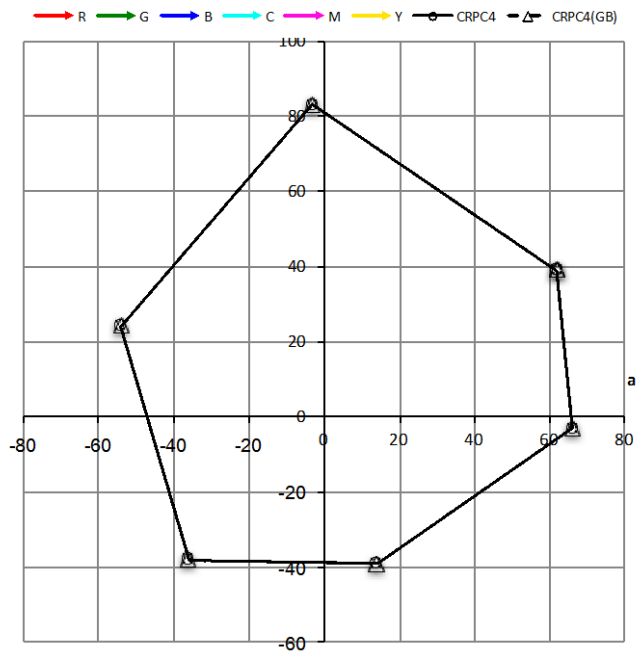
Verify the Altered Dataset to CRPC4

- CRPC4 vs. CRPC4 (Large)
 - Different gamut volume
 - Same 95th percentile ΔE_{00} , tone reproduction and gray balance



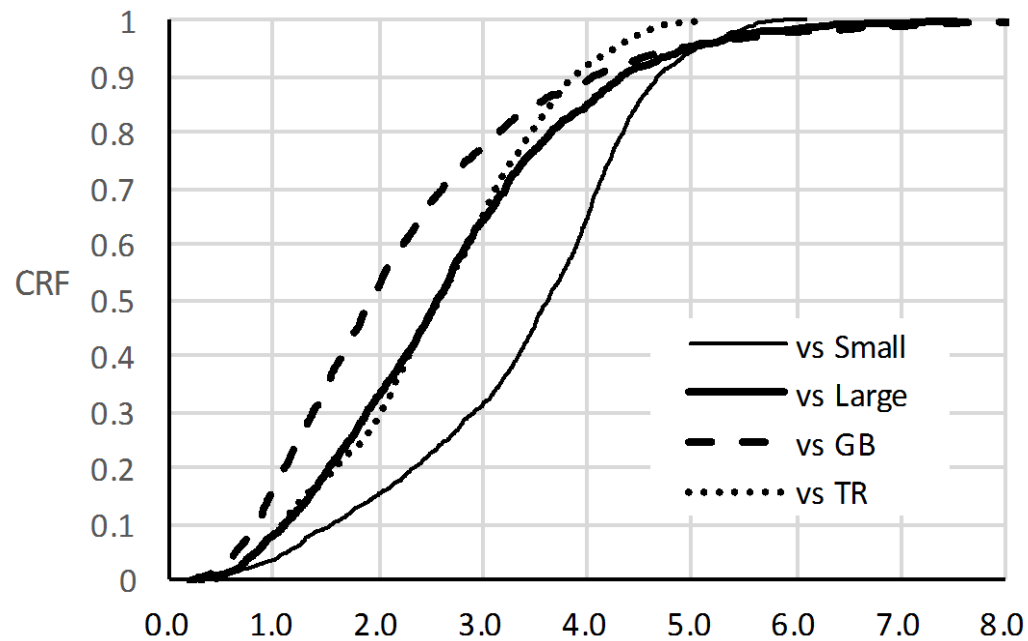
Verify the Altered Dataset to CRPC4

- CRPC4 vs. CRPC4 (Gray balance altered)
 - Different gray balance
 - Same gamut volume, 95th percentile ΔE_{00} , and tone reproduction



Verify the Altered Datasets to Epson-CRPC4

- The CRF and the 95th percentile ΔE_{00} of the four altered datasets are shown below:



CRPC4 Alteration	95 th Percentile ΔE_{00}
Small	4.5
Large	4.3
TR	4.2
GB	5.0

- All four altered datasets meet the design criteria, i.e., $4.5 \pm 0.5 \Delta E_{00}$ at the 95th percentile.

Verify Image-based 95th Percentile ΔE_{00}

- Device-based 95th percentile ΔE_{00} is scene independent.
 - The average (yellow highlighted) between the four altered datasets and CRPC4 is 4.5 with a range of 0.8 (4.2~5.0).
 - The GB altered sample shows larger value (5.0).
- Image-based 95th percentile ΔE_{00} is scene dependent.
 - The dataset and the scene contribute to the 95th percentile ΔE_{00} metric.

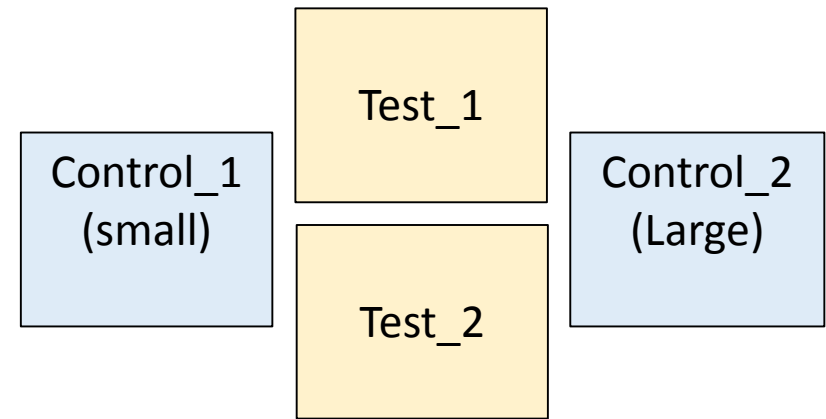
	ΔE_{00} at 95th percentile vs Epson-CRPC4 profile			
	Control Dataset Reduced	Control Dataset Expanded	Alteration TR 4.2	Alteration GB 5.0
Scene 1_Roman16_11_brown	4.0	4.1	3.7	5.6
Scene 2_Roman16_05_magenta	4.3	3.9	3.2	4.4
Scene 3_Roman16_03_lowkey	2.7	3.9	3.4	5.6
Scene 4_Roman16_02_midtone	2.5	3.2	4.2	6.0
Scene 5_Roman16_01_highkey	3.9	2.4	3.8	5.6
Scene 6_N7	4.3	4.0	4.0	4.9
Scene 7_N4A	3.3	3.5	4.3	5.7
Scene 8_N3	4.4	4.4	4.5	4.4
Ave.	3.7	3.7	3.9	5.3
Range	1.9	2.0	1.3	1.6
Device_TC1617	4.5	4.3	4.2	5.0

- The GB altered sample also show a larger average of 5.3 with a range of 1.6 in terms of the 95th percentile ΔE_{00} metric.

Exp #1 – Does CCA of the Same Scene Depend on TR and GB?

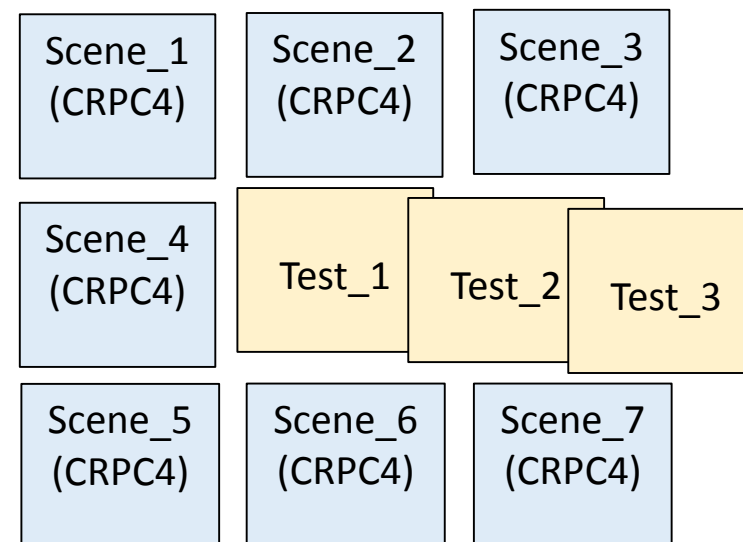
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- Observers are presented with two control images (blue), and two of 3 test images (yellow) differing in TR, GB or None, of the same scene.
- Observers are asked to select a test image that appears to yield more color consistency in the triplet.
- There are three pairs per scene.
- Eight scenes are tested.



Exp #2 – Does CCA of Multiple Scenes Depend on TR and GB?

- 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.
- 12 Observers participated in both experiments



Results — Paired Comparison

- 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 j^{th} column was chosen over the image in the i^{th} 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.



Roman16_02_midtone

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

Results– Average Rank for Ordinal CCA scale

- 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.
 - It indicates that the CRPC4 image, GB- and TR-altered images have different ranks.

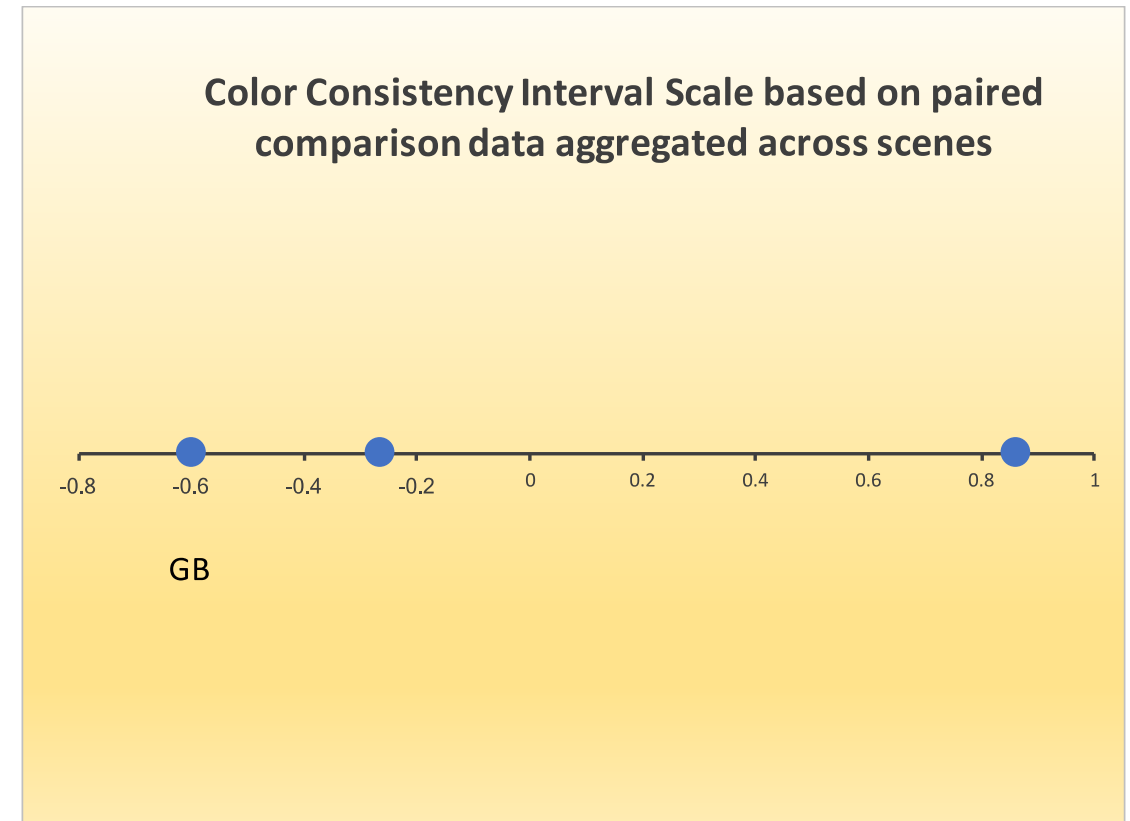
SCENE-BASED PAIRED COMPARISON

CHOICE FREQUENCIES COMBINED ACROSS SCENES

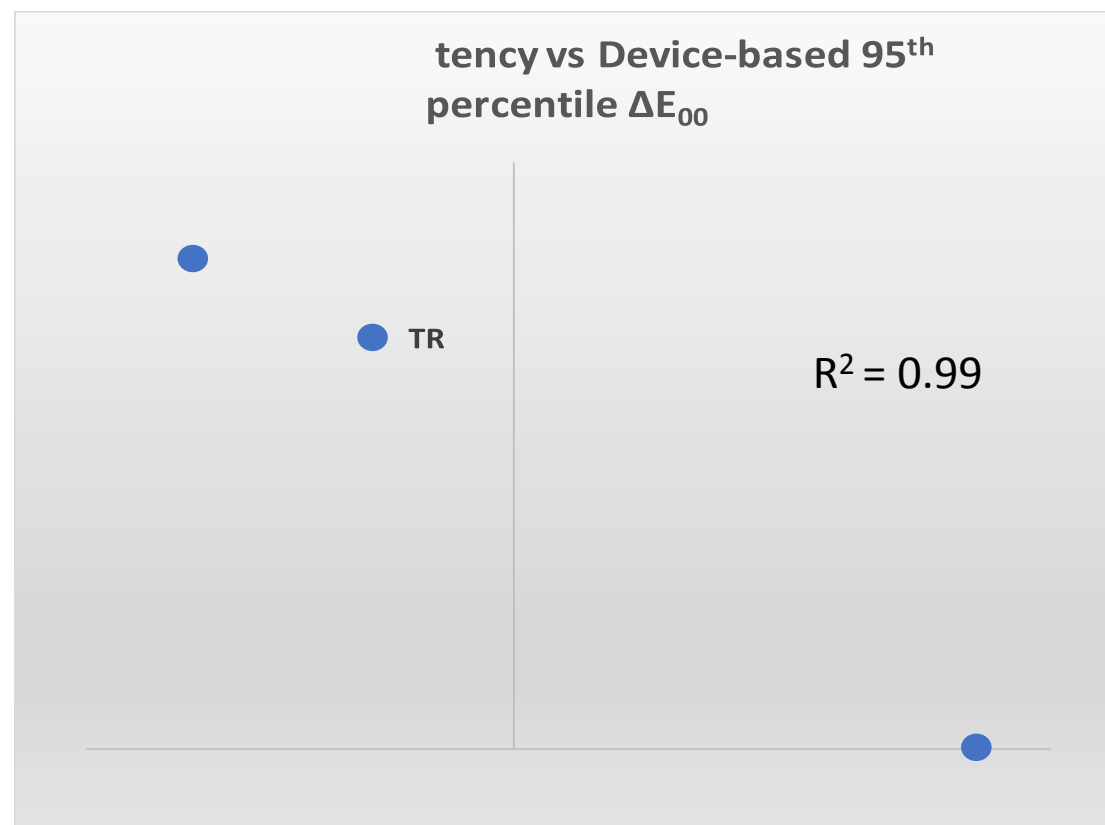
	GRAY BALANCE	TONE REPRODUCTION	CRPC4
GRAY BALANCE		190	264
TONE REPRODUCTION	98		255
CRPC4	24	33	
AVERAGE RANK	0	1	2

Results – Color Consistency Scale

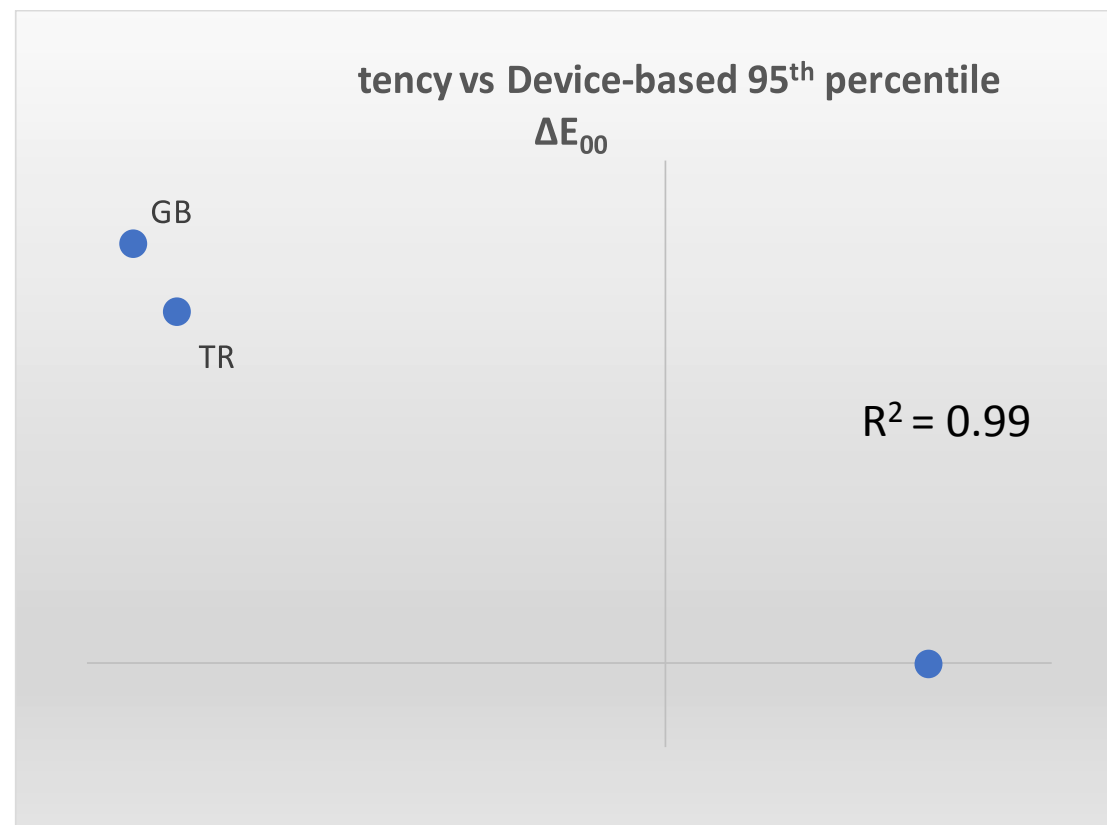
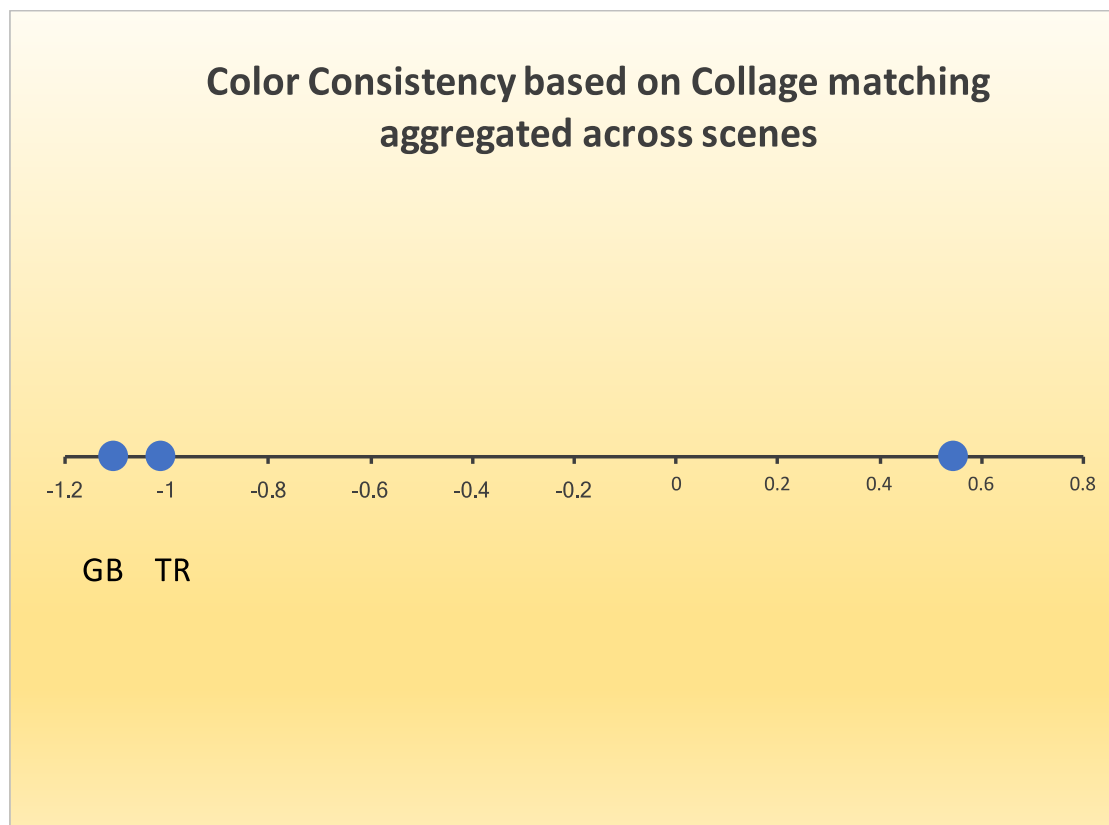
- Color Consistency scale based on Thurstone's Law of Comparative Judgement, Case V (Thurstone, 1927):
 - Divide Frequencies by the number of observations and convert to Proportions
 - Convert Proportions to z-scores
 - Calculate columns' mean to get scale values



Color Consistency vs Device-based 95th percentile ΔE_{00} ³¹



Results — Color Consistency for the Collage Experiment



Conclusions

- CCA of images of the same scenes, reproduced in multiple reference printing conditions, depends on GB and TR. When Tone Reproduction and Gray Balance deviate from the reference CRPC (CRPC4), CCA significantly decreases.
- CCA of multiple scenes, reproduced in one reference printing condition, also depends on similar GB and TR. Observers were able to group different scenes based on the uniformity of GB and TR.
- Device-based 95th percentile ΔE_{00} is shown to be a good predictor for Consistent Color Appearance in the present experiment.

Next Steps

- Include multiple gradations of gamut volume (chroma) and GB and TR changes using reference CRPC – CRPC4.
- Run experiments to measure visual equivalency of these alterations with respect to perceived CCA.
- Develop a metric for CCA differences based on colorimetrically derived data
- Test the metric in verification experiments