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Determination of Individual-Observer Color Matching Functions for Use in Color Management Systems

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Abstract

In color management applications, it is essential to know the color responses of observers to arbitrary spectral radiances so that objective colorimetric quantities can be determined for use in quantitative color-matching applications. These spectral responses are typically transformed to color matching functions (CMFs) such as for the average CIE standard observer which is commonly used for the computation of various colorimetric, perceptual, and appearance attributes. While the standard CIE CMFs for the average observer have been extremely useful for this purpose, it is well-known that there is significant variation in the spectral response amongst color-normal observers. For color-critical applications, there is widespread interest in determining individual-observer color matching functions with minimal knowledge of field-of-view, age, state-of-adaptation, and other viewing conditions in the actual use-setting. By combining eigenvector analysis of CMF datasets with simple individual-observer metameric color matching exercises and multi-dimensional reconstruction, individual-observer CMFs can be predicted, transformed, and profiled for color-managed workflow.

Background

The CIE standard colorimetric observer [1] defines the CMFs of the average human observer and these average CMFs have been used successfully for many years with widespread use in various commercial and academic fields. Given that there is significant variation in the spectral response amongst color-normal observers, this can be problematic in color-critical applications. For instance, in the case of narrow-band primary, wide-gamut, high-dynamic-range displays, the interactions between variations in individual-observer CMFs and display primary spectra can cause significant color perception differences as simulated with the color-normal observers of Stiles and Burch [2,3], Figure 1 and Table 1.

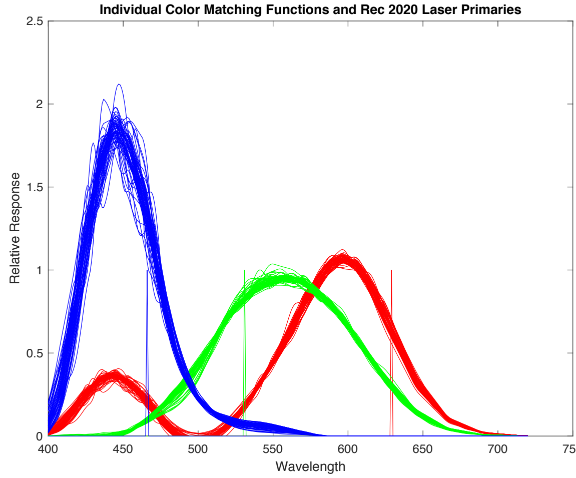

Figure 1. *Individual color matching functions and Rec 2020 laser primaries*

Data Set	Average	Maximum
Rec 2020 Primaries	6.2	10.1
Macbeth Color Checker 24	4.5	11.2

Table 1. *CIECAM16 ΔE differences amongst the individual observers of Figure 1*

Consider the case of multi-collaborator color-managed workflow with color professionals in distributed and remote workplace locations all viewing the same content based on the CIE standard observer. For instance, various directors, photographers, editors, and graders could all be working on producing the same content but at their individual locations each with identically calibrated display and viewing condition setups that are color-managed based on the CIE standard observer. While they may all be color-normal observers, their individual CMFs may be somewhat different from each other and from the CIE standard observer. None of the collaborators are guaranteed to perceive the same color of the content as each other or of the intended CIE-based color-managed content.

One possible solution to this problem is to take advantage of the extensibility and profiling capabilities of well-known color management systems such as ICC and ACES: Profile each collaborator by determining their CMFs (transforming and scaling them appropriately) and including these individual-observer CMF profiles along with the CIE CMFs in the color-managed workflow. With spectral characterization of the display device, new individual-observer output device profiles can be computed with the result that for each color, different device signals can be output to compensate for each collaborator’s difference from the CIE CMFs, yet they would perceive the same colors as each other and as specified by the color-managed content. The solution can be generalized to other classes of devices and included in color-managed workflow, Figure 2.

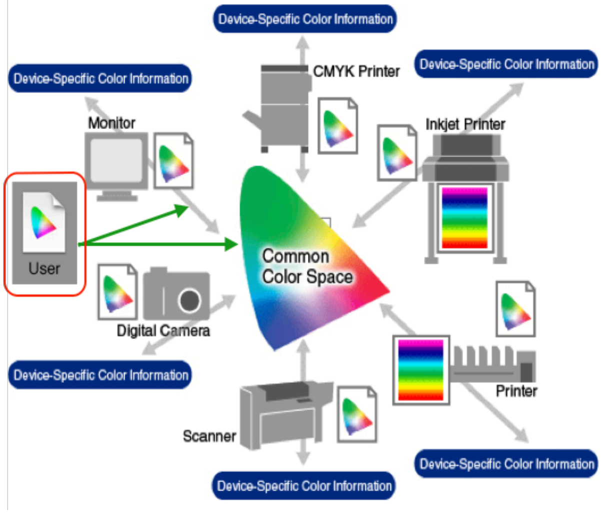

Figure 2. *Individual-observer color matching functions encoded as profiles for use in color-managed workflow*

Unfortunately, direct measurement of individual-observer CMFs in actual use-settings is tedious and impractical for many reasons. However, in the camera industry, estimation of individual unit device spectral sensitivities is often used for production-line per-module color calibration. One method [4] extracts the most significant eigenvectors from relevant historical spectral sensitivity data. Then several test stimuli whose spectral characteristics are chosen to co-optimize orthogonality, dimensionality, and producibility considerations are presented to the camera and the camera response to each test stimulus is recorded. From the eigenvectors, test stimuli spectra, and camera responses, the camera spectral sensitivities can be computed.

Since human CMFs also vary significantly only along a few dimensions, this same method can be extended to efficiently determining individual-human-observer CMFs with a few simple measurements and little knowledge about the user-setting or viewing conditions. Figure 3 shows the first four eigenvectors for the combined Stiles and Burch 2 and 10 degree individual-observer CMFs of Figure 1. Table 2 shows that these CMFs over a range of fields-of-view and observer-ages are, at most, four-dimensional.

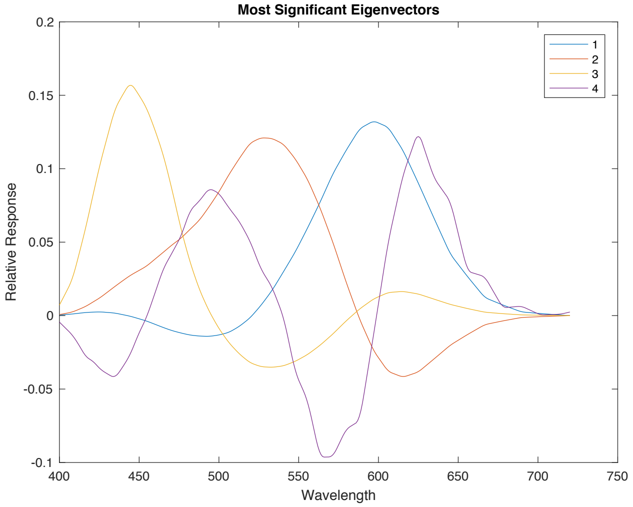

Figure 3. *First 4 most significant eigenvectors for the combined Stiles and Burch 2 and 10 degree individual-observer color matching functions of Figure 1*

Dimensions	Individual	Cumulative
1	87.5	87.5
2	12.1	99.6
3	0.02	99.8
4	0.01	99.9

Table 2. *Percent contributions to the total variance of the 4 eigenvectors of Figure 3.*

Approach

The aforementioned method for estimating each color channel camera spectral sensitivity separately is extended to estimating the complete set of an individual-observer's CMFs simultaneously [5]:

1. Deduce CMF eigenvectors **P** from the relevant multi-observer databases.
2. Present a small set of test spectral radiance stimuli **T** to the observer.
3. Record the observer response **C** to the test stimuli.
4. Solve for the estimated set of observer CMFs **E**.

Taking an idealized noise-free linear systems approach, assume an individual observers' responses **C** to a set of test spectral stimuli **T** depends on the individual's true set of CMFs **S**:

$$\mathbf{C} = \mathbf{S}^t\mathbf{T} \tag{1}$$

where **T** is a column matrix of spectral radiances presented to the observer whose dimensions are *i* wavelengths by *j* spectral radiance samples. The goal is to determine **E**, an estimate of the complete set of unknown individual-observer CMFs:

$$\mathbf{C} = \mathbf{E}^t\mathbf{T} \tag{2}$$

Since direct inversion of **T** to estimate **E** is typically not full-rank, noise-sensitive, poorly-conditioned, and problematic for many reasons, **E** may be estimated instead by determining *k* weights **w** of a selected set of the *i*x*k* most significant eigenvectors **P** of Figure 3:

$$\mathbf{E} = \mathbf{w}^t\mathbf{P}^t \tag{3}$$

so:

$$\mathbf{C} = \mathbf{w}^t\mathbf{P}^t\mathbf{T} \tag{4}$$

then:

$$\mathbf{w} = \mathbf{C}^t(\mathbf{P}^t\mathbf{T})^t[(\mathbf{P}^t\mathbf{T})(\mathbf{P}^t\mathbf{T})^t]^{-1} \tag{5}$$

therefore, the individual-observer CMF estimate **E** reduces to:

$$\mathbf{E} = \mathbf{P}(\mathbf{P}^t\mathbf{T}\mathbf{T}^t\mathbf{P})^{-1}\mathbf{P}^t\mathbf{T}\mathbf{C} \tag{6}$$

and the resulting minimum norm solution for the estimate of an individual observer's CMFs **E** is thusly determined.

Simulation

To predict the upper limit on the best-case performance of the method (without the noise model of [4]), the set of test spectra shown in Figure 4 was used as **T**. These spectra have the advantage that they are reliably producible with inexpensive LED-based devices. While not strictly necessary to satisfy the degrees of freedom of the problem, the use of the complete set allows for an overdetermined estimate of **E**. By choosing a subset of these or similar spectra, orthogonality, dimensionality, and sample size considerations can be co-optimized to determine the minimum set size and characteristics of **T** for most efficiently and reliably determining **E** to minimize the effort required of the individual-observer color matching exercises required to measure **C** in the actual use-setting.

Given these **T** and the complete set of individual-observer CMFs shown in Figure 1 as **S**, the simulated responses **C** from equation (1) can be computed and substituted in equation (6) to determine **E**. Then the true individual-observer CMFs **S** can be compared with the simulated estimated individual-observer CMFs **E**. Figure 5 shows typical results for one particular observer, comparing the Measured (**S**), Estimated (**E**), and Reconstructed (from the first four most significant eigenvectors and eigenvalues) CMFs.

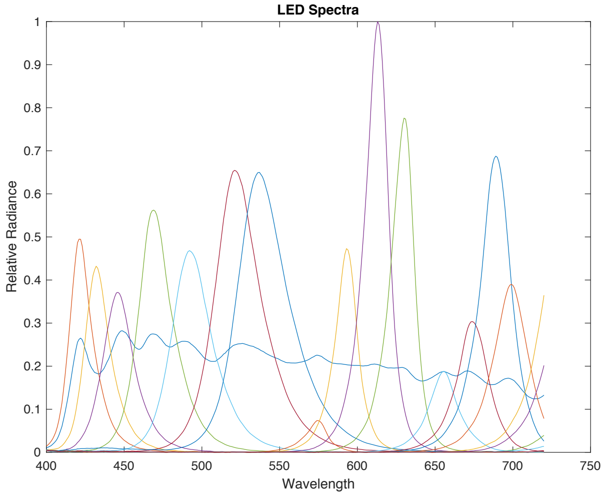

Figure 4. *Spectral radiances used as **T** to simulate **C** and compute **E**.*

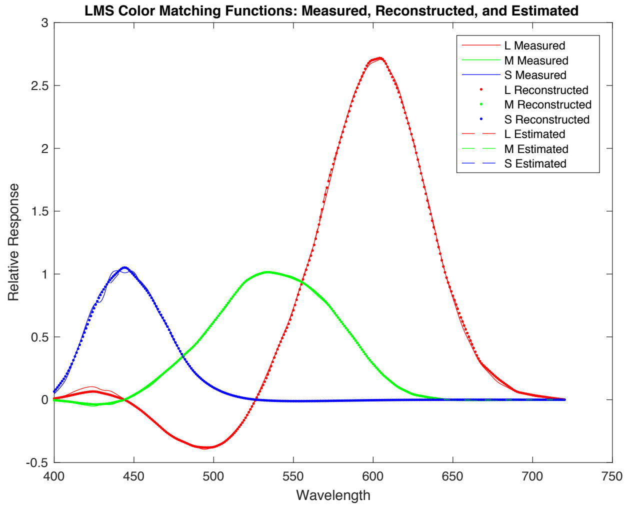

Figure 5. *Typical simulation performance shown for one individual observer.*

Table 3 shows the errors aggregated across all of the individual observers of Figure 1. The RMS error relates to spectral mismatch while the integral error shows the cumulative mismatch and is important in the development of colorimetric transforms.

Error	Average	Maximum
RMS	0.026	0.35
Integral	0.54%	3.12%

Table 3. *Simulated estimation errors aggregated across all observers.*

Experimental

In collaboration with the University of Nevada, Reno at the Center for Integrative Neuroscience in the Department of Psychology, research is underway to further develop the method and perform the experimental verification. One key issue is to determine an effective, efficient, and relevant setup for measuring the individual observer response **C** to the test stimuli **T**. In the case of estimating the spectral sensitivities of a camera, it is a simple matter to read out the camera responses (e.g. RGB) as the test stimuli are presented. In the case of estimating the CMFs of an individual human observer, no such simple readout is practical.

The challenge becomes to develop a setup that can be used to perform the experiments in a manner that is translatable and practical for the intended application – deployment in the field for use by color editors and other color management professionals. It must be compact, inexpensive, reliable, easy-to-use, efficient, and effective. Fortunately, producing such devices for color professionals to perform these exercises in the actual use-setting is practical with currently available components using methods similar to those described next.

The classical approach is to perform maximum-saturation bipartite field metameric color matching exercises, though with luminance levels, viewing conditions, and adaptation states typically associated with color-managed workflow. In one field, a test stimulus **t** is presented while in the other field the observer adjusts the intensities **c** of three primaries until a metameric match is achieved between the two fields, Figure 6. Alternatively, a single uniform field may be displayed and the two sets of lights are presented sequentially at well-chosen temporal frequencies. This can improve the reliability of the matches by eliminating the border between the bipartite fields in addition to making for a simpler device. In either case, the three intensities thusly determined relate to the individual observer response **c** to that test stimulus **t**. The procedure is repeated for all test stimuli of interest (e.g. Figure 4) to build the complete set of **C** and **T** from each of the individual **c** and **t**. This provides the data set necessary to estimate the individual-observer's CMFs **E**.

Similarly, to determine the ground truth individual-observer's CMFs **S**, the same procedure can be employed, but substituting monochromatic stimuli in the test field and repeating for all visible wavelengths of interest, then computing the CMFs as usual. In this manner, the known **S** and estimated **E** individual-observer CMFs may be compared.

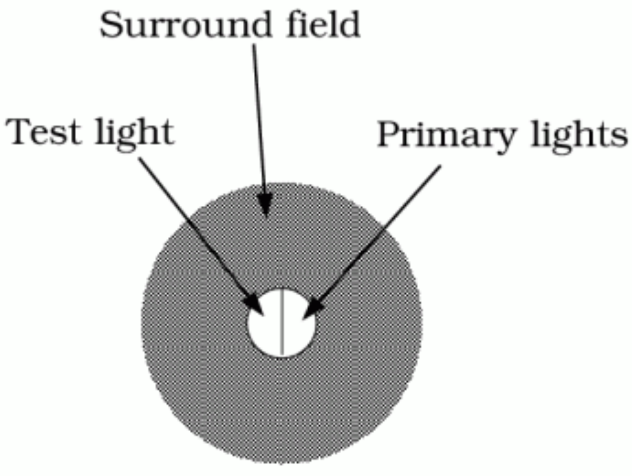

Figure 6. *Bipartite field metameric color matching.*

Discussion

This eigenvector-based method is somewhat related to factor-analysis-based methods in that in both cases the resulting basis functions account for the variation in the original observer data, though in very different ways. The eigenvector-based method computes the minimal set of useful orthogonal basis functions that account for the maximum total variance in the original observer data without differentiating between the contributions to the total variance from the diagonal variances or from the off-diagonal covariances. It is purely computational and the resulting basis functions do not necessarily have any physiological interpretation.

Factor analysis assumes an underlying latent model based on external considerations that account for the maximal covariances attributable to the model's factors instead of the total variance. The resulting basis functions may well have a physiological interpretation [6] but are generally different from the basis functions produced by the eigenvector-based method. While extremely useful for analytical purposes, in order to apply the factor-based model in the required predictive manner to perform the CMF estimation, the model must be assumed, the factors must be known, and the parameters (loadings) must be provided.

As has been shown above, the eigenvector-based method is relatively assumption-free and no underlying physiological model for the basis functions is required. Therefore, the conditions associated with factor analysis for prediction need not be met to obtain the CMF estimation solution with the eigenvector-based method.

It is also important to recognize that the eigenvector-based method produces CMF estimates **E** that are inherently potentially metameric with the actual CMFs **S** in the following sense. Suppose that **E** is a column matrix of the full set of exactly-determined individual-observer CMFs and **S** is a column matrix of the known ground truth individual-observer CMFs. Further suppose **C** is the set of individual-observer response values to a set of spectra **T** used to exactly-determine **E**. Then:

$$\mathbf{E}^{t}\mathbf{T} = \mathbf{C} = \mathbf{S}^{t}\mathbf{T} \tag{7}$$

producing the result that the estimated CMFs **E** are potentially observer-metameric with the actual ones **S** over the exactly-determined test spectra set **T**.

Typically the various estimates and colorimetric transforms are computed in an overdetermined manner, so the results can be considered to be approximately potentially metameric in a least-squares sense. This is actually a favorable result in that the possible estimation errors range between an exact replication of the true individual-observer CMFs and a very close metameric match, depending on the degree to which the dimensionality of the individual observer matches that of the databases from which the eigenvectors were originally extracted.

In order for the estimated CMFs to be useful in color management systems that are based on the CIE standard colorimetric observer **O**, it may be desirable to map the estimated CMFs **E** to **O** by solving for **m** in the following transform:

$$\mathbf{O} = \mathbf{mE} \tag{8}$$

where **m** is an operator (not necessarily a linear transform) that minimizes errors in the prediction of **O** (or a related cost function) and may have other useful properties such as ensuring proper scale in the prediction of the Y tristimulus value. Once **m** is determined, then the mapped individual-observer CMFs **E'** and **m** can be used in color management systems more conveniently as in Figure 6:

$$\mathbf{E'} = \mathbf{mE} \tag{9}$$

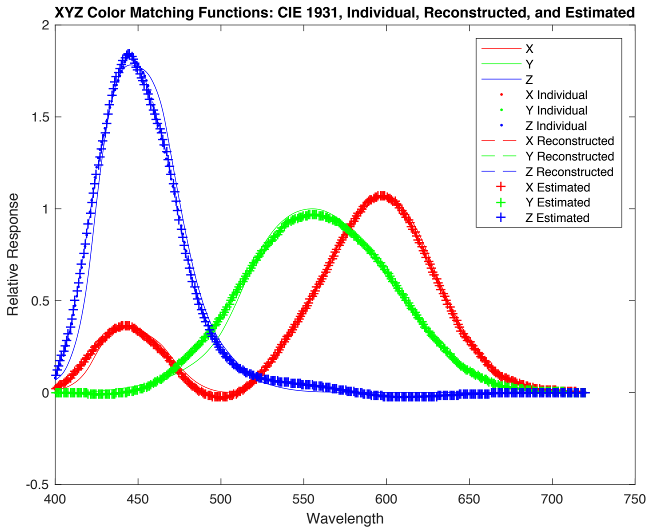

Figure 6. *CIE standard observer and transformed individual-observer CMFs*

Conclusions

A simple method is proposed and simulated with the potential to efficiently characterize the CMFs of individual observers in their use-settings in a manner suitable for color-managed workflow applications. Work is currently underway to perform the experimental verification.

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Author Biography

Eric Walowit's interest is in appearance estimation, color management, camera characterization, and digital photography. He is founder (retired) of Color Savvy Systems, a color management company. He currently helps friends and colleagues with interesting color problems and ventures. He graduated from RIT's Image Science program in 1985, concentrating in Color Science. He has authored more than 50 patents, publications, and presentations. Eric is a member of ICC, ISOTC42, IS&T, and CIEJTC10.

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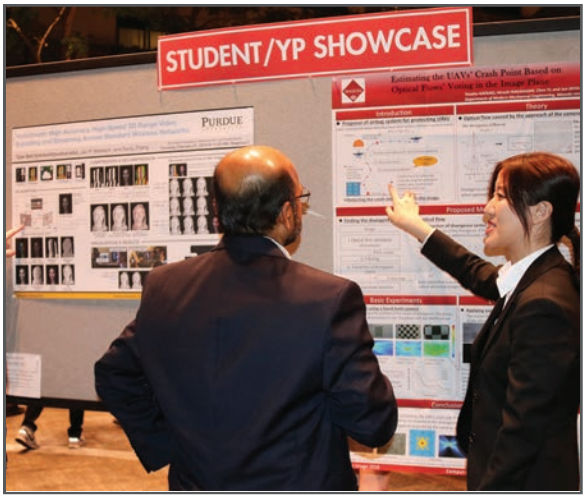

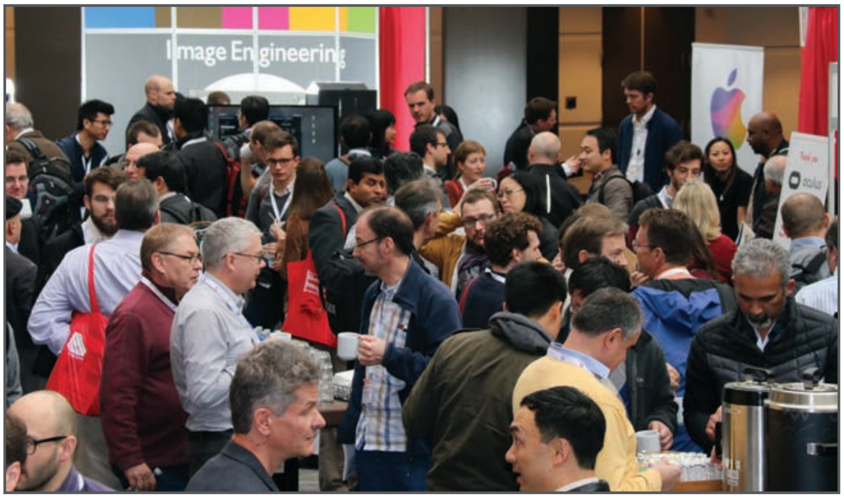

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