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Validation Experiment for Individual Observer Color Matching Functions

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Abstract

Color matching functions (CMFs) form the foundation of colorimetric calculations. Among color-normal observers, individual differences in visual perception lead to substantial variability in CMFs. While this variability was historically less critical due to the broad spectral characteristics of most stimuli, it has become increasingly important with the growing use of narrowband spectral sources in wide-gamut displays and lighting technologies. As a result, individual observer CMFs have become an important topic of study. Li et al. [9] introduced modifications to Asano's Individual Colorimetric Observer Model (AICOM+), including the adoption of the 2012 CIE ocular media model and the removal of LMS normalization prior to CMF conversion. A rapid approach for estimating individual observer CMFs—a reduced model with fewer parameters—was also developed to avoid overfitting while maintaining high predictive accuracy. These individualized CMFs were previously validated using achromatic matches.

In the present study, the colorimetric accuracy of the individual observer CMFs derived from both the full AICOM+ model and its reduced version was validated, using a rating-based experimental method with the same setup. Nine observers, randomly selected from the original cohort, participated. Their individual CMFs were compared to the CIE 2015 10° CMFs using the rating data. The reduced AICOM+ model yielded more accurate predictions than both the full model and the CIE 2015 10° CMFs for 7 out of 9 observers. Future work will apply recent improvements to individual observer models to evaluate potential further gains in predictive accuracy.

Introduction

Accurate colorimetry fundamentally depends on the accuracy of color matching functions (CMFs), which are a set of three spectral response functions characterizing the trichromatic nature of human vision. Among color-normal observers, individual differences in visual perception result in substantial variability in CMFs [2]. While this variability was historically less critical due to the broad spectral characteristics of most stimuli, it has become increasingly important with the proliferation of narrowband spectral sources in wide-gamut displays and lighting technologies—such as LEDs, quantum dots, and lasers [14,15, 22].

To address this variability, the International Commission on Illumination (CIE) introduced standard observer models derived from empirically measured CMFs of a large number of observers. The currently recognized CIE observers for central 2° and 10° fields of view include: CIE 1931 2°, CIE 1964 10°, and the CIE 2015 2° and 10° colorimetric observers [1]. Of these, the CIE 1931 2° observer is most widely used in industry and applied technologies [1]. It was developed using data from Guild [3] and Wright [4], but has notable limitations, particularly an underestimation of short-wavelength sensitivity. In 1959, Stiles and Burch published a more comprehensive dataset of centrally-viewed 10° CMFs obtained from 49 observers [5], which was subsequently used to develop the CIE 1964 10° CMFs [1].

To improve upon the limitations of the 1931 and 1964 observers and to better align with cone spectral sensitivities, the CIE later introduced the CIE Physiological Observer Model (CIEPO06). This model, based on the work of Stockman and Sharpe [11] and Stiles & Burch's 1959 dataset [5], allows for generating CMFs across field sizes from 1° to 10° and for different observer ages [2]. The 2° and 10° CMFs from this model were defined as the CIE 2015 cone-fundamental-based CMFs. David [10] found that the CIEPO06 model provides reasonable estimates of average observer chromaticities within an age group, but does not accurately predict individual observer responses. Similarly, Sarkar [13-14] and Li et al. [6-8] reported that substantial mismatches remain between visual and predicted results when applying the CIE 2015 10° CMFs to individual observers, possibly due to unaccounted age and field size-dependent physiological factors.

The physiological factors underlying spectral sensitivity can be quantified through color matching experiments [16–18]. In a seminal study, Webster et al. [16] performed a factor analysis on the Stiles and Burch dataset [5], revealing that inter-observer variability in color matching was attributable to differences in lens and macular pigment densities, cone photopigment spectral positions and densities (L, M, S), and rod intrusion. Each factor's contribution to variability was characterized by its standard deviation [16]. To model these variations, Asano et al. [19] extended the CIEPO06 model by incorporating eight individual physiological parameters, including the optical densities of the ocular media, macular pigment, and L-, M-, and S-cone photopigments, as well as the spectral shifts of cone photopigment peak sensitivities. This resulted in the development of the Individual Colorimetric Observer Model (AICOM), which also supports the computation of XYZ covariance matrices to quantify observer variability, as proposed by Nimeroff [21]. Studies have shown that the use of individualized CMFs improves predictions of observer metamerism compared to the CIEPO06 model, which tends to underestimate actual inter-observer variability by considering only age [20].

In a recent study by Li et al. [9], modifications to Asano's AICOM model—referred to as AICOM+—were introduced. These included replacing the ocular media model in CIEPO06 with that proposed by the CIE in 2012 [23] and removing the normalization step prior to converting LMS fundamentals into CMFs. Additionally, a reduced version of the AICOM+ model was developed, incorporating fewer parameters to prevent overfitting while maintaining high predictive accuracy. The resulting individual CMFs were previously validated using achromatic color matches obtained under the same experimental setup, with the reduced model yielding superior colorimetric accuracy.

In the current study, we evaluate the colorimetric accuracy of individual observer CMFs derived from both the AICOM+ and reduced AICOM+ models using a different psychophysical method—rating—while keeping the experimental apparatus constant. The validation was carried out with nine observers, randomly selected from the original group who participated in the achromatic matching experiment. The predictive performance of each observer's individualized CMFs was compared against the CIE 2015 10° observer CMFs based on their responses in the rating experiment.

Methodology

Experimental Setup

The validation experiment was conducted using a 10° circular bipartite field housed within a black wooden enclosure, as shown in Figure 1b.

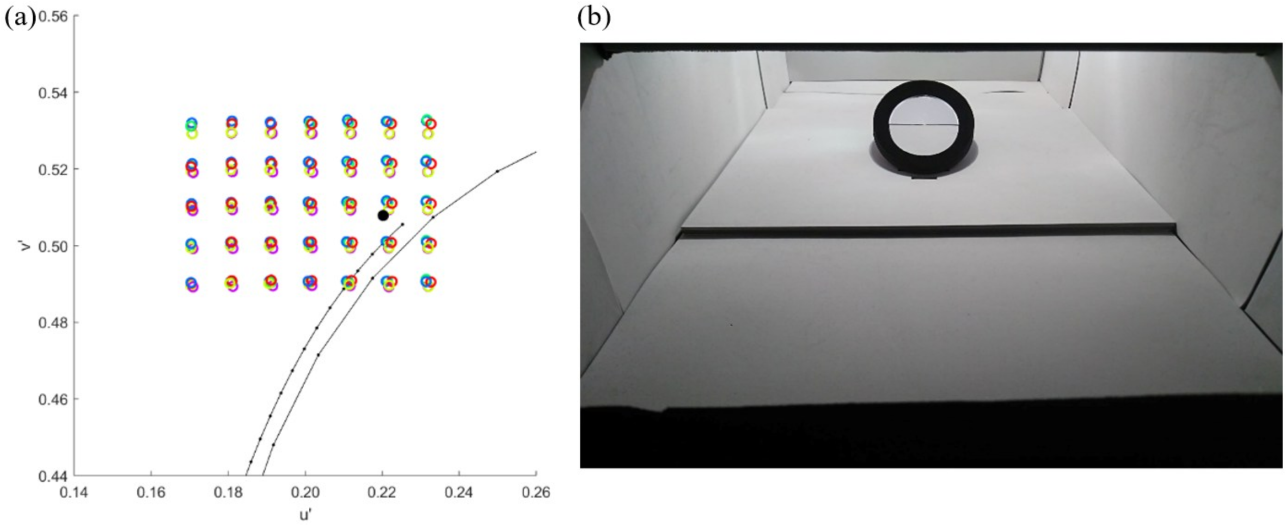

Figure 1. *a) The chromaticities of the grid points for the matching stimuli used in the validation experiment are plotted in the CIE 1976 u'v' color space. Stimuli produced with different primary sets are represented as empty circles in different colors. The black-filled circle indicates the chromaticity of the broadband reference. The long and short black lines represent the blackbody and daylight loci, respectively. (b) The 10° bipartite field from the observer's point of view: the upper field displays a color with the same u'v' chromaticity (calculated using the CIE 2015 10° CMFs) as the reference stimulus in the lower field.*

Through an open window, observers viewed a 10° field composed of a semi-elliptical mirror in the upper half, reflecting the RGB LED mixture, and a spectrally broadband grey card in the lower half, illuminated by a filtered halogen source. The overall luminance of the bipartite field was approximately 70 cd/m². The surrounding area was also neutral grey, with a field size exceeding 150°, providing an immersive viewing environment that helped stabilize the observers' adaptation state throughout the experiment. The chromaticity of the grey surround was slightly above the blackbody locus (CCT = 4673 K, *Duv* = 0.0050), and its luminance was similar to that of the bipartite field. The experimental setup and viewing conditions were consistent with those used in our previous achromatic matching experiment; however, a different experimental method was employed in the current study. Detailed descriptions of the achromatic matching experiment are provided in Li et al. [6,7,38].

In the validation experiment, the reference stimulus (lower half of the bipartite field) remained achromatic, while the upper half sequentially presented a series of colored test stimuli. These stimuli were distributed across a uniform 5 × 7 chromaticity grid in the CIE 1976 *u'v'* color space (Figure 1a), with a spacing of 0.1 Δ*u'v'* between adjacent points. The grid area was selected based on results from the achromatic matching experiment to fully encompass the range of recorded observer matches.

Test stimuli were generated via additive mixing of RGB primaries. Five RGB primary sets—P1, P3, P4, P5, and P8 from the achromatic matching experiment—were selected for the validation study. These sets were identified through sensitivity analysis [9] as being particularly effective for deriving individual CMFs. The peak wavelengths of the red, green, and blue LEDs for each set are provided in Table 1.

Table 1. Peak wavelengths (nm) of RGB primary sets used in the validation experiment

Primary sets (ID in Matching Experiment)	Red	Green	Blue
P1	636	502	447
P3	636	521	447
P4	636	521	404
P5	598	521	447
P8	636	521	475

The test stimuli on the grid were first simulated using the measured spectral power distributions of the LEDs. The intensities of the RGB primaries were optimized to minimize the chromaticity difference between the test stimuli and the corresponding grid points. Chromaticities in the simulation were calculated using the CIE 2015 10° CMFs. The optimization was performed using the "fminsearch" function in MATLAB. The average minimized chromaticity difference between the simulated stimuli and the grid points was less than 0.0001 Δ*u'v'*. These test stimuli were then physically reproduced using the five RGB primary sets and calibrated with an Ocean Optics QE65 Pro spectroradiometer. A total of 175 test stimuli were produced (35 grid points × 5 primary sets). Across the five primary sets, the average chromaticity difference between the realized stimuli and the corresponding grid points was approximately (0.0009 + 0.0003) Δ*u'v'*, with average luminance differences of less than 2%. The chromaticities of the test stimuli generated using different primary sets are shown as distinct colors in Figure 1a.

To enable direct comparison, the chromaticity of the broadband gray reference was designed to overlap with one of the grid points, with a chromaticity difference of less than 0.001 $\Delta u'v'$ (see the black dot in Figure 1a). An example of a stimulus with chromaticity closely matching the reference is shown in Figure 1b.

Experimental Procedure

At the beginning of each experimental session, observers were given a brief explanation of the procedure. During the experiment, test stimuli were randomly selected and presented on a mirror positioned in the upper half of the bipartite field. Observers compared each test stimulus with the reference and rated the perceived color difference on a 0–5 scale, where higher scores indicated greater similarity to the reference (with 5 denoting identical color) and lower scores reflecting larger differences. Observers recorded their ratings by pressing designated keys on a keyboard, once the rating was completed. At any time during the experiment, if an observer wished to revise a previous rating, they could return to that stimulus by pressing the 'back' key.

Each observer rated a total of 370 stimuli, comprising 5 primary sets × 35 grid points × 2 repetitions, plus 20 additional trials. The presentation order of these 370 stimuli was fully randomized. To minimize fatigue, observers were allowed to take breaks upon request. Following each break, they were required to readapt to the background illumination for one minute before resuming the experiment. The average duration of an experimental session was approximately 35 minutes, with observed durations ranging from 20 to 40 minutes.

Observers

Nine observers (4 females and 5 males) were randomly selected from those who had previously participated in the matching experiment to participate in the validation experiment. Their color vision was tested as normal in the achromatic matching experiment. The mean age of the observers was 32 ± 9 years, similar to the average age in the achromatic matching experiment (33 ± 11 years). Observers were asked to perform the experiment without glasses to avoid the blue primary light (404 nm) being filtered out by glasses containing UV filters.

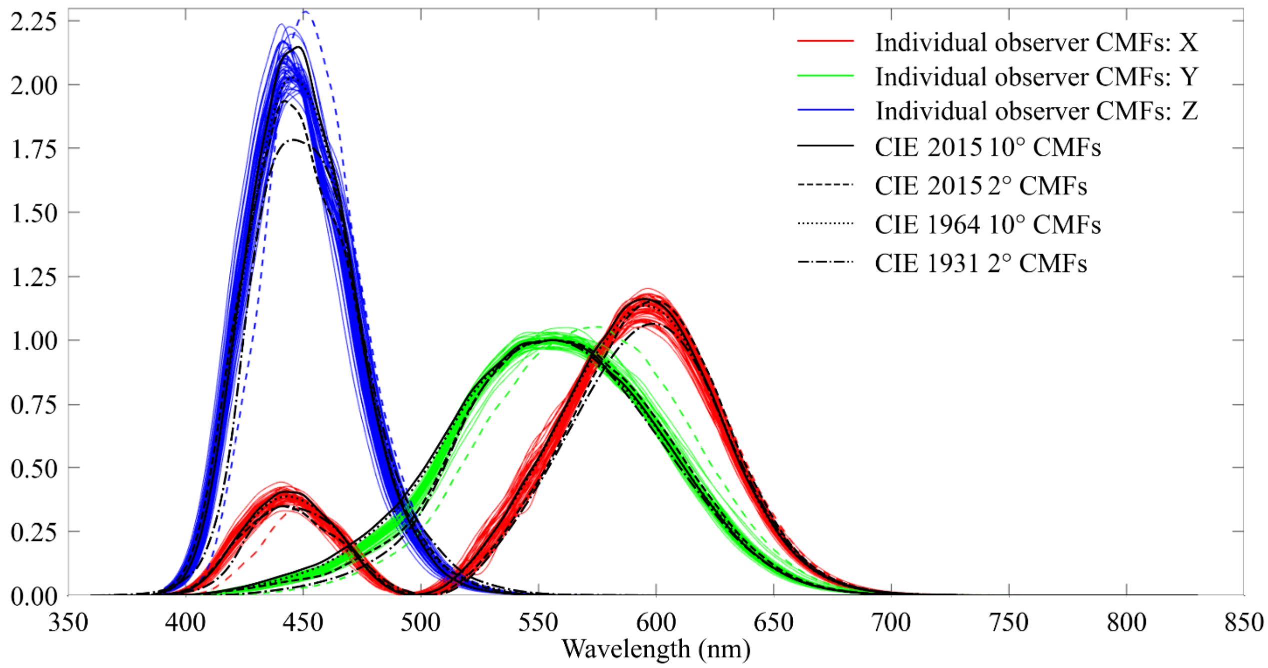

***Figure 2.** Individual XYZ-CMFs generated by the AICOM+ model (red, green, blue solid lines) aiming to best predict current experimental results. Cited from the Figure 6 in Li et al [9].*

Results & Discussion

Gaussian fit for the rating scores

Individual CMFs for each observer were derived using both the full and the reduced AICOM+ models. The reduced AICOM+ model, with a fixed 6° field size and includes only three parameters—age, variation in lens pigment density, and macular pigment density—was previously shown to reduce overfitting and more accurately predict "true" individual observer CMFs [9]. Further details regarding the derivation process can be found in a previous publication in LEUKOS [9]. Figure 2 from that publication presents the AICOM+ individual CMFs of 54 observers in total, including the 9 observers who participated in the current study.

For each observer in the current study, a total of 370 test stimuli were predicted using the individual observer CMFs optimized by the full AICOM+ model and converted to CIE 1976 $u'v'$ chromaticity coordinates. As shown in Figure 3, the scores assigned by the observer were plotted as scatter points in three dimensions, with the corresponding $u'v'$ chromaticity coordinates of the stimuli located on the xy-plane.

Next, based on the distribution of scores as a function of the $u'v'$ chromaticity coordinates, a bivariate Gaussian model was fitted to the rating data for each primary set. The goal was to estimate the observer's rating at the chromaticity of the reference stimulus while also smoothing out noise in the rating data. The bivariate Gaussian surface was fitted to the scored stimuli using the bvgpdf function from the Luxpy package (Smet, 2019), along with the global minimization algorithm “basinhopping” to avoid convergence to local minima.

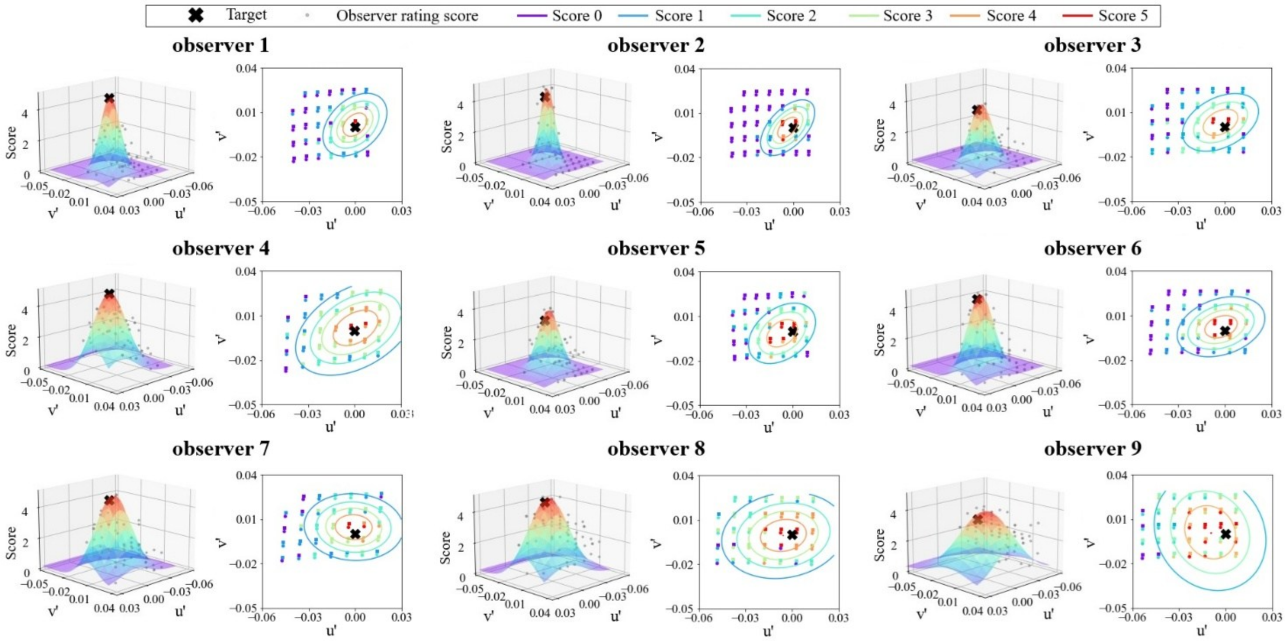

Figure 3. 3D plots and contour maps of bivariate Gaussian surfaces fitted to the scores of test stimuli from primary set P1 for nine observers. Test stimuli and the reference stimulus, predicted using individual observer CMFs from the full AICOM+ model, are shown as gray dots and black “×”, respectively. Contours are drawn in different colors for scores from 0 to 5 in steps of 1. The color of each stimulus indicates its score. Repeat stimuli are shown slightly offset from the first presentation.

Figure 3 shows the bivariate Gaussian surface fitted to the rating scores at the grid points (black dots) for primary set P1. Almost all primary sets yielded results similar to those shown for P1. The reference stimulus, indicated by black ‘x’, are generally located near the centers of the fitted Gaussians for most observers, suggesting that the highest scores were indeed assigned to predicted chromaticities—derived using the estimated individual CMFs—that are close to the reference chromaticities. To better visualize the relative positions of the references and the Gaussian centers, the contours of the fitted Gaussians are also plotted. From Figure 3, the Gaussian contours encompass stimuli with colors closely matching those of the contour lines, indicating that the bivariate Gaussian surface provides a good fit to our results. Additionally, the predicted reference stimuli for all observers lie within their smallest contour lines (score = 4). For some observers, such as #1, #2, and #4, the predicted references are very close to their stimuli rated with a score of 5, demonstrating strong performance of their individual observer CMFs for the P1 primary set.

Bivariate Gaussian surfaces were also fitted to the rating scores as a function of chromaticity coordinates derived using the CIE 2015 observer CMFs and the individual CMFs obtained from the reduced AICOM+ model.

Characterize the performance of the individual observer CMFs

The colorimetric accuracy (i.e., performance) of the optimized individual observer CMFs and the CIE 2015 observer CMFs was evaluated as follows.

As an observer’s perceived match to the reference stimulus corresponds to a chromatic region rather than a single chromaticity point, the center of the fitted Gaussian surface cannot be directly interpreted as the color matching point. Instead, the contour of the Gaussian surface corresponding to a score of 4.5 (the midpoint between scores of 5 and 4) was considered to define the observer’s color matching area—within which the observer could not perceive a difference between the test stimuli and the reference.

The Mahalanobis distance between the reference chromaticity and the boundary of this matching area was computed for each primary set. If the individual observer CMFs are accurate, the Mahalanobis distance between the reference and the matching boundary should fall within one just noticeable difference (JND), indicating that the reference stimulus lies within the observer’s matching area. Mahalanobis distances for all five primary sets were calculated and visualized as box plots in Figure 4 for each observer, representing the color matching error. For reference, the Mahalanobis distance corresponding to 1 JND (0.0033 $u'v'$ unit) at the chromaticity of the reference stimulus was also computed and is indicated by a solid blue line.

From Figure 4, for three observers (#1, #5, and #7), both the median and interquartile range of chromaticity differences between the reference and the observer’s matching area exceed 1 JND. For the remaining observers, median matching errors are within 1 JND, except for observer #3, whose error of 1.1 JND slightly exceeds the threshold. Individual observer CMFs do not consistently outperform the CIE 2015 10° observer CMFs. However, for five of nine observers (#1, #2, #3, #5, and #8), individual CMFs generally predict matches more accurately, with smaller median errors. Among these, observers #1, #3, and #8 show substantial improvement, with predictions shifting from outside to within the 1 JND threshold when using individual CMFs. Observer #5 also exhibits a scientifically relevant improvement, reducing the median matching error by more than 1 JND compared to the CIE 10° CMFs. For the remaining observers, prediction accuracy is comparable to or slightly worse than that of the CIE 10° observer CMFs. As seen with observers #4 and #6, the CIE 10° CMFs already provide accurate predictions for these observers, with median and interquantile ranges of matching errors within 1 JND. In such cases, further improvement using individual CMFs may be limited. It is possible that, the individual CMFs of these observers may not differ substantially from the CIE average CMFs. This hypothesis needs to be further evaluated by examining the similarity between the two sets of CMFs. It would also be valuable to compare the matching regions predicted by different CMF sets, as we did in our earlier validation analysis using achromatic matches [9]. Another possibility is overfitting of the individual observer CMFs, as identified in our previous study. In such cases, the individual CMFs derived from the reduced AICOM+ model may yield more accurate predictions.

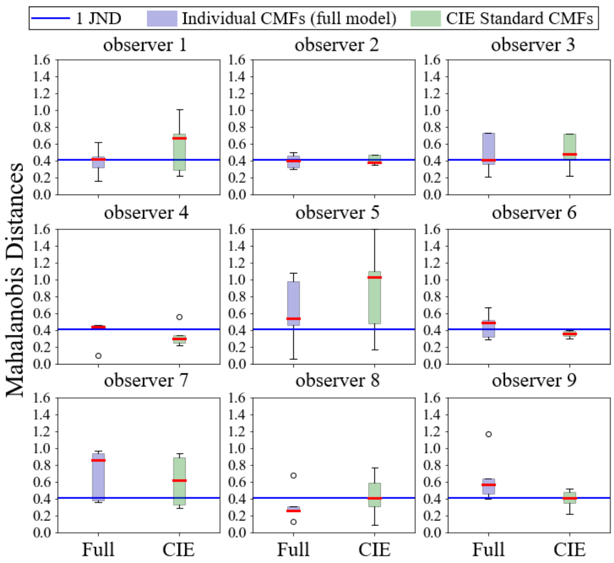

Figure 4. *Mahalanobis distances between the observer's matching region and the reference stimuli predicted by individual CMFs and the CIE 2015 10° average observer CMFs. Each subplot corresponds to a single observer. The blue solid line represents 1 JND converted to Mahalanobis distance.*

To more clearly distinguish the predictive differences between the two CMF sets, the score difference between the reference and the center of the matching area was calculated and compared. This score difference is derived from the Mahalanobis distance (MD) using the equation:

$$\text{Score Difference}=(S_{max}-S_{min})\times\left(1-e^{-\frac{1}{2}MD^2}\right) \quad (1)$$

where S_{max} and S_{min} are the maximum and minimum scores on the Gaussian surface, respectively. The score differences corresponding to the Mahalanobis distance for each observer—predicted using the optimized individual-observer CMFs (from the full and the reduced AICOM+ model) and the CIE 2015 10° average-observer CMFs—are shown as boxplots in Figure 5. To facilitate comparison of predictive performance between the three CMF sets, a solid horizontal blue line at a score difference of 0.5 is included; this line represents the perceptual threshold at which an observer begins to detect a color difference between the test and reference stimuli. This threshold corresponds to the midpoint (score = 4.5) between scores 5 and 4 on the bivariate Gaussian surface, which defines the boundary of the observer's matching area.

Figure 5 shows that, with individual CMFs derived from the AICOM+ full model, the reference stimulus falls within the visual matching area for only four of nine observers (#1, #2, #4, #8). Only three observers (#1, #5, #8) exhibited a noticeable improvement in prediction accuracy, as indicated by smaller median score differences and narrower interquartile ranges relative to the CIE 2015 10° CMFs. This outcome may be due to overfitting of the full AICOM+ model's individual CMFs, which contain ten optimizable parameters.

Compared to the full-model CMFs, the individual CMFs from the reduced AICOM+ model show clear improvement (Figure 5). The reduced model produces optimized individual CMFs with substantially better predictive performance. Comparison of median score differences and interquartile ranges reveals that, for seven of nine observers (#1, #2, #3, #5, #6, #8, #9), the reduced AICOM+ model yields improved predictions relative to the CIE 2015 10° CMFs: for these observers, all reference stimuli calculated with the optimized individual CMFs fall within the matching area. Although no statistically significant improvement of individual observer CMFs was detected by the Wilcoxon signed-rank test. No improvement was observed for observers #4 and #7; further investigation is required.

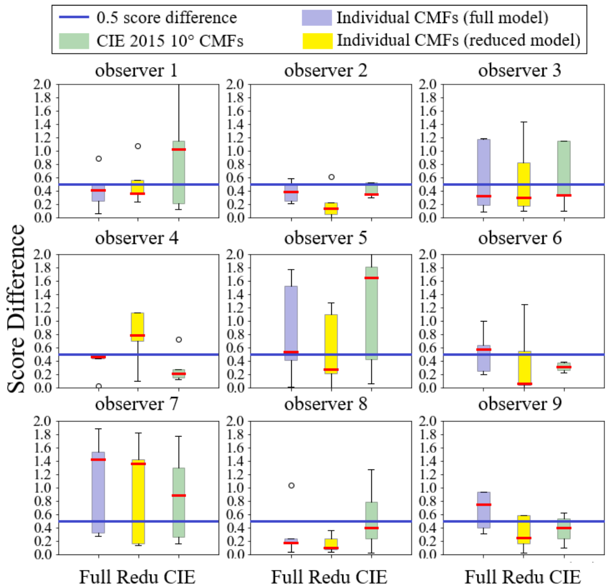

Figure 5. *Score differences between the center of the bivariate Gaussian and the reference stimuli predicted by individual observer CMFs from the full and reduced AICOM+ models, as well as the CIE 2015 10° average observer CMFs. Each subplot represents one observer. The blue solid line indicates a score difference of 0.5.*

Based on our earlier findings, individual observer CMFs optimized from partial matches in the achromatic-matching experiment produced significant improvement in colorimetric accuracy relative to the CIE 2015 10° observer when validated against the remaining matches from that experiment [9]. However, when the same optimized individual CMFs are validated using data from the rating experiment, the improvement is markedly smaller. Thus, the benefit of individualized CMFs is clearer under achromatic-matching validation but attenuated under rating-based validation. We attribute this discrepancy to methodological differences between the two experiments: the optimization and validation datasets differ in measurement technique, intra-observer variability, and the chromaticity distribution of matches, which reduces the apparent advantage of individualized CMFs when validation uses rating data.

Conclusions

In the current study, we validated the matching accuracy of individual CMFs derived from both the full AICOM+ model and the reduced AICOM+ model using data from a rating experiment involving primaries in wavelength regions sensitive to individual differences. The individual CMFs from the reduced AICOM+ model were found to more accurately represent observer colorimetry than those from the full AICOM+ model. Substantial improvements in colorimetric accuracy were observed for 7 out of 9 observers when using the reduced model compared to the CIE 2015 10° observer CMFs. For the remaining two observers, no improvement was found, which may be attributed to slight differences in intra-observer variability and the chromaticity distributions of observer matches resulting from the distinct experimental methods. Further investigation is warranted.

In the future, it would be valuable to examine the similarity between individual observer CMFs and the CIE average CMFs, and to compare their predictions of the color matching area alongside our earlier achromatic matches. Future work will also incorporate recent improvements proposed to individual observer models [12,24] into our modeling framework to assess whether the resulting individual CMFs yield improved colorimetric accuracy. This research on individual CMF prediction has important implications beyond color matching, influencing a wide range of colorimetric computations and applications that depend on CMFs, such as color difference formulas, color appearance models, computer rendering, and virtual reality.

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