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Investigating Soft-proofing Performance using Individual Color Matching Functions

Hong Yu-Kai*, Chris Yi-Ho Bai

Color Technology Lab, BenQ Corp., Taiwan, Taipei.

*Edward.YK.Hong@BenQ.com

Abstract

CCFL displays have long been favored in professional applications for their spectral stability and neutral grayscale rendering. In contrast, LED-backlit monitors dominate the current market for their higher efficiency and wider color gamuts. Despite identical calibration settings, spectral differences between the two technologies often lead to significant perceptual mismatches, posing challenges in color-critical workflows such as soft proofing [1][2].

To investigate individual differences in color perception, we conducted a large-scale psychophysical experiment involving 45 observers. Each observer used custom software to adjust seven color images (white, red, green, blue, cyan, magenta, and yellow) to visually match corresponding printed targets. White image adjustments were performed using RGB gain controls, while chromatic images were adjusted using HSL sliders.

From these adjustments, individual color matching functions were derived for each observer. ΔE_{2000} values were computed to assess spectral curve differences between individuals and across groups. K-means clustering was applied to classify observer patterns. Results showed that individual color matching functions consistently outperformed the CIE 2° Standard Observer in terms of perceptual accuracy, except for magenta and yellow [3]. Interestingly, several K-means cluster-based color matching functions also delivered good performance representing individual color matching functions.

Spectral differences across groups were visible directly through color matching functions comparisons, validating the effectiveness of clustering and supporting the use of perceptual group modeling [4].

This study demonstrates that incorporating individual color matching functions can significantly improve cross-media color matching. Observer-specific models built on K-means categories offer a scalable, perceptually based approach to user-aware color management [5].

Introduction

Achieving consistent color reproduction between displays and printed media remains a fundamental challenge in workflows such as digital photography, soft proofing, and visual design. Even when devices are calibrated to identical colorimetric standards, users often perceive colors differently due to biological variations and the spectral properties of modern display technologies [6].

Research shows that factors such as age, macular pigment density, cone distribution, neural processing, and environmental conditions affect human color perception [7][8][9]. Although CCFL and LED displays can be calibrated to match in XYZ values and white points, differences in spectral power distribution led to variations in visual experience, especially under high-chroma or near-neutral image conditions [10]. Recent findings also suggest that mesopic luminance conditions significantly influence chromatic adaptation, particularly in dark surround environments [11].

The CIE 2-degree Standard Observer color matching functions (CMFs) assume uniform cone responses across individuals, but real-world data suggests significant observer variability [12]. To address this, researchers such as Fairchild and Braun have proposed observer-specific modeling frameworks to enhance perceptual accuracy in cross-media reproduction [13]. ICC also proposed a new architecture framework, namely iccMAX, to incorporate individual color matching functions into color transformation. iccMAX allows personalized color management solutions to be realized, for example, individual CMFs based softproofing solution [14]. However, due to its complexity, iccMAX has not yet been commercially available since the announcement of 2019. Currently, ICC is working on integrating part of the iccMAX functionalities into current ICC v4 specification [15].

Meanwhile, a growing body of work explores psychometric scaling, contrast perception, and naturalness in color reproduction. These studies provide foundational tools for evaluating perceived similarity between stimuli and generating perceptually balanced image renderings [16][17][18].

Building on these insights, this study incorporates LMS-based perceptual modeling bases on human adjustment result. Observers were asked to manually adjust the displayed colors to match the printed targets using an intuitive HSL interface. This process allows both white point and chromatic hues to be tuned according to each individual observer color matching functions. These adjustments were transformed into LMS cone sensitivity curves. RMSE analysis was used to evaluate perceptual similarity across observers and clusters. K-means clustering was then utilized to identify representative observer groups based on these curve differences.

This approach allows us to construct a perceptual observer model that enhances color consistency in soft proofing applications. Furthermore, spectral data analysis enabled us to visualize LMS curve differences between groups, supporting earlier work on metameric diversity and wide gamut LED backlight spectral optimization [11][19].

Methodology

2.1 Psychophysical Experiment

A large-scale psychophysical experiment was conducted with 45 observers (24 male and 21 female; age ranges from 25 to 45 years old), all of whom passed the Ishihara test to confirm normal color vision. The experiment took place in a standardized laboratory using a professional LED-backlit display calibrated to D50 (5000K) white point, 150 cd/m² luminance, Adobe RGB gamut, and a 0.5 cd/m² black level. Printed samples were produced by using a color-managed inkjet printer and viewed under an ISO 3664 compliant-light booth with D50 illumination [14][20].

Seven images were evaluated and adjusted by each observer during the first part of experiment. The image set including one white image and six chromatic images (red, green, blue, cyan, magenta, and yellow). RGB gain controls were used to adjust the white image, and HSL sliders were used to adjust the chromatic images. Each adjustment was repeated three times per image, resulting in 945 adjustments. This process results in a perceptual method to form an approximate set of individual color matching functions.

***Figure 1.** Psychophysical Adjustment Procedure*

***Figure 2.** Experiment Software for HSL adjustment*

2.2 LMS Curve Derivation and Clustering

The perceptual adjustment results were converted into LMS cone responses using the following procedure:

1. Apply RGB gain to white point matrix adjustments.
2. Convert adjusted HSL values to RGB, then to XYZ using the display's characterization model.
3. Transform XYZ to LMS using the Hunt-Pointer-Estevez matrix [13].

Each observer's LMS curve was normalized and aligned for comparison. K-means method was applied to the whole dataset to obtain the most representative categories. The elbow method determined the optimal number of clusters, which k was determined to be 3. The cluster centroids were used as group LMS profiles. Each LMS cone response functions were then transformed back to x, y, z color matching functions to calculate the color difference between each individual CMFs and CIE 2-degree Standard Observer CMFs. ΔE_{2000} was used to calculate the color difference between each individual CMFs and CIE 2-degree Standard Observer CMFs, and could be used as a metric to verify the individual CMFs is unique to CIE 2-degree Standard Observer CMFs. The same method was also applied to each individual CMFs and derived K-means Group 1 - 3 CMFs. The ΔE_{2000} was to determine if any of the individual CMFs can be represented by K-means Group 1 - 3 CMFs.

To illustrate the variations among the observers, each observer's color matching functions were compared to CIE 2-degree Standard Observer color matching functions. while Figures 7–9 visualize deviations from the K-means Cluster 1 centroid. RMSE values are used throughout to quantify perceptual differences in cone response.

To assess spectral variation across groups, we compared the shape of LMS curves directly and noted consistent differences in the S-cone and M-cone bands. These variations aligned with prior findings on mesopic sensitivity and cone stimulation under spectrally optimized white LEDs [19].

2.3 Validation Experiment

Five expert observers with backgrounds in color assessment participated in a preliminary validation experiment. The five expert observers were recruited to pre-test the experimental setup and validate the procedure. Based on the feedback, additional observers will be recruited for future experiment to confirm the reliability and generalizability of the findings. Seven images (white and six chromatic images) were rendered with six different sets of color matching functions:

1. Standard CIE 2° observer,
2. Averaged CMFs from all 45 observers,
3. Each individual's CMFs,
4. K-means LMS cone response Group 1.
5. K-means LMS cone response Group 2.
6. K-means LMS cone response Group 3.

Experts compared each rendered image on a calibrated display with the corresponding printed target in a light booth under D50 lighting. Each expert was asked to evaluate the perceptual similarity between the displayed images and the printed images. Each expert evaluated each pair three times, and a total of 105 assessments were made [21].

Results

Three categories of CMFs were derived from 45 observers' dataset using K-means method. The three sets of representative CMFs are shown in Figure 3. The three sets of K-means CMFs are very distinct as shown in Figure 3. ΔE_{2000} analysis was applied to all three K-means CMFs in relation to CIE 2-degree Standard Observer CMFs, and the results are shown in Figure 4. The ΔE_{2000} values with respect to K-means group 1, 2, 3 are 4.39, 5.49, and 8.60, and are all larger than 1. Hence, the three sets of K-means CMFs are considered to be unique from CIE 2-degree Standard Observer.

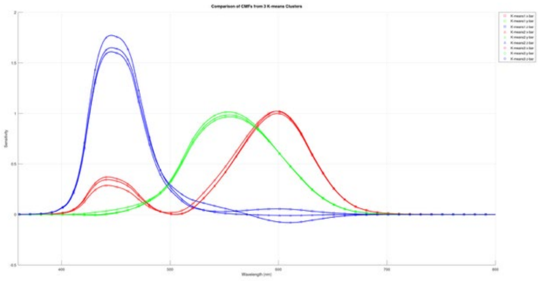


Figure 3. *Comparisons Between Three Sets of Derived K-means Color Matching Functions*

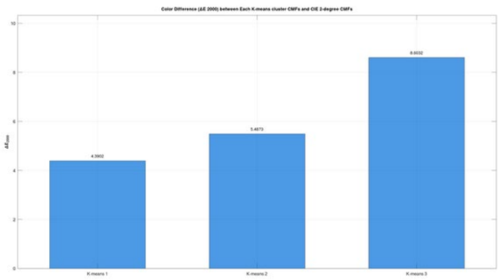
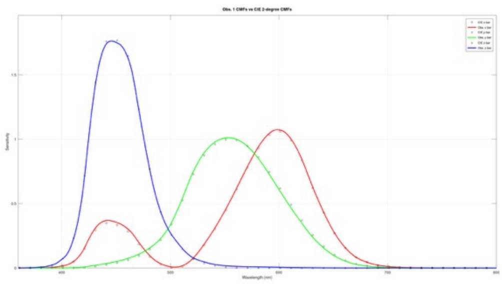
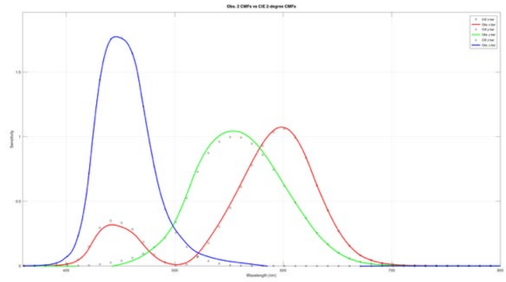


Figure 4. *ΔE_{2000} values between each Derived K-means Categories Color Matching Functions and CIE 2-degree Standard Observer*

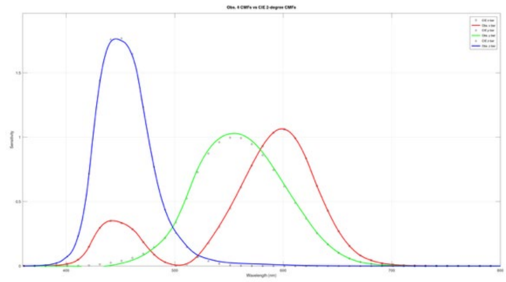
Comparison between each observer's color matching functions and CIE 2-degree Standard Observer is shown in Figure 5. Individual observer's color matching functions are presented in solid lines, and CIE 2-degree Standard Observer is presented in dots. Discrepancies could be found between each observer's color matching functions and CIE 2-degree Standard Observer. ΔE_{2000} analysis was conducted on each individual CMFs and CIE 2-degree Standard Observer to confirm the individuality of the derived individual CMFs. The comparisons are shown in Figure 6. ΔE_{2000} values with respect to Observer 1 to 5 are found to be 2.20, 1.80, 4.51, 1.19, and 1.25. All five sets of individual CMFs indicate large color differences (ΔE_{2000} > 1) to the CIE 2-degree Standard Observer. Therefore, it can be concluded that the individual CMFs obtained are different from the CIE 2-degree Standard Observer.



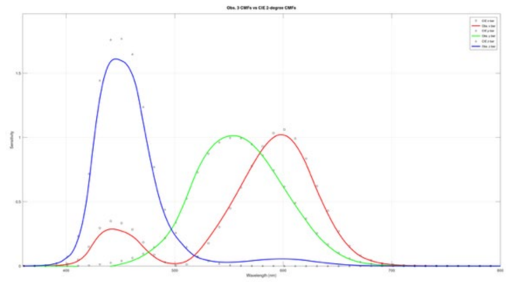
(a): Observer 1



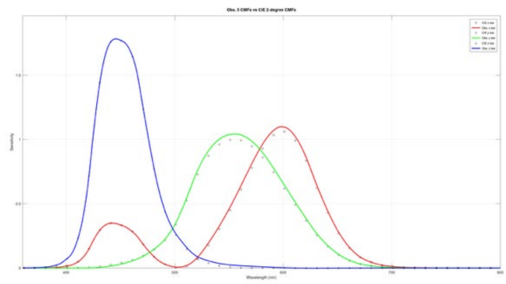
(b): Observer 2



(c): Observer 3



(d): Observer 4



(e): Observer 5

Figure 5. *Observer's Color Matching Functions vs CIE 2-degree Standard Observer*

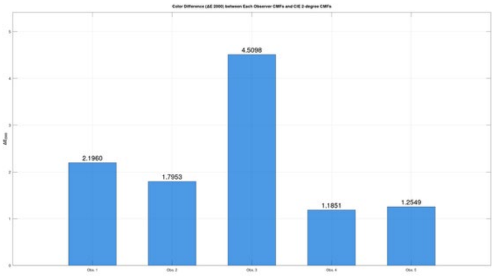
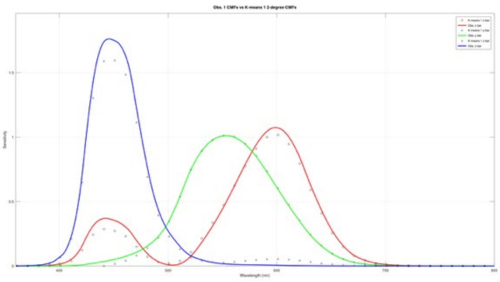
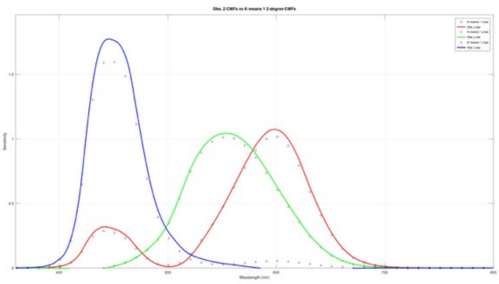


Figure 6. *ΔE$_{2000}$ values between each Observer's Color Matching Functions and CIE 2-degree Standard Observer*

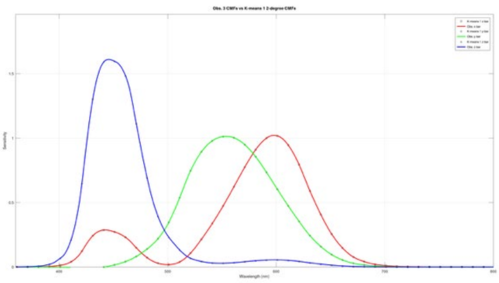
Comparison and analysis were conducted on all three K-means groups, however, for simplicity reason, only K-means group 1 are shown here. Comparison between each observer's color matching functions and K-means group 1 color matching function is shown in Figure 7. Individual observer's color matching functions are presented in solid lines, and K-means group 1 is presented in dots. Discrepancies could be found between each observer's color matching functions and K-means group 1, except for Observer 3. ΔE$_{2000}$ analysis was also conducted on each individual CMFs and K-means group 1 color matching functions. The results are shown in Figure 8. ΔE$_{2000}$ values with respect to Observer 1 to 5 are found to be 4.38, 2.68, 0.14, 3.51, and 3.16. Most of the observers indicated no association with the K-means categories except Observer 3. From Figure 8, it could be noted that the ΔE$_{2000}$ values from Observer 3 is less than 1, therefore, it could be concluded that Observer 3 is highly related to K-means Group 1.



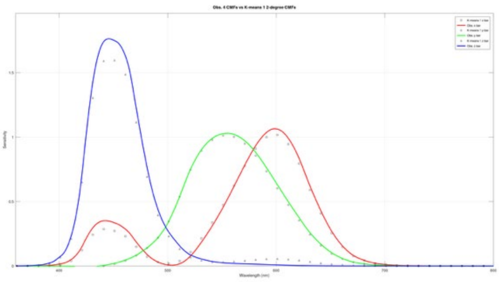
(a): Observer 1



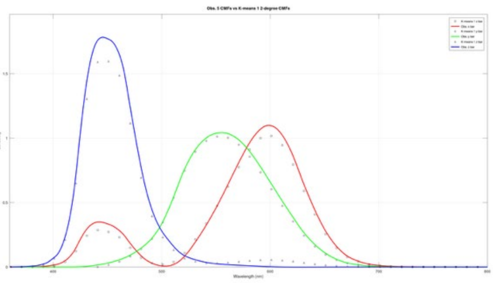
(b): Observer 2



(c): Observer 3



(d): Observer 4



(e): Observer 5

Figure 7. *Observer's Color Matching Functions vs K-means Group 1 Color Matching Functions*

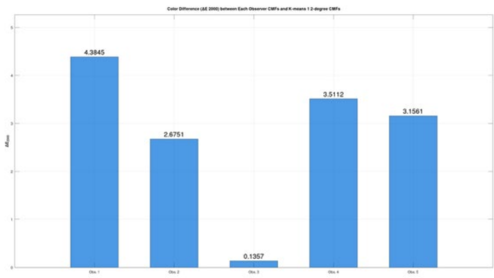


Figure 8. *ΔE$_{2000}$ values between each Observer's Color Matching Functions and K-means Group 1 Color Matching Functions*

Once the individual color matching functions and the K-means group 1, 2 and 3 color matching functions were established, the validation experiment could be conducted. The six sets of CMFs were applied to the seven images mentioned earlier, and the white, red, green and blue images are shown in Figure 9 to 12. The observers were asked to force choose one of the representative images displayed on the monitor among the six representative images. The image has the appearance matched to the hardcopy print in the light booth shall be selected.

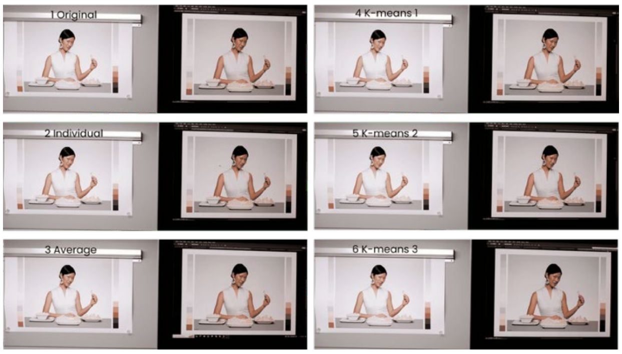


***Figure 9.** Visual Comparison Between Print and Display Under Observer-Specific LMS-Based Profiles (White)*

***Figure 10.** Visual Comparison Between Print and Display Under Observer-Specific LMS-Based Profiles (Red)*

***Figure 11.** Visual Comparison Between Print and Display Under Observer-Specific LMS-Based Profiles (Green)*

***Figure 12.** Visual Comparison Between Print and Display Under Observer-Specific LMS-Based Profiles (Blue)*

The validation experiment results are shown in Table 1. The results revealed that individual CMFs outperformed the CIE 2-degree Standard Observer CMFs in five of the seven test images (white, red, green, blue, and cyan). CIE 2-degree Standard Observer CMFs showed better performance in magenta and yellow images [3][12]. K-means Group 1 also indicated a comparable choice among the judgements. The results support the need for individual color matching functions for softproofing application and the potential of using clustered color matching functions.

1. Standard CIE 2° observer,
2. Averaged CMFs from all 45 observers,
3. Each individual's CMFs,
4. K-means LMS cone response Group 1.
5. K-means LMS cone response Group 2.
6. K-means LMS cone response Group 3.

Table 1. Preliminary Experiment Result

Observer	W	R	G	B	C	M	Y
1	3	3	3	3	3	4	1
2	4	3	4	3	3	1	1
3	4	3	4	3	3	4	1
4	3	3	4	3	4	1	1
5	3	3	4	5	4	4	1

Discussion

The findings confirm that perceptual modeling color matching functions derived from individual adjustment data can effectively represent observer-specific variability. ΔE_{2000} values proved to be an effective metric for comparing spectral curve similarity and determining meaningful clusters. Unlike PCA, which abstracts variation into orthogonal components, ΔE_{2000} values directly measures perceptual color differences, offering a more intuitive framework for color modeling [7][15].

Derived individual CMFs demonstrated consistent superiority over the CIE 2-degree Standard Observer model. This confirmed the prior work showing the limitations of using fixed average observers [2][4]. The few exceptions—magenta and yellow—suggest specific cone sensitivity overlaps or adaptation effects that further exploration is required [11].

K-means grouping presents a promising middle-ground approach between fully individualized modeling and single-observer standards. The spectral curve divergence among groups was perceptually meaningful and aligns with studies of observer metamerism and mesopic optimization [10][19]. This result supports developing practical solutions for soft-proofing application based on limited grouped user profiles.

The visual comparisons (Figures 9-12) and expert judgments (Table 1) further confirm that individual color matching functions are required for softproofing application. Further investigation with representative color matching functions categories can lead to better display fidelity with simplified workflow, especially on soft-proofing application.

Conclusion

This study confirms that observer-specific color matching functions derived from perceptual data can significantly enhance cross-media color consistency[22][23]. By adjusting both white and RGBCMY chromatic hues, it is possible to create individual color matching functions that reflect the real visual experiences of a particular observer.

K-means clustering constructed three representative color matching functions that balanced perceptual fidelity and implementation practicality. These profiles can be integrated into ICC workflows via CHAD or A2B tags, or implemented in iccMAX structures for next-generation personalized color management systems [17][18].

ΔE_{2000} analysis of color matching functions curves provided meaningful insight into perceptual structure, supporting a shift from device-centric to perception-centric calibration. The resulting models show promise for adoption in future color-critical applications such as soft proofing, medical imaging, and digital content creation [6][8][24].

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