https://doi.org/10.2352/EI.2024.36.16.COLOR-170

Investigating Consistency of Color Appearance using Different Reproduction Approaches

Apurva Zunjarrao; Elena Fedorovskaya. ROCHESTER INSTITUTE OF TECHNOLOGY, Munsell color science laboratory (MCSL),1 Lomb Memorial Dr, Rochester, NY 14623.

Abstract

Consistency of color appearance (CCA) can be defined as an image attribute that gives a sense of identity among a set of images with different tones and colors, where the relationship between a group of colors in one embodiment is consistent with the relationship between the corresponding set of colors in another image [1]. *The consistency of color is a complex and important aspect of color reproduction. Maintaining color consistency is particularly crucial for printing and graphic communications, in general, where precise reproduction is required for scene identification, brand identity, and image quality. Characterizing consistency of color appearance in images is a challenging task because it is affected by differences in reproduction processes, viewing environments, and the output requirements.*

This research addressed the necessity for standardized approaches to assess and model CCA, a pivotal aspect in ensuring precise and uniform color replication across diverse media and platforms. In the experiment observers evaluated and compared the effects of gamut and gray balance variations on visual appearance of printed and displayed images and correlated the resulting CCA scale with image-based colorimetrical data. The study results showed that there is a close similarity between observed CCA for images presented under hard proofing (printed images) and soft proofing (display images) conditions. A high correlation between image-based CCA metrics for displayed and printed images when tested with observers' CCA responses, indicates the feasibility of using display images to study CCA for print production. The use of image data in the analysis offers a fruitful approach for modeling CCA.

Introduction:

Consistent Color Appearance (CCA) involves the process of monitoring perceptual color consistency, or similarity of visual appearance, between images or among a collection of images under different reproduction conditions, such as in printing or screen display [2] .

Color has a significant role in conveying the quality and desirability of items across industries. Consumers quickly recognize familiar visuals, therefore any change from the expected color appearance is likely to evoke adverse reactions [3]. Accurate color reproduction is crucial to preserving quality in the printing business, with color proofing emerging as a key tool for successful quality control [3]. Media production techniques use images for many applications, including printing products, webpages, and displays [4]. Therefore, CCA changes depending on reproduction conditions. The conventional hard-proofing technique has long been utilized to provide a visual representation of the final output before going to press. However, recent improvements in digital technology, software development, and internet connectivity have fostered a growing need for soft proofing, giving a faster, less expensive, and uniform digital workflow [3].

The demand for a blueprint that allows brand owners, designers, and printers to assess color quality and content in the final output encouraged the shift from hard to soft proofing to color proofing [5]. Despite the evident benefits of soft proofing, there is currently no standardized way for verifying color consistency across a different reproduction [3]. To address this gap, the International Commission on Illumination (CIE) formed the TC8-16 technical committee on CCA to make recommendations for evaluating and measuring the effects of color reproduction on the visual consistency of appearance in a single medium.

TC8-16 conducted a study on sets of reproductions of the same source image with consistent color appearance. They focused solely on the effect of color reproduction on appearance and identified an assessment method for comparing color reproduction strategies to maintain color appearance consistency [6]. Furthermore, they evaluated a method to describe the degree of consistent color appearance for predicting different gamuts [6]. In a separate study, Fogra developed an experiment to ensure consistent color appearance during color conversion in printing reproduction systems by utilizing color names and evaluating relevant image colors [7].

Recently, a method for changing and evaluating CCA in the context of chroma, tonality, and gray balance reproduction for hard proofing was developed and the device-based 95th percentile ΔE00 was shown as a suitable and useful method for quantifying CCA [2]. However, there is a noticeable lack of research on color appearance consistency in soft proofing, especially given its importance in the reproduction process workflow. This study intends to close this gap by defining and quantifying CCA particularly for soft proofing using display images. The present study utilized the mean delta E2000 (ΔE00) method for CCA evaluation. To quantify visual differences in CCA among sets of images psychometric evaluation was conducted, and the results for both display and print conditions were compared. Additionally, color difference measures were calculated using individual image data to develop a robust metric for evaluating CCA. This research aims to improve our understanding of color consistency assessment by overcoming past study limitations and providing additional insights toward developing models to predict CCA.

Problem Statement

There have been considerable advancements in color science and color management technology in the color appearance field, yet some important topics for further improvement still need to be addressed. Despite the recognized importance of ensuring color appearance consistency across reproduction platforms and systems, factors that affect the consistency of color appearance are not completely understood in general.

Furthermore, the development of comprehensive approaches for properly analyzing and quantifying color appearance consistency, especially in the context of screen-based soft proofing systems, is an ongoing challenge.

Research Objectives

1. To check the feasibility of soft proofing using display images to study CCA for print production.
2. To develop CCA model using colorimetrical data.

Materials

In this experiment, the researchers used one composite image as illustrated in Figure 1. A primary dataset and secondary datasets were created by systemically varying reproduction parameters for that one composite image.

Figure 1. Original composite image. The image consists of three pictures of people with different skin tones and the color test targets with 24 color control patches.

Primary datasets

The datasets for this study were generated as described in [2]. The primary dataset simulated Characterized Reference Printing Conditions (CRPCs), where the CRPCs comprise specified sets of colors defined by CMYK values along with their corresponding target CIELab values. The specifications for CRPCs outlined in ISO/PAS 15339-1 are depicted in Figure 2 [8]. Chung (2020) states: “The seven CRPCs cover a range of substrates, which results in different color gamut sizes. The larger the color gamut is, the more expensive the substrate will be. Although differing in gamut volume, CRPC1 to CRPC7 have common hue angles of the primaries. CRPC1 to CRPC7 also have similar highlight-to-midtone contrast, and gray reproduction characteristics in relation to pre-defined neutrals.” [9]. The gamut sizes of simulated CRPCs′ are more equally spaced, as evidenced from the projections for both simulated CRPCs′ and the ISO 15339 CRPCs on the CIELab a*b* plane shown in Figure 3 [2]. Figure 4 (top row) schematically illustrates the simulated CRPCs′ with progressively increasing gamut sizes, from the smallest gamut (CRPC1′) to the largest gamut (CRPC7′). The CRPC5′ reference dataset was selected and modified by linear scaling CIEXYZ to obtain the remaining datasets with 3.0 ΔE00 95th percentile gaps. The primary datasets were created using the G7 methodology to simulate characterized reference printing conditions. The color gamut was both decreased and increased to simulate CRPC1 to CRPC7, which are labeled as G7_1, G7_2, G7_3, G7_4, G7_5, G7_6, and G7_7.

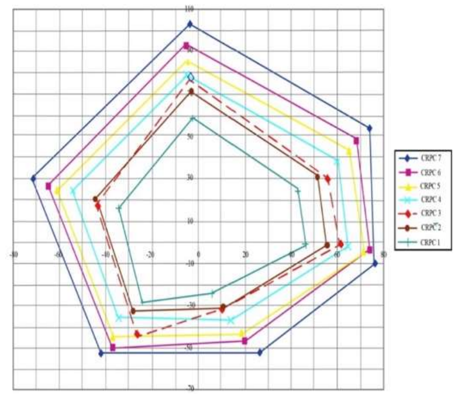

Figure 2. The 7 ISO 15339 CRPC gamut. Adapted from “ISO/PAS 15339-printing from digital data across multiple technologies” [8]

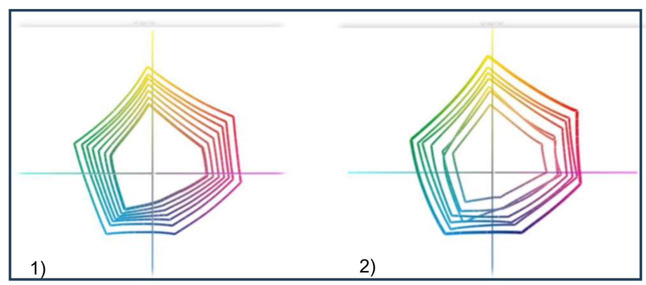

*Figure 3. Gamut projections on the a*b* plane in the CIELab color space for the simulated CRPCs′ (left panel, 1)) and the ISO 15339 CRPCs (right panel, 2)). Reproduced from [8]*

Secondary datasets

Eighteen further datasets were created by altering the gray balance while maintaining the G7_6 gamut volume constant.

The adjustments were made to ensure that the datasets exhibited a 3.0 ΔE00 95th percentile for adjacent images within the -3 to +3 steps of 3.0 ΔE00 95th percentile. The gamut of simulated CRPC6 closely resembled the GRACoL (General Requirements for Applications in Commercial Offset Lithography) 2013 color gamut, widely utilized in commercial and packaging applications. Figure 4 in three bottom rows illustrates the sets with gray balance variations in Cyan-Red, Yellow-Blue, and Magenta-Green directions, each with adjustments of +1, +2, and +3 steps of ΔE00, respectively.

ICC profiles were created for all primary and secondary datasets.

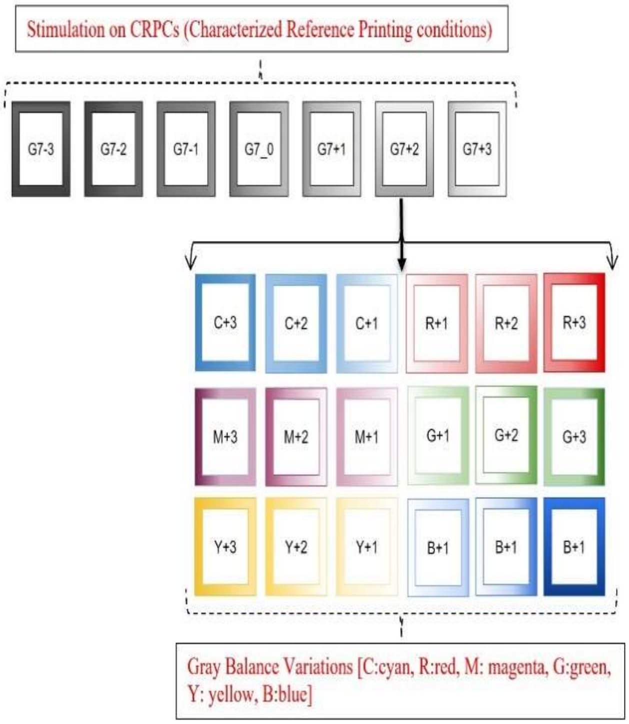

Figure 4. Illustration of primary and secondary datasets. The image variations in the secondary datasets are labeled using the type of gray balance manipulation from cyan to red, magenta to green and yellow to blue.

Printed images for hard proofing

The ICC profiles were applied to the test images and the output hard copies were produced using Epson P5000 printer as illustrated on the flowchart of Figure 5.

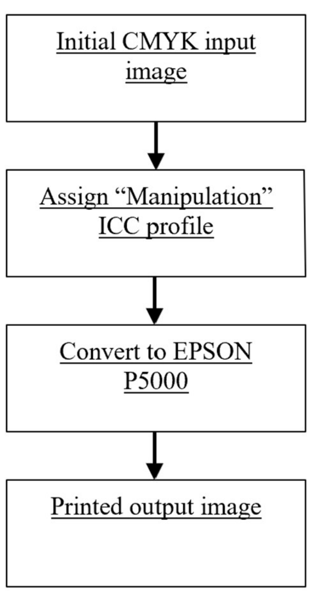

Figure 5. Flowchart to illustrate print production process.

Display images: digital images for softproofing

The processed CMYK images were converted to Adobe RGB1998 format with absolute colorimetric rendering intent for the soft proofing experiment.

Experimental design and setup

Two experiments were carried out: hard proofing and soft proofing. Both experiments were conducted in dark rooms with non-reflective black walls. For the soft proofing experiment, EIZO CG319X monitor used for image presentation. The monitor was calibrated for Adobe RGB1998 color space with D50 white point and 120 cd/m2 luminance level. The hard proofing experiment was conducted using the ISO 3664:2009-compliant GTI viewing booth with D50 light, and 120 cd/m2 luminance level measured at the center of the surface where prints were placed [10].

Participants

Thirty participants took part in the experiments. 15 participants were women with the average age of 25.3. Men's average age was 26.4. They had normal or corrected to normal visual acuity and normal color vision assessed using X-Rite Color Challenge and Hue Test [11].

Experimental Procedure

The rank order method was used for psychophysical experiments. First, the definition of CCA was introduced to the participants as follows: *"CCA is an image attribute that produces a sense of identity for images in the presence of observable visual differences"*.

During the first experiment, the observers were presented with printed images from the primary dataset as described earlier, ordered in the row from G7_1 to G7_7 where G7_6 was missing with the gap instead of it, along with the options set of twenty-five images. The options set had all seven images from the primary datasets and image variations of the secondary datasets (eighteen alternate images). Participants were asked to order the given 25 images from best to worst according to their CCA preference, in order to replace the missing G7_6 image of the primary dataset.

In the second experiment, the procedure was the same as the first experiment, except that all the images, including the primary and secondary datasets, were displayed on the EIZO CG319X monitor in a soft proof format. Participants were asked to conduct the second experiment by following the same procedure as the first experiment for the printed images. Figure 6 illustrates the arrangement of stimuli that was used for both hard proof and soft proof experiments.

Results

As described above, the research experiments consisted of two experiments conducted under the standard similar viewing conditions. The goal of the first experiment was to derive a relative CCA scale for image sets of display images using soft proofing method. Similarly, the goal of the second experiment was to develop a relative CCA scale for image sets of printed images using hard proofing method.

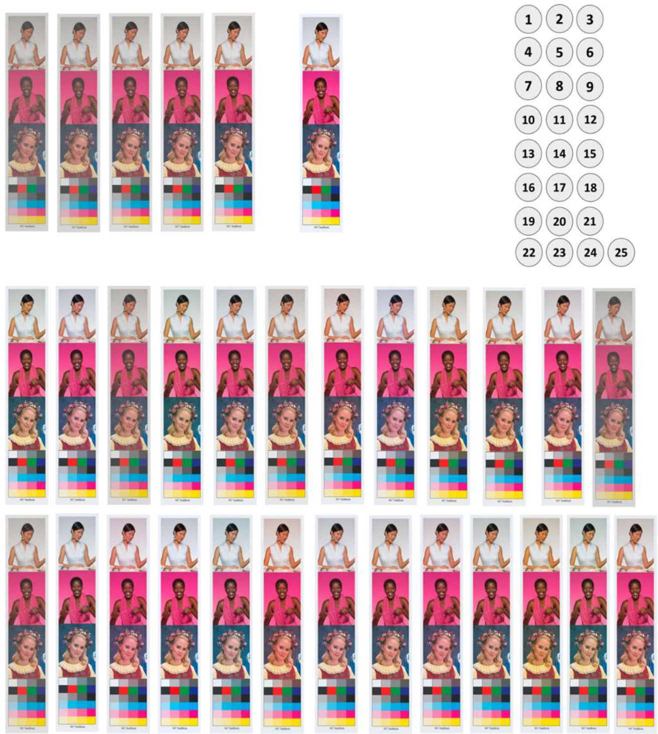

Figure 6. Arrangement of images for CCA evaluation used in both display and print experiments. Numbers on the right were assigned based on the rank order of each image according to its CCA preference.

To analyze observers' responses, first, interval scales from the rank data were calculated using Thurstone's law of comparative judgment[12]. The frequency of assigned ranks and the resulting interval CCA scales were calculated for both printed and display images. The obtained scale values are shown in Figure 7.

Next, we computed colorimetric data in following way:

1. For the display images:
   Calculated CIELab values for 24 color control patches comprising the lowest portion of the composite image (see Figure 1).
   Calculated pairwise mean Delta E2000 (ΔE00) between G7+2 and all other images for the color control patches.
   Calculated pairwise mean Delta E2000 (ΔE00) between G7+2 and all other images for the color control strips between G7+2 and all other images for the entire image.
2. For the printed images:
   Measured CIELab values of color control patches using i1 profiler.
   Calculated pairwise mean Delta E2000 (ΔE00) between G7+2 and all other printed images for the color control patches.

Display Images	Relative CCA
G7+2	1.49
C+1	1.27
G7+3	1.11
B+1	0.85
G7+1	0.77
G+1	0.76
Y+1	0.59
C+2	0.51
R+1	0.26
B+2	0.23
M+1	0.18
G+2	-0.03
C+3	-0.27
Y+2	-0.53
R+2	-0.63
G7_0	-0.76
M+3	-1.00
Y+3	-1.14
R+3	-1.27
G+3	-1.33
M+2	-1.48
G7-2	-1.57
G7-1	-1.57
B+3	-1.67
G7-3	-2.99

Printed images	Relative CCA
C+1	0.93
G7+2	0.90
B+1	0.80
G+1	0.77
Y+1	0.67
G7+3	0.63
M+1	0.43
C+2	0.35
R+1	0.31
B+2	0.29
G7+1	0.20
G+2	-0.18
C+3	-0.22
Y+2	-0.54
G+3	-0.66
R+2	-0.76
M+2	-0.77
Y+3	-0.86
B+3	-0.87
M+3	-0.90
R+3	-1.05
G7_0	-1.13
G7-1	-1.33
G7-2	-1.73
G7-3	-2.99

Figure 7. Relative CCA scale scores of all image variations including both display and printed images.

From Figure 7 it can be seen that the set with the reference image G7+2 has the highest CCA score, followed by C+1 for the display images in soft proofing experiment. In hard proofing experiment, C+1 achieved the highest CCA score, closely followed by G7+2. Following these, G7+3, B+1, G+1, Y+1, R+1, and M+1 have considerably higher rankings for their corresponding CCA assessments. On the other hand, it demonstrates that all of the gray balance +3 variations have the lowest CCA values when compared to the +2 variations. As evidenced by their lower scores in the plot, the gray balance +3 variations are less favorable in terms of the CCA judgement. The interval scale shows how far the sets are from each other in terms of CCA.

Figure 8 demonstrates the linear correlation of the CCA scale values between display images and printed images resulted from soft proofing and hard proofing experiments. The high R^2 (0.91) value represents a good agreement between the perceived CCA of the display images and those of the printed images. The obtained results for both reproduction methods indicate that there is a high similarity in the appearance of color consistency for images presented in hard proofing and soft proofing conditions.

Figure 9 shows the correlation between the ΔE00 values of the display images (derived from image data) and the printed images. The coefficient of determination examines the correlation between the ΔE00 values of both image types. The R^2 value of 0.82 indicates a significant correlation between the ΔE00 values of the displayed and printed images. This linear relationship implies that the color differences measured in the display images correspond closely to the color differences measured in the printed images, therefore providing a strong support for the use of soft proofing for the assessment of print reproduction.

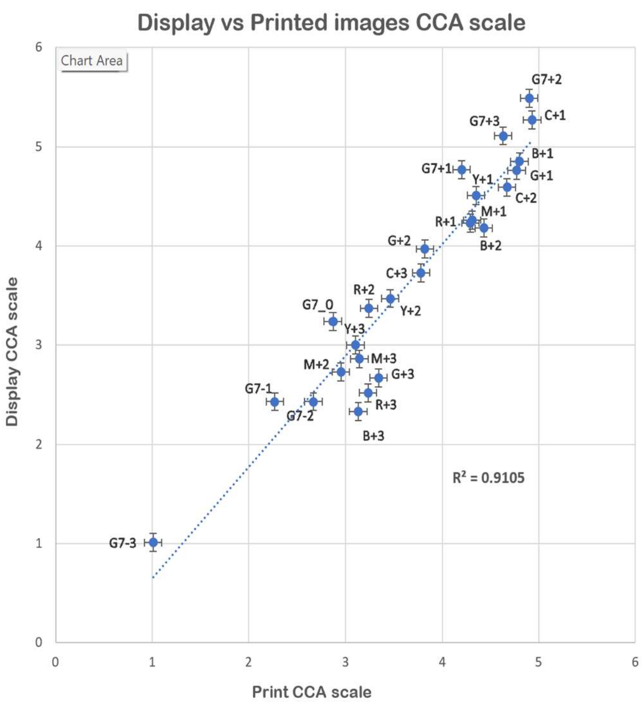

Figure 8. Graphical representation of display vs printed images CCA scale output.

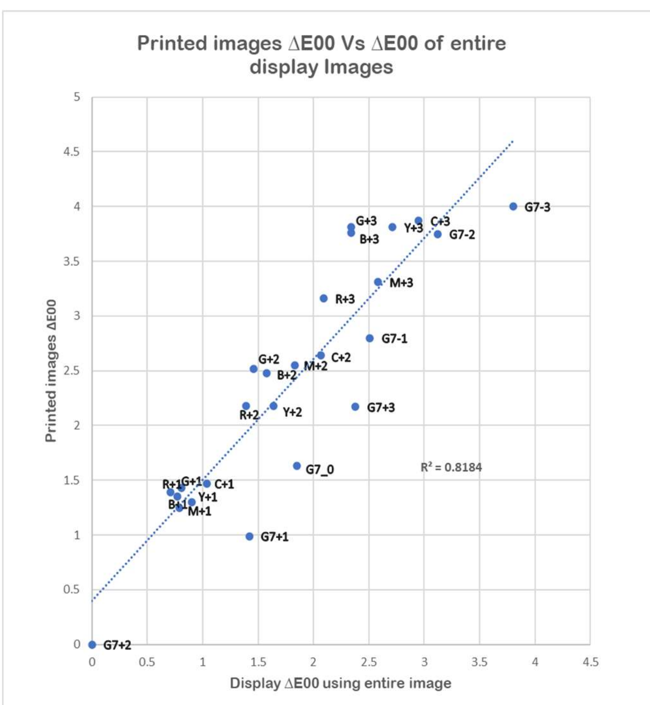

Figure 9. Graphical representation of printed images ∆E00 Vs display images ∆E00.

Figure 10 illustrates the correlation of the CCA scale values of the display images and the measured ∆E00 (mean ∆E) with respect to the reference image (G7+2) using the color control strips of corresponding images.

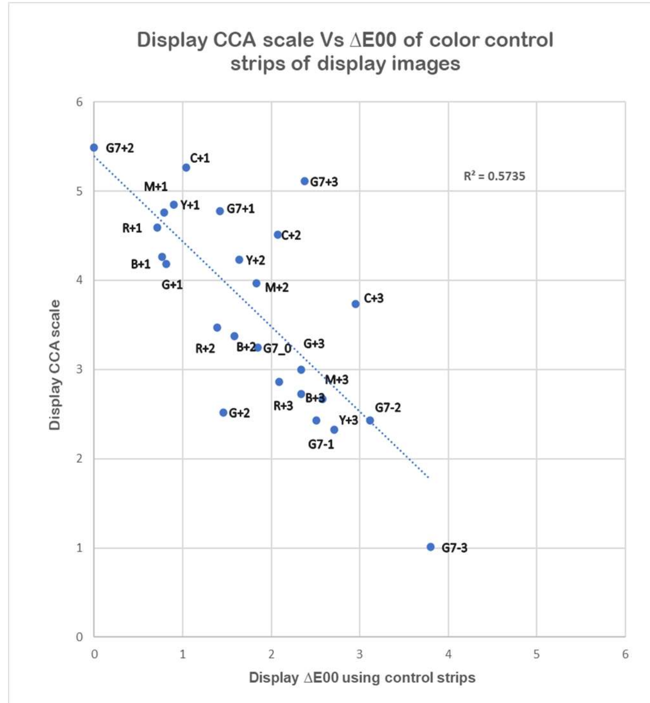

Figure 10. Graphical representation of display CCA vs mean Delta E2000 (∆E00) of control color strips.

There is a moderate R^2 (0.57) fit between the CCA scale values and ∆E00 between the control color strips for display images, showing that some images considerably deviate from the trend line. This indicates that the ∆E00 values calculates from the color control strips are moderately predictive of the consistency of color appearance judgments.

Figure 11 demonstrates the correlation of the relative CCA scores for the display images and the measured ∆E00 (mean ∆E) with respect to the reference image (G7+2) using pixel values of the entire images. There is a reasonably good fit R^2 (0.66) between the CCA scale and the mean ∆E00 values. As it can be seen in Figure 11, the data points cluster around the fitted regression line, showing a stronger linear relationship compared to previously described results in Figure 10.

To evaluate the relationship between the print colorimetry and perceived CCA in soft proofing condition, the linear regression analysis between the display images CCA scores and ∆E00 values measured from the prints was performed. As described previously, the ∆E00 values were calculated in comparison to the reference G7+2 image. Figure 12 illustrates the results of this analysis. The R^2 of 0.64 indicates a reasonable linear fit between the relative CCA scores of the display images and the ∆E00 values of the printed images. As illustrated below, data points cluster around the fitted regression line. The clustering around the regression line indicates that the linear regression model sufficiently accurately approximates the relationship between these variables. Thus, it can be suggested that the assessment of the perceived color consistency CCA scores of display images can serve as a valuable indicator of the color differences measured in printed images, and, conversely, the perceived CCA can be approximated based on the measured mean ΔE00.

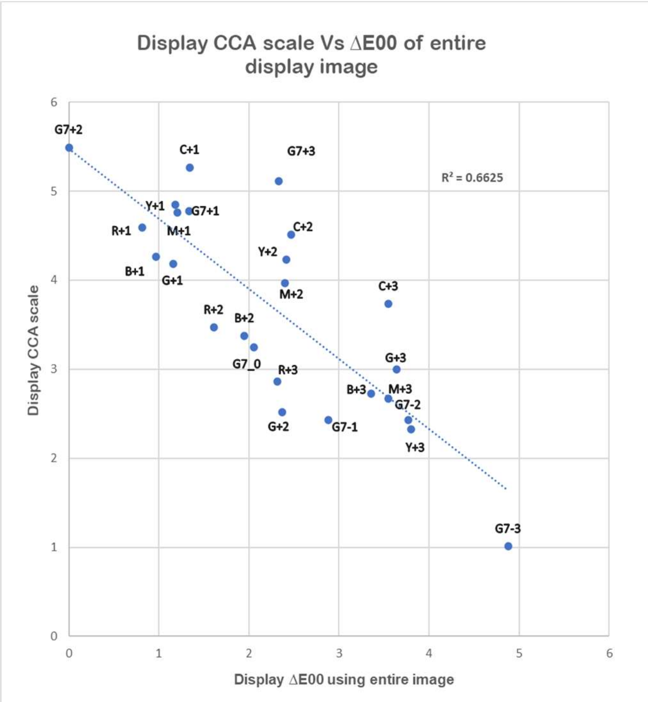

Figure 11. Graphical representation of display CCA vs Delta E2000 (ΔE00) for entire images.

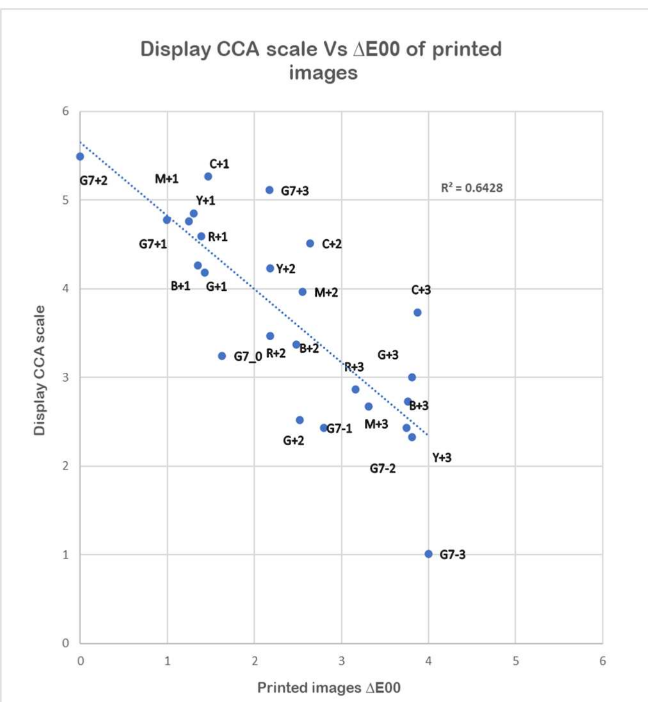

Figure 12. Graphical representation of display CCA vs Delta E2000 (ΔE00) for entire images.

From the resulting data, the comparison of CCA scale of display images with the colorimetric data from control strips and the entire image indicates that the prediction accuracy of the CCA scale using the full image data is superior to that achieved using the colorimetric data from only control strips, which underscores the importance of considering image-based calculations when modeling perception of consistency of color appearance.

Also, the demonstrated relationships between perceived CCA, the ΔE00 measurements using the entire display image data and the ΔE00 of printed images data, show close similarity in terms of predicting the appearance of CCA using colorimetrical measurements.

It is noteworthy to point out that colorfulness as an attribute may play a significant role in perception of CCA. As it can be seen from Figures 9,10, and 11, G7-3 has disproportionally low CCA value compared to the calculated mean ΔE00. This result can also be due to the progressive sequential arrangement of the primary image set in the experimental design. This assumption requires further testing.

Discussion

Psychometric tests show that the consistency of color appearance of an image set with an ideal reference image and a small, one step, 3 ΔE00 95% changes appears to be clearly superior and noticeable compared to two and three-step changes in gamut and gray balance reproduction. Changes in colorfulness may have an enhanced effect on the perceived consistency of color appearance despite relatively modest colorimetrical differences.

Metrics using image-based data provided an improved predictive performance compared to the set of measurements from a limited number of color patches utilized in the present study.

The resulting CCA scales for both reproduction methods indicate that there is a close similarity in the appearance of color consistency for images presented in hard proofing using printed images and soft proofing using display digital images. Despite the varied reproduction processes (physical printing versus digital display), the resulting CCA scales for both methods show similarities in the appearance of color consistency for the image sets. Thus, the proofing strategy used has no significant effect on the perceived CCA of image sets. In other words, the method used for proofing has no significant effect on the perceived color consistency of the images as evaluated by the CCA scales.

Overall, comparing observer data from soft and hard proofing is helpful to find patterns and understand how different reproduction methods affect color consistency between images. This information can help streamline proofing techniques and ensure consistent color reproduction across various mediums and viewing conditions.

Moreover, the comparison reveals a close similarity between the display image data and the printed image data when subjected to the CCA testing. In other words, the CCA scores obtained through either soft proofing (display images) and hard proofing (printed images) provide equal results when predicting color consistency.

Consequently, we can infer that employing either method interchangeably for CCA assessment yields comparable results, suggesting that the choice between the two methods has negligible impact on the output performance. Thus, advocating for the utilization of soft proofing and utilizing display data for print production can ensure consistency in color appearance evaluation. This approach offers an economical, convenient, and time-saving solution, adaptable to individual preferences and convenience.

Limitation and future scope

The individual variations can impact the resulting data. Thus, understanding the role of individual variations in color perception is important for comprehensive analysis. Future study efforts need to investigate how factors, such as expertise, influence color appearance perception.

To evaluate the effects of pictorial scene content on CCA, a varied and expanded collection of images is required.

Further research is needed to develop more precise models based on image analysis, including using image segmentation and the assessment of memory colors.

Acknowledgement

We would like to thank Dr. Malcom G. Keif and Dr. Bruce Myers, RIT, for their support and insights throughout the research project; Robert Chung, David Hunter, Pierre Urbain, Chromachecker, and Don Hutcheson, HutchColor, for their invaluable role in designing and developing the datasets. We also appreciate the contribution of RIT students, faculty, and staff who participated in the experiments.

References

[1] International Color Consortium, “Consistency of color appearance,” 2018.

[2] E. Fedorovskaya, R. Chung, D. Hunter, P. Urbain, and D. Hutcheson, “Defining Consistent Color Appearance for Print Images,” 2018.

[3] H. Zhang, “Color in scientific visualization: Perception and image-based data Color in scientific visualization: Perception and image-based data display,” 2008. [Online]. Available: https://scholarworks.rit.edu/theses.

[4] K. Braun, “Color-appearance modeling for cross-media image reproduction,” 1996. Accessed: Jul. 27, 2023. [Online]. Available: https://scholarworks.rit.edu/theses.

[5] S. Kang Ha, “An analysis of the consistency of brand color reproduction in print packaging and magazine advertising,” 2004. Accessed: Jul. 28, 2023. [Online]. Available: https://api.semanticscholar.org/CorpusID:167087725.

[6] Y. Yamauchi, “TC8-16 Consistent Colour Appearance Progress Report,” 2022.

[7] Fogra, “Common color appearance,” 2019. Accessed: Feb. 29, 2024. [Online]. Available: https://www.color.org/resources/r8-13/1.2018-11-12_CIC_Update.pdf.

[8] ISO/PAS 15339-2, “Graphic technology-Printing from digital data across multiple technologies-Part 2: Characterized reference printing conditions, CRPC1-CRPC7,” 2015. [Online]. Available: www.iso.org.

[9] R. Y. Chung, *Printing-process control and standardization*. RIT Press, 2020.

[10] ISO 3664, “Graphic technology and photography-viewing conditions,” 2009.

[11] PANTONE, “The X-Rite Color Challenge and Hue Test.” Accessed: Feb. 29, 2024. [Online]. Available: https://www.xrite.com/hue-test.

[12] P. Engeldrum, *Psychometric scaling.* Imcotek Press., 2000.

Author Biographies

Apurva Zunjarrao received her MS in Print Media and communication from the Rochester Institute of technology (2023). She has worked as graduate research assistant in the Munsell Color Science Laboratory, RIT. She received recognition as the recipient of both the PGSF and TAGA Scholarships for her outstanding academic achievements. Her research has focused on the advancement of consistent color reproduction, color image quality testing and camera color imaging.

Elena Fedorovskaya is a Research Professor at the Munsell Color Science Lab, RIT. She received her M.S. degrees in Psychology and Applied Mathematics, and Ph.D. in Psychophysiology from Lomonosov Moscow State University, Russia. Previously, Elena held the positions of the Paul and Louise Miller Endowed Chair at the School of Media Sciences, RIT, and Research Associate at Eastman Kodak Research Laboratories. Her research focuses on studying human color image perception and cognition and multisensory integration within extended reality systems.