Improving Perceptual Color Matching Performance between Different Backlight Displays and Color Managed Prints using Observer Correction Matrix in ICC Architecture

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Abstract

This study investigates methods to improve perceptual color matching between CCFL-backlight and LED-backlight displays evaluated against color-managed prints in professional soft-proofing workflows, through two sequential experiments. In the first experiment, a psychophysical paired-comparison study involving seven expert observers and 11 test images compared each backlight technology, hardware-calibrated to identical colorimetric targets, against reference prints on color similarity, saturation appearance, and overall preference. Results showed the CCFL display was consistently rated as perceptually closer to the prints and preferred over the LED display, despite the two displays being colorimetrically near-identical, indicating that the discrepancy originates from spectral rather than colorimetric differences. Building on this finding, the second experiment derived observer correction matrices for the LED display from a large-scale psychophysical matching study involving 45 observers, who interactively adjusted seven color patches to visually match printed references. K-means clustering reduced the 45 individual matrices into three representative observer classes. In a forced-choice validation, individual observer-specific matrices and the Cluster 1 representative matrix consistently outperformed the CIE 1931 2° Standard Observer baseline. Quantitative validation against ISO 14861:2015 criteria corroborated these results, with the corrected LED profile achieving statistically significant reductions in average and maximum ΔE00 and meeting ISO compliance thresholds. Together, these findings demonstrate that perceptually significant differences exist between CCFL and LED backlight displays even under identical colorimetric calibration, and that embedding observer correction matrices within standard ICC v4 profile architecture offers an implementable solution for improving LED soft-proofing fidelity without requiring migration to iccMAX.

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Introduction

Achieving consistent and perceptually accurate color reproduction between display devices and printed media remains one of the most persistent challenges in professional color management workflows, including digital photography, prepress, graphic design, and soft proofing. Soft proofing—the practice of using a calibrated display as a visual substitute for a physical print proof—is central to modern production pipelines, as it enables rapid iteration and reduces material waste while relying on the assumption that the displayed image faithfully represents the expected print output [1][2]. However, in practice, even when displays and prints share identical colorimetric targets, significant perceptual mismatches continue to arise, undermining the reliability of soft proofing as a cross-media evaluation tool.

Historically, CCFL-backlight displays have traditionally been favored in color-critical professional applications due to their relatively continuous spectral power distribution, stable phosphor emission, and consistent neutral grayscale rendering performance [3]. These spectral properties confer greater spectral compatibility with the broadband spectral reflectance characteristics of color-managed prints, making CCFL displays less prone to observer metamerism in typical viewing conditions. In contrast, contemporary LED-backlight displays, while offering superior energy efficiency, higher luminance, and extended color gamuts, emit narrowband spectral peaks that produce significantly different cone excitation patterns compared to CCFL backlights—even when both are calibrated to nominally identical colorimetric targets such as CIE Standard Illuminant D50 white point, identical luminance levels, and identical tone response curves [4][5]. This spectral divergence between backlight technologies has well-documented implications for observer metamerism: two stimuli that are colorimetrically equivalent under one measurement condition may nonetheless appear perceptually different to a human observer due to differential interaction between the narrowband LED spectrum and individual cone sensitivities [6].

Observer variability adds a further layer of complexity to this problem. Biological differences among individuals—including variations in macular pigment optical density, lens yellowing, photopigment spectral sensitivity, cone distribution across the retina, and neural processing pathways—cause the same physical stimulus to be perceived differently by different observers [6][7][8]. The CIE 1931 2° Standard Observer color matching functions (CMFs), which underpin the conventional color management pipeline, represent a statistical average derived from a limited population of observers under narrowly defined experimental conditions. While this standardization enables interoperable color communication across devices and industries, it necessarily fails to capture the full range of individual perceptual responses, particularly when comparing media with substantially different spectral power distributions [9]. Several researchers have demonstrated that individual CMFs derived from psychophysical matching

experiments can deviate substantially from the CIE 2° standard, and that these deviations are perceptually meaningful in color reproduction contexts [1][10].

The existing color management infrastructure, built around ICC profiles and the ICC v4 specification, addresses cross-media color consistency through device characterization, gamut mapping, and rendering intent transformations, but it fundamentally assumes a single universal observer and does not accommodate observer-specific color correction [11]. The ICC.2 specification, commonly referred to as iccMAX, was proposed to address this limitation by enabling the incorporation of individual CMFs and observer-specific transformations within the color management architecture [12][13]. However, iccMAX has seen limited commercial adoption since its initial announcement in 2019, partly due to implementation complexity and the absence of broad tool support. As a result, practitioners working with LED-backlight displays in soft proofing environments continue to experience reduced perceptual color matching accuracy that existing calibration procedures cannot fully resolve. Consequently, there remains a practical need for observer correction approaches that operate within the current ICC v4 framework without requiring migration to iccMAX.

Previous studies have addressed aspects of this problem from complementary directions. Comparative spectral analyses of CCFL and LED backlights have reported colorimetric differences and metamerism index differences between the two technologies [5][14]. Psychophysical studies have explored observer variability in color matching tasks and proposed observer-specific modeling frameworks to improve perceptual accuracy [1][15]. Work by Fairchild, Braun, and others has demonstrated the value of perceptual scaling and cross-media color matching experiments in characterizing individual observer behavior [1][3]. More recently, methods for deriving representative observer categories through clustering of individual adjustment data have shown promise as a scalable middle-ground between fully personalized calibration and rigid single-observer standards [16]. Nevertheless, a systematic investigation combining all of these elements—empirical comparison of CCFL and LED backlight perceptual performance, derivation of observer correction matrices from large-scale psychophysical matching experiments, and practical integration of these matrices into existing ICC profile structures validated against ISO soft-proofing standards—has not been comprehensively reported.

This paper addresses this gap through two sequential experiments. The first experiment establishes, through a structured psychophysical observer study with expert evaluators, the extent and nature of perceptual color matching differences between CCFL and LED backlight displays when both are hardware-calibrated to identical colorimetric targets and evaluated against the same color-managed reference prints. The second experiment develops an observer correction matrix methodology in which individual observers perform explicit visual matching adjustments between the LED backlight display and reference prints, from which

personalized correction matrices are computationally derived. K-means clustering is then applied to categorize the individual matrices into representative observer classes, enabling practical deployment without requiring per-user calibration. The resulting matrices are embedded within the ICC display profile architecture and validated through both psychophysical evaluation and quantitative colorimetric analysis against ISO 14861:2015 soft-proofing compliance criteria. Together, these experiments provide both empirical evidence of the problem and a technically implementable solution within the established color management ecosystem.

Methodology

Psychophysical Experiment

Experimental Environment and Viewing Conditions

All psychophysical experiments were conducted in a dedicated dark room under standardized viewing conditions. The laboratory employed a neutral gray surround with no extraneous ambient illumination to minimize flare, chromatic adaptation, and stray light. These controlled conditions ensured consistent observer evaluations and complied with the recommendations of ISO 3664 and established psychophysical soft-proofing practices [16][17].

Display Calibration

Two professional-grade displays (CCFL-backlight and LED-backlight displays) were used in the experiment. Both were hardware-calibrated with a spectrophotometer before each session to ensure traceable colorimetric accuracy. Identical calibration targets were applied, including the Adobe RGB gamut, 120 cd/m² white luminance, D50 white point, 0.5 cd/m² minimum black level, and an L* tone response curve. This controlled setup ensures that any perceptual differences arise from backlight spectral characteristics rather than differences in display calibration.



Figure 1. Psychophysical Adjustment Procedure

Reference Print Preparation and Viewing Setup

Reference prints were produced using a color-managed inkjet workflow and evaluated in an X-Rite Judge QC viewing booth under D50 illumination at 2000 lux, following ISO 3664 standards. The viewing conditions were matched to display calibration targets as closely as possible to ensure consistent chromatic adaptation across print and display, minimizing cross-media perceptual bias.

Experiment 1: Perceptual Comparison of CCFL and LED Backlight Displays

The first experiment was designed as a two-stage paired comparison study to systematically characterize and quantify the perceptual color matching performance of CCFL and LED backlight displays relative to the reference color prints. Observers participated in two sequential evaluation conditions: in the first condition, they compared the CCFL backlight display against the reference prints; in the second condition, they compared the LED backlight display against the identical set of reference prints. The order of conditions was counterbalanced across observers to control for order effects and perceptual fatigue.

Test Image Set

Eleven test images were incorporated into the experimental stimulus set to provide comprehensive coverage of perceptually critical color categories. Nine chromatic images were included, representing the following categories: red, green, blue, cyan, magenta, yellow, human skin tone, neutral colors, and a multi-chromatic blended composition incorporating a range of saturated and desaturated hues

simultaneously. Two additional achromatic grayscale gradient images were included to evaluate neutral tonal reproduction across the full luminance range from near-black to near-white. This selection ensured that both chromatic accuracy and neutral gray stability were systematically assessed, as the latter is known to be a particularly sensitive indicator of backlight spectral differences in professional soft-proofing contexts. This custom image set was designed to complement standardized prepress test image data, such as the ISO 12640 series of CIELAB/SCID reference images [18], ensuring both practical relevance to soft-proofing workflows and comparability with established test-image conventions.

Observers

Seven observers with a minimum of 10 years of professional color judgment experience in printing, prepress, or display calibration were recruited to participate in the first experiment. The selection of highly experienced observers, rather than a naive general population, reflects the practical context of this research: the primary end users of professional soft-proofing workflows are expert practitioners whose judgments have high reliability and who are sensitive to the subtle perceptual differences that less experienced observers may fail to detect. All observers were confirmed to have normal color vision prior to participation.

Evaluation Procedure

For each test image, observers were seated at a fixed viewing distance from the display and asked to evaluate three distinct perceptual attributes through a structured forced-choice and rating methodology:

(1) Color similarity, defined as the degree of color match between the displayed image and the corresponding reference print.
(2) Saturation appearance, defined as whether the displayed image appeared more saturated, less saturated, or equivalent in saturation relative to the print.
(3) Overall preference, defined as which display provided the more acceptable and faithful soft-proofing appearance for practical professional use.

Responses were recorded on structured evaluation forms under consistent session supervision.

Experiment 2: Observer Correction Matrix Derivation

The second experiment was designed to quantify individual observer color matching preferences between the LED-backlight display and the reference prints, and to derive observer-specific correction matrices from these measurements for subsequent incorporation into the ICC profile architecture.

Adjustment Procedure

Forty-five observers with varying levels of color expertise participated in the second experiment. Each observer was seated at the LED backlight display and presented sequentially with seven target color patches displayed on the screen: white, red, green, blue, cyan, magenta, and yellow, representing the primary and secondary corners of the RGB color cube. For each displayed color patch, observers were simultaneously presented with the corresponding printed color patch in the D50 viewing booth and were instructed to adjust the displayed color interactively using a custom graphical user interface until they perceived the displayed and printed colors to be as visually similar as possible. The graphical user interface exposed independent sliders for hue angle, saturation magnitude, and lightness level, enabling observers to independently control the three perceptual dimensions of the displayed color without coupling between parameters. This adjustment procedure directly captures each individual observer's perceptual color matching preference, including any idiosyncratic deviations from the CIE 1931 2° Standard Observer that arise from individual differences in cone photopigment spectral sensitivity, lens optical density, macular pigment distribution, or neural chromatic processing [6][8].

Spectrophotometric Measurement and Matrix Computation

Upon completion of the interactive adjustment procedure for all seven target colors, the final adjusted display color states were measured using a calibrated spectrophotometer. Individual observer correction matrices were then computationally derived from these measurements. Each matrix encodes the transformation between the CIE 1931 2° Standard Observer–based colorimetric representation of the displayed color and the observer-specific perceptual preference, expressed in terms of modifications to the CIE XYZ tristimulus values derived from the standard observer color matching functions. This formulation ensures that the correction matrices are interoperable with the existing ICC profile color management infrastructure, as it operates entirely within the CIE XYZ colorimetric framework.

Observer Clustering

Given the infeasibility of deploying a personalized correction matrix for each end user, the 45 individual correction matrices were reduced to a manageable number of representative observer classes. K-means clustering, an unsupervised machine learning classification method, was applied to the full set of 45 individual correction matrices to identify compact clusters of observers with similar correction preferences. The optimal number of clusters was determined through joint analysis of the within-cluster sum of squares (elbow method) and silhouette coefficients, both of which consistently indicated that $k = 3$ clusters provided the most meaningful and stable partitioning of the observer population. Three

representative K-means cluster-based correction matrices—designated Cluster 1, Cluster 2, and Cluster 3—were computed as the centroid of each observer group and used as the representative profiles for subsequent validation.

Validation Conditions

In the validation phase of the second experiment, six distinct correction matrix conditions were systematically applied to the displayed images on the LED backlight display and presented to observers for comparative evaluation against the reference prints:

(1) The CIE 1931 2° Standard Observer matrix, representing the conventional colorimetric calibration baseline.
(2) The individual observer-specific correction matrix personalized to each participating observer.
(3) The population average correction matrix computed as the mean across all 45 individual matrices.
(4) K-means cluster-based matrices: Cluster 1 correction matrix.
(5) K-means cluster-based matrices: Cluster 2 correction matrix.
(6) K-means cluster-based matrices: Cluster 3 correction matrix.

For each of the seven target color patches (white, red, green, blue, cyan, magenta, and yellow), observers were asked to select, through a forced-choice comparative judgment, which of the six correction matrix conditions provided the most perceptually accurate match to the corresponding printed color patch under the D50 viewing booth illumination. This forced-choice paradigm was selected to minimize response bias and to yield directly interpretable comparative preference data across correction conditions.

Result

Experiment 1: Perceptual Comparison of CCFL and LED Backlight Displays

Color Similarity and Saturation Appearance

The results of the first experiment consistently demonstrated that the CCFL backlight display exhibited a substantially higher perceptual color similarity to the reference prints than the LED backlight display, as judged by seven expert observers across all 11 test images. Observer ratings for color similarity were significantly higher for the CCFL condition than for the LED condition across the majority of chromatic test images, indicating that the CCFL display more faithfully reproduced the color appearance of the reference prints despite both displays having been hardware-calibrated to numerically identical colorimetric

targets. These findings are summarized in Table 1, which presents the mean color similarity scores for each test image under both backlight conditions.

With respect to saturation appearance, the LED backlight display consistently produced color appearances that observers rated as more saturated relative to the reference prints across the majority of the nine chromatic test images. This effect was most pronounced for highly chromatic images in the red, green, blue, and cyan categories, and was less marked for the skin tone and neutral color categories. In contrast, the CCFL backlight display produced saturation appearances that observers judged to be substantially closer to those of the reference prints, with the majority of observers rating the CCFL condition as equivalent or near-equivalent to the print in saturation. The achromatic grayscale gradient images showed comparatively smaller differences between the two backlight conditions in terms of saturation appearance, consistent with the expectation that narrowband LED spectral effects are most consequential for highly chromatic stimuli.

Test Image	Selection rate for CCFL display	Average for CCFL display	Selection rate for LED display	Average for LED display
1	0.00%	5.29	25.00%	5.29
2	87.50%	6.43	62.50%	5.43
3	25.00%	5.29	50.00%	5.86
4	83.33%	6	50.00%	5.86
5	100.00%	5.29	100.00%	5.14
6	50.00%	5.29	50.00%	4.71
7	87.50%	6.14	87.50%	4.29
8	50.00%	5	50.00%	5.29
9	50.00%	5.86	25.00%	5.29
10		4.57		4.71
11		4.29		4.71

Table 1. Similarity evaluation of CCFL and LED displays

Overall Preference

Overall preference ratings strongly favored the more acceptable soft-proofing medium. The majority of observers across all chromatic test image categories selected the CCFL condition as providing a more faithful and reliable soft-proofing appearance relative to the reference prints. These preference differences were statistically significant across the observer group as a whole, confirming that the perceptual advantage of the CCFL-display over the LED display is not attributable to chance but reflects a consistent and reproducible perceptual phenomenon under the experimental conditions employed.

A particularly notable finding is that these perceptual differences were observed despite the two displays producing colorimetric outputs that were practically indistinguishable from one another within the measurement uncertainty of the spectrophotometer used for hardware calibration. This dissociation between colorimetric equivalence and perceptual equivalence constitutes the central empirical finding of the first experiment and motivates the development of a correction methodology as pursued in the second experiment.

Inter-Observer Variation

Substantial inter-observer variation was observed across the seven expert evaluators; even within this highly experienced and carefully selected group, observers differed not only in the magnitude of their preference for the CCFL condition but also in which specific test images they found most problematic under the LED condition. This inter-observer variability was most pronounced for the skin tone, multi-chromatic, and magenta test images, and least pronounced for the red, green, and blue single-hue images where observer consensus was stronger. The presence of meaningful individual differences among experienced color evaluation professionals, all operating under identical and tightly controlled experimental conditions, highlights the role of observer metamerism as a significant and unavoidable factor in cross-media soft-proofing and underscores the importance of observer-specific correction approaches as pursued in the second experiment.

Experiment 2: Psychophysical Validation of Observer Correction Matrices

Individual Adjustment Variability

Substantial variation in color matching adjustments was observed across the 45 observers who participated in the second experiment. The magnitude and direction of hue angle, saturation, and lightness adjustments differed considerably between individuals for all seven target colors, reflecting the well-documented phenomenon of observer metamerism and the diversity of individual cone photopigment sensitivity characteristics within the general population. Notably, the degree of inter-observer variability was not uniform across colors: the largest spread of individual adjustments was observed for the blue and cyan target patches, while the smallest spread was observed for the white and red targets. This color-dependent pattern of variability is consistent with the known spectral sensitivity differences of the S-cone system relative to the M- and L-cone systems, and with the spectral characteristics of the LED backlight's blue primary emission peak, which produces particularly heterogeneous cone excitation patterns across observers. Figures 2 and 3 present the distribution of individual observer correction matrix parameters across the 45-observer population, together with the K-means cluster assignments and centroid matrices for the three identified observer classes.

Cluster Analysis

The K-means analysis with k = 3 produced three well-separated and internally cohesive observer clusters, as confirmed by the silhouette coefficient analysis and the within-cluster sum of squares elbow diagnostic. The three cluster-representative matrices M_C1, M_C2, and M_C3 exhibited clearly distinguishable correction characteristics. M_C1 was characterized by moderate reduction with minor lightness adjustment; M_C2 exhibited more pronounced hue rotation corrections particularly in the green-cyan region; and M_C3 required the largest overall magnitude corrections across multiple chromatic axes, suggesting that Cluster 3 encompasses observers whose individual cone sensitivities deviate from CIE 1931 2° Standard Observer assumptions. The three cluster centroids are shown in Figure 4, and the ΔE_{00} distances between each cluster centroid and the CIE 2° Standard Observer matrix (Figure 5) were all found to be greater than 1.0, confirming that each cluster-representative matrix is perceptually distinct from the standard observer baseline.

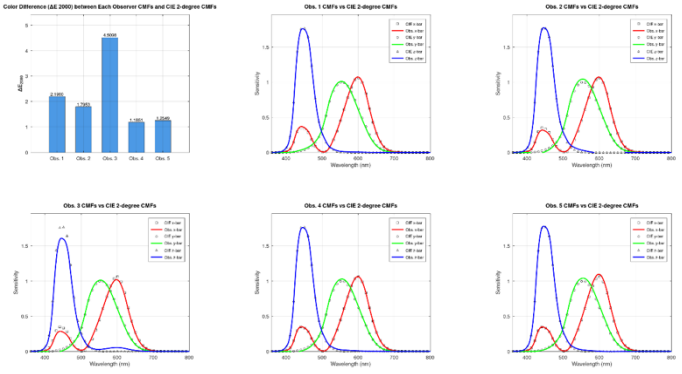


Figure 2. ΔE_{00} values between each Observer's Color Matching Functions and CIE 2-degree Standard Observer

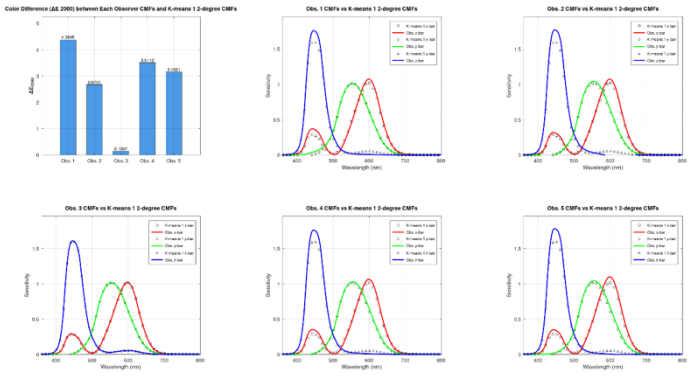


Figure 3. ΔE_{00} values between each Observer's Color Matching Functions and K-means Group 1 Color Matching Functions

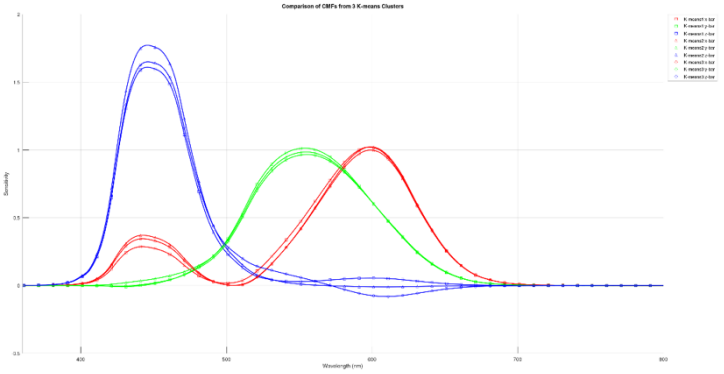


Figure 4. Comparisons Between Three Sets of Derived K-means Color Matching Functions

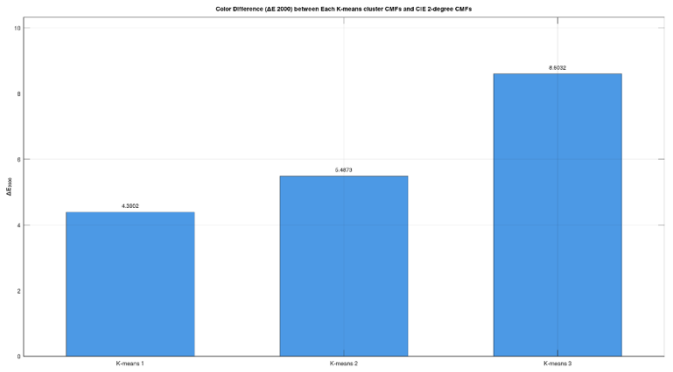


Figure 5. ΔE_{00} values between each Derived K-means Categories Color Matching Functions and CIE 2-degree Standard Observer

Forced-Choice Validation Results

The results of the forced-choice validation phase revealed the proportion of observer selections for each of the six correction matrix conditions across the seven target color patches. The individual observer-specific matrices (M_ind) and the Cluster 1 matrix (M_C1) consistently received the highest selection rates across the majority of test colors, demonstrating statistically superior matching performance relative to the CIE 2° Standard Observer baseline condition (M_std). For the white, red, green, blue, and cyan target patches, individual observer-specific matrices and M_C1 were selected by significantly more observers than any other condition, confirming that these corrections provide a perceptually closer match to the reference prints than standard colorimetric calibration alone. The population average matrix (M_avg) showed moderate improvement over M_std but was generally outperformed by both individual observer-specific matrices and M_C1, suggesting that simple population averaging insufficiently captures the observer-specific structure of the correction requirements. M_C2 and M_C3 showed more variable performance across colors, performing well for their respective cluster member observers but providing less consistent improvements across the full observer panel.

These findings provide strong and consistent evidence that observers perceive LED backlight displays with applied observer correction matrices as more faithful soft-proofing representations of the reference prints than displays operating under conventional colorimetric calibration alone, and that the Cluster 1 representative matrix in particular provides a practical and generalizable correction that substantially benefits a significant proportion of the observer population without requiring fully individualized calibration.

ISO 14861 Quantitative Validation

The ISO 14861:2015 test chart, shown in Figure 6, comprises 72 color patches, including paper white, spanning a representative range of hue, chroma, and lightness combinations relevant to soft-proofing evaluation. Chromaticity coordinates of each patch were measured for the LED display under each correction matrix condition and for the reference prints using a calibrated spectrophotometer [5].



Figure 6. ISO 14861:2015 Test Chart

A quantitative validation was conducted according to the ISO 14861:2015 evaluation criteria to objectively verify the effectiveness of the proposed observer correction matrices. For each of the six correction matrix profile conditions, the average ΔE_{00} and maximum ΔE_{00} values were computed across the ISO 14861 standardized test target color patches and compared with those of the reference prints.

Under the baseline condition, M_std, which represents conventional colorimetric calibration of the LED display without observer correction, the measured color differences reflected the perceptual discrepancies observed in the psychophysical experiments, indicating the inherent spectral mismatch between the narrowband LED backlight and the broadband reflectance characteristics of the reference prints.

The observer correction matrices were subsequently applied to evaluate their influence on the objective color difference metrics. The results demonstrate that the proposed observer correction methodology effectively reduces the color differences between the displayed soft proof and the reference prints while maintaining compatibility with the standard ICC color management workflow. These objective measurements are consistent with the psychophysical findings, supporting the conclusion that incorporating observer-dependent correction improves the colorimetric accuracy and perceptual fidelity of LED-based soft-proofing displays.

Discussion

Spectral Origin of CCFL–LED Perceptual Differences

The results of the first experiment provide clear empirical confirmation that perceptually significant color matching differences exist between CCFL and LED

backlight displays against color-managed reference prints, even under conditions of rigorous and verified colorimetric equivalence. This finding is consistent with the theoretical expectation that narrowband LED backlight spectral power distributions will generate differential cone excitation patterns compared to the broader, more continuous spectral emission of CCFL backlights, a consequence that is invisible to spectrophotometric calibration procedures operating within the CIE XYZ framework but is directly experienced by human observers through the mechanism of observer metamerism. The specific character of the perceptual discrepancy—manifesting predominantly as an apparent saturation excess in the LED condition relative to the print—is consistent with the higher spectral purity of the LED primaries stimulating opponent chromatic channels more strongly than the equivalent XYZ stimulus would predict under standard observer assumptions, leading observers to perceive the displayed colors as systematically more saturated and chromatically intense than their nominally identical print counterparts. The continuing prevalence of CCFL displays in professional color-critical environments, despite the commercial obsolescence of the technology, has historically been attributed by practitioners to the superior soft-proofing reliability of CCFL over LED. The present results provide the first systematic empirical quantification of this practitioner experience through a controlled observer study, establishing that this preference is not merely subjective conservatism but reflects a genuine and reproducible perceptual phenomenon with measurable colorimetric underpinnings. This finding is directly relevant to equipment procurement and workflow decisions in professional prepress, photography, and graphic arts environments.

Observer Metamerism and the Limits of Standard Observer Calibration

The substantial inter-observer variation observed in both experiments underscores the fundamental limitation of the CIE 1931 2° Standard Observer as the sole basis for color management in cross-media soft-proofing applications. Even among expert observers with extensive professional experience and demonstrably reliable color judgment capabilities, individual differences in cone sensitivity, macular pigment density, and chromatic processing introduced meaningful variation in color matching performance that no single observer-agnostic calibration procedure can simultaneously optimize for all users [6][7][8]. This finding aligns with a growing body of psychophysical research demonstrating that the CIE 2° Standard Observer CMFs, while adequate for many practical purposes, systematically underrepresent the diversity of real human color perception in dissimilar cross-media comparisons [4][9][19]. The large-scale observer study in the second experiment, involving 45 participants across a range of expertise levels, revealed that individual correction matrices derived from perceptual matching adjustments were consistently preferred over the CIE 2° Standard Observer baseline by the majority of observers. This preference was both statistically robust and practically substantial, confirming that the improvement offered by observer-specific correction is not marginal but constitutes a meaningful enhancement in

soft-proofing fidelity across the full observer population. Importantly, the degree of variability in individual correction matrices further confirms that a single average correction—while beneficial compared to no correction—is insufficient to capture the full range of individual observer requirements, motivating the clustering approach as a practical compromise between full personalization and population-level correction.

ICC Architecture Integration and Practical Implementation Aspect

A defining characteristic of the proposed methodology is its full compatibility with the current ICC v4 color management infrastructure. By encoding the observer correction as a linear matrix transformation applied within the display ICC profile's colorimetric transformation path, the approach requires no modification to color management engines, host applications, or any other component of the existing workflow. This is a practically significant advantage over iccMAX-based approaches, which offer greater generality and expressiveness but have not achieved broad commercial tool support since the specification's publication. The present work demonstrates that the perceptual improvements achievable through observer-specific correction in the LED soft-proofing context are attainable within the existing ICC v4 framework, suggesting that adoption does not need to await the eventual widespread deployment of iccMAX. The ISO 14861:2015 compliance results further confirm that the methodology meets the objective performance requirements of the established international standard, providing a commercially and technically defensible basis for implementation in professional display products.

Limitations and Future Directions

Several limitations of the present study merit consideration in interpreting and extending these findings. The observer pool for the second experiment, while substantial at 45 participants, was drawn from a specific professional and geographic context; future work should validate the generalizability of the three identified observer clusters across more diverse populations, including broader age ranges and different cultural backgrounds, to assess the universality of the correction requirements identified here. The current implementation employs a 3×3 linear matrix transformation, which accurately captures systematic hue rotation and scaling corrections but cannot accommodate nonlinear observer-specific effects such as differential chromatic adaptation responses or contrast-dependent saturation shifts; higher-order correction approaches may offer further improvements for observers whose individual deviations from the standard observer are not well characterized by a linear model. Finally, while the present study focused on the LED-to-print direction of the soft-proofing relationship, future investigation into the applicability of the same observer correction matrix approach to wide-gamut and high dynamic range display technologies would

extend the practical relevance of this methodology to emerging display environments in the professional color-critical market.

Conclusion

This study addressed a persistent and practically consequential challenge in professional soft-proofing workflows: the perceptual color matching disparity between LED backlight displays and color-managed reference prints that persists even under conditions of rigorous colorimetric equivalence. Through two sequential experiments combining controlled psychophysical observer evaluation with large-scale individual color matching data collection, the research has established both the empirical reality of this disparity and a technically implementable solution within the existing ICC color management infrastructure. The first experiment confirmed through structured evaluation by seven expert observers that CCFL backlight displays provide significantly superior perceptual color matching to reference prints compared to LED backlight displays calibrated to identical colorimetric targets. The LED display consistently produced color appearances that observers judged as systematically more saturated than the corresponding prints across the majority of chromatic test images, a perceptual phenomenon that is invisible to spectrophotometric calibration procedures but directly experienced by human evaluators. This finding validates the long-standing practitioner preference for CCFL displays in color-critical environments and attributes it to a genuine and quantifiable spectral mismatch mechanism rather than subjective convention.

The second experiment demonstrated that an observer correction matrix methodology, derived from a large-scale psychophysical matching study involving 45 observers, can effectively compensate for the perceptual discrepancies identified in the first experiment. Individual observer-specific correction matrices and K-means Cluster 1 representative matrices consistently outperformed the CIE 1931 2° Standard Observer baseline in forced-choice perceptual evaluations, providing observers with a significantly more faithful soft-proofing experience on the LED display. The K-means clustering approach, which reduced the full diversity of 45 individual correction matrices to three representative observer classes, demonstrated that practical and generalizable soft-proofing improvements can be achieved without requiring per-user individualized calibration, addressing a critical requirement for commercial product deployment. Objective quantitative validation against ISO 14861:2015 soft-proofing standard criteria corroborated the psychophysical findings, with observer correction matrix application yielding statistically significant reductions in both average and maximum ΔE_{00} values, and bringing the corrected LED display profile into formal ISO 14861 compliance.

Taken together, these results demonstrate that it is both technically feasible and practically beneficial to substantially improve the soft-proofing performance of

LED backlight displays relative to color-managed prints by incorporating observer correction matrices into the display ICC profile structure. Crucially, this improvement is achievable through modification of existing ICC v4 profile architecture without requiring fundamental changes to color management engines, host applications, or any other component of the established color management ecosystem, and without necessitating migration to iccMAX. This positions the proposed methodology as an immediately deployable solution for contemporary LED display products in professional color-critical applications, offering the professional community a path toward perceptually reliable LED-based soft proofing that preserves full compatibility with the industry-standard ICC workflow.

Future work should investigate the generalizability of the identified observer clusters across more demographically and professionally diverse populations, explore higher-order nonlinear correction approaches for observers whose deviations from the standard observer are not adequately captured by a linear matrix model, and extend the methodology to wide-gamut and high dynamic range display technologies that represent the next frontier of professional display adoption in color-critical workflows.

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