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# Observer Metamerism Models and Multiprimary Display Systems

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**Abstract.** Television and cinema display are both trending towards greater ranges and saturation of reproduced colors made possible by near-monochromatic illumination technologies. Through current broadcast and digital cinema standards work, system designs employing laser light sources, narrow-band LED, quantum dots and others are being actively endorsed in promotion of Wide Color Gamut (WCG). However, spectrally selective excitations of naturally different human color response functions exacerbate variability of observer experience. Further, singular 'standard observer' summaries of human color vision, such as those found in the CIE's 1931 and 1964 color-matching-functions and used extensively in motion picture color management, are deficient in recognizing expected human vision variability. Many researchers have confirmed the magnitude of observer metamerism in color matching, but few have shown explicit color management with an aim of minimized observer perception variability. This research shows that not only can observer metamerism influences be quantitatively predicted and confirmed psychophysically but that intentionally engineered multiprimary displays employing more than three primaries can offer increased color gamut with drastically improved consistency of experience.

Keywords. observer metamerism, multiprimary display, laser projection, ITU-R Rec. 2020

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# Introduction

Color matching functions (CMFs) defined for a single statistical standard observer are insufficient for describing spectral responsivity variability amongst a population of color-normal observers. Several recent studies have shown where color management employed under the direction of the 1931 or 1964 standard observer alone yields unacceptable results for color critical applications such as reference display calibration and cinema color grading<sup>1,ii</sup>. Research focused on more inclusive definitions, respectful of physiological variations, suggests a wide distribution of CMFs is necessary to accurately reflect realities of color vision. Candidate CMF models include those of CIE 2006, which account for gross demographic performance against age and observed field-of-view<sup>iii</sup>. Others from Sarkar, et al. and Heckaman et al. utilize statistical clustering of more complex anatomical and psychophysical experiment data to derive most likely CMF distributions<sup>iv,v</sup>.

Color-matching tasks performed by real and simulated observers have also been shown to vary significantly as a function of the spectral signature of test stimuli<sup>vi</sup>. In the cinema industry, there is great concern about a potentially diminished quality of experience (QoE) as a result of emerging color trends in display technology. Next-generation cinema and television systems promise to deliver a wider color gamut through implementation of laser, LED and quantum dot illumination under the mandate of ITU-R Rec. 2020 color specifications. These essentially monochromatic color primaries have been shown to greatly increase variability of color perception and color matching<sup>vii</sup>. In an industry that imposes rigorous controls on the color reproduction characteristics of wardrobe, makeup and set decoration across a myriad of image capture and display technologies, the potential for exaggerated differences of perception amongst audience members defeats the efforts of directors, cinematographers and colorists to dictate every element of the communicated imagery.

A solution to the increase of observer variability associated with larger color gamut and more selective spectral primaries may lie in multispectral color management and multiprimary display systems. In previous publications, the design of a seven-channel multiprimary display (MPD) engineered at Rochester Institute of Technology (RIT) has been outlined, the intent of which is to intentionally minimize observer metamerism and to narrow observer perception variability while simultaneously delivering an increased color gamut<sup>viii</sup>. In this paper, we will describe color-matching experiments configured to validate the implemented color models and the constructed display system.

# **Prior Experience with Highly Metameric Color Matching**

In research closely associated with that presented here, Asano, et al. have sought to characterize the magnitude of observer metamerism present in color-matching tasks, based on both uniform expanses of color and real images<sup>ix</sup>. In their work, a commercial LCD display was pitted against a pico laser projector (not conforming to ITU-R Rec. 2020) to assess how much variation would result from intentional color corrections made by real observers. Reference stimuli were shown on the laser projector and again on an LCD display in a paired comparison. Observers were asked to manipulate the mean CIE L\*a\*b\* of the LCD image until it best

matched the fixed laser projector image. From their results, Asano, et al. found inter-observer variability for the matches was significant versus any intra-observer noise. Further, trends were noted in average observer color matches as a function of scene complexity. Mean performance for expansive uniform areas was best simulated by wide fields-of-view using CIE2006 CMF models, while the performance in more spatially complex scenes was substantiated using narrow field-of-view CMF models. As a visualization of the magnitude of differences in the results, Figure 1 shows the sRGB-rendered LCD images matched to the baseline laser projector images by five extreme observers and the hypothetical 1964 observer for both uniform color stimuli and a high-spatial complexity image. Though each of the respective observers in the included examples believed they had created a perfect match between laser and LCD during the experiment, an objective interpretation of each sample by the 1931 standard observer revealed large variation.

As a complement to the work of Asano, et al., the current experiments serve to validate that observer color matches across disparate display technologies can, on average, be predicted and that failures of observer metamerism and variability in cross-media applications can be minimized with an intentionally-designed display system. These results are intended to confirm the vision models and metamerism indices derived in recent research, including the CMF sets of CIE2006, Sarkar, et al. and Heckaman and Fairchild. Color difference indices used have been published previously and are summarized in equations 1 and 2.

$$OM_{x} = max(\overline{\Delta E_{y,P,l}}) \tag{1}$$

where **OM**<sub>x</sub> refers to observer metamerism magnitude based on CMF sets from  $\mathbf{x} =$ Sarkar/Fedutina (S), CIE 2006/TC1-36 (C) or Heckaman (H). Color difference values between a reference stimuli and test sample are computed for  $\mathbf{y} = \Delta E_{ab}$  (ab),  $\Delta E_{94}$  (94) or  $\Delta E_{00}$  (00) for each patch in a patchset **P** for each observer **i** in the CMF set. The observer metamerism magnitude is the maximum individual observer average patchset color difference across all the patches in **P**. In this manner, the observer metamerism represents the on-average poorest color matching observer from the population of CMFs for the patchset. To minimize this index suggests a move towards improving the color match between two stimuli for all observers in a population, and thus a minimization of observer metamerism magnitude.

$$OM_{x,var} = \overline{Vol(\Delta(L^*a^*b^*)_P)}$$
(2)

where  $OM_{x,var}$  refers to observer metamerism variability, the mean CIELAB ellipsoid volume constructed from CMF-based error vectors in L\*, a\* and b\* from each patch in a patchset **P**. The index is again dependent on the CMF set chosen as above. For the present work, covariance analysis is used to construct the ellipsoid volumes from individual observer CIELAB error vectors with a 90% statistical significance.

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Figure 1. Sample observer color matching variability from the work of Asano, et al. showing rendered sRGB reproductions for a uniform color patch (left) and a high spatial complexity image (right)

# **Equipment Used in This Experiment**

Observers participating in this experiment were asked to assess color matches from uniform stimuli generated in a simultaneous, paired comparison. Three different emissive color systems were compared for observer preference in confirmation of the developed observer metamerism models. The first was the RIT multiprimary display introduced in reference [viii], comprising seven spectral channels optimized to deliver minimized observer metamerism (OM<sub>s</sub>) when reproducing Kodak/AMPAS training spectra<sup>x</sup> illuminated by four practical cinema light sources, consisting of CIE illuminants D65, A and F2 and a measured HMI cinema light. This system employs the neutral illumination spectra from one retrofitted Optoma DX339 digital projector focused onto a grid of optimized transmissive color filters, using 8-bit native modulation and a spatial segregation scheme. The individually-modulated channels are then recombined through focusing optics and an integrating sphere in order to present a uniform color patch to the observer. The displayed spectra fluctuated slightly over the course of all experiment sessions conducted due to some instability in the consumer-grade UHP lamp, but a representative measurement is shown in Figure 2. Also shown are representative, peak-normalized EOTF curves from the seven primaries for the system. Even though the system was powered by a single lamp, spatial non-uniformity across the image field yielded slight variations amongst these response functions for all of the channels. The resultant chromaticity gamut, along with images summarizing the optical configuration of the MPD, are seen in Figure 3.



Figure 2. RIT MPD representative spectral output and EOTF





Figure 3. RIT MPD chromaticity gamut and illumination optics

The second system was a Panasonic PTAX200U LCD projector capable of 1920x1080 resolution; employing an optical block with three independent LCD modulators, internal color filters and a splitting/re-combining prism to isolate the RGB signal paths. This projector is driven natively in 8-bit mode and focused onto a diffuser so as to produce a uniform color patch to the observers. This system delivers native SMPTE-431 gamut and is thus representative of contemporary standard digital cinema color reproduction. Spectra and EOTF, again, varied slightly over the course of experimentation, but representative samples are shown in Figure 4.



Figure 4. Panasonic PTAX200U representative spectral output and EOTF

The final color system comprised a Necsel Matrix 250 laser illumination engine and a Necsel Intelligent Controller used to modulate laser intensity. The RGB laser emissions conform to center wavelengths of 465, 525 and 638nm, very close to the specifications for ITU-R Rec. 2020 wide-gamut primaries (467, 532 and 630nm). Output spectra were confirmed using a PhotoResearch 655 spectroradiometer with 8nm bandwidth and 5nm sampling. Radiometric control was implemented using pulse-width modulation (PWM) at 50Hz, near the threshold for human flicker fusion. To further minimize flicker, each 20ms PWM period was split into 200 duty-cycle spans that were alternately indexed with 'on' state commands, based on 0.5% drive increments. White balance was controlled to the three independent channels via individual amperage settings. Figure 5 summarizes representative spectra and EOTF responses for the system. Influences of variable laser 'on' state rise and fall times are evidenced in the nonlinearity of the three channel EOTFs as a function of duty cycle. The outputs of each laser were directed into an integrating sphere to present uniform color stimuli to the observer. Cooling fans directed onto the system also served to vibrate the laser sub-assembly slightly, thus eliminating any visual speckle from coherent diffraction. Some fringe aberrations were visible through the integrating sphere exit port and observers were asked to ignore those in making color assessments. Images of the optical assembly are shown in Figure 6.



Figure 5. Necsel Matrix 250 Laser representative spectral output and EOTF



Figure 6. Necsel Matrix 250 Laser and optical assembly

Reference stimuli for color matching were generated using Color-aid artist papers and a JUST LED lightbooth set to CIE D65 output. The spectral emission from each of the available papers were measured and a subset was chosen to deliver a representative range of observer metamerism performance across all three display systems. Care was also taken to not deliver any color stimuli out of gamut for the three color reproduction systems. The nature of LED illumination in the lightbooth allowed for significant spectral variability in the reference stimuli. Representative spectra of the 25 sample colors used in the experiments is shown in Figure 7.

Figure 8 shows the experiment setup as experienced by the observer. The reference color patch is visible through a round port on the front of the lightbooth (left) and the exit ports of the integrating spheres for the comparison displays are isolated to the right. For each experiment session, the room lights were turned off and the observer was aware only of the 3 color stimuli in front of them. Each sample patch subtended an approximate 2° visual field.



Figure 7. Color-aid paper / JUST lightbooth reference spectra

# Calibration

A total of 88 observers took part in color matching experiments over the course of several weeks. Each of the four optical assemblies used drifted with daily power-cycling, so an extensive calibration process was performed at the beginning of every observation session. The JUST lightbooth was turned on and allowed to warm up for 20 minutes. Then, the spectra of each reference Color-aid paper intended for that day's experiment was measured. A Teflon diffuser was also measured within the booth to quantify radiometric output and to provide a reference white for all color difference formulae for that session. All spectral measurements were taken from the vantage of the seated observer with the PR-655 spectroradiometer.



Figure 8. The two-alternative, forced-choice experiment setup with aim stimuli from Color-aid papers in the lightbooth on the left and integrating sphere exit ports for the two compared displays on the right.

Primary spectra for each of the display systems were measured so that reconstruction models could be customized to precise system performance on a given day. With each spectra measurement, separate white and black calibrations were also performed. Absolute radiometric scalars, necessary to gain the peak-normalized spectra to match the black-corrected white output, were needed to establish radiometric translation in all channels, consistent with the reference stimuli reproduction models. EOTF responses were also re-measured periodically as these were used to generate drive values responsible for specific spectral output, as well as to refine spectral matches in subsequent calibration steps.

With the daily characterization of each system complete, spectral models were then used to generate drive values for each display with the intent to match the color of each reference Color-aid stimuli, under constraints of each experiment's design. Ideal values were computed in simulation, utilizing constrained nonlinear optimization per patch and sent to each display for measurement affirmation. An iterative adjustment loop was then executed to refine drive values until color difference indices measured against design objectives were as consistent as possible. These refined values were then saved for use during the observer experiments. The process described here was completed every day that experimental data was collected.

# **Spectral Optimizations and Experiment Design**

Validation of the RIT seven-channel MPD design for reducing observer metamerism was executed using a two-alternative, forced-choice experiment in four optimization configurations. In Experiment 1, the RIT MPD was compared to the Panasonic SMPTE-431 display system. Both systems were calibrated to deliver an excellent metameric match to the 25 Color-aid paper reference spectra, using the 1931 2° standard observer. This scenario mimics typical color management strategies employed in professional cinema equipment calibration. The Panasonic system theoretically yields a single ideal match within the limitations of quantization error due to the 8-bit drive system and system noise. The RIT MPD, on the other hand, is overspecified. Accordingly, a nonlinear co-optimization was executed where observer metamerism, OM<sub>s</sub>, was minimized using the seven primary channels under constraint of a perfect standard observer colorimetric match. 28 observers participated across four different days of testing. Most samples delivered  $\Delta E_{94}$  well below 1.0 in each system with reasonable consistency across the experiment sessions and with the two displays evenly matched. The top row of Figure 9 shows the observer metamerism performance realized in each system for each of the four days of Experiment 1. Here, the three-channel system is inferior to the RIT MPD for all but a very few of the patches as is consistent with the MPD design objectives.

During the course of the experiment, participating observers were seated directly across from the middle of the three stimuli. Room lights were turned off and a short period of dark adaptation was permitted while instructions were delivered to observers. One at a time, the Color-aid reference papers were placed in the lightbooth and presented to each participant as the reference color to be compared to each of the other two stimuli visible. The Panasonic and MPD systems were then controlled to display their optimized attempt for a color match to the shown aim. The observer was asked to enter their choice for which of the two was a better color match to aim using keyboard input. Observers were instructed to ignore any optical aberrations or imperfections in the colored circles. They were also instructed to simply select which of the two test stimuli was a better match to the reference in their opinion and they were encouraged not to be concerned about any trending in their selections. Observers had a short time to rest between each selection as papers had to be manually replaced in the lightbooth.

Experiment 2 used the same two displays and 25 Color-aid reference spectra, however, the optimization scenario enforced on the two systems was a minimization of  $OM_s$  versus the reference spectra irrespective of any consequential impact to standard observer colorimetric match. Figure 10 shows the achieved calibration performance for the two display systems across four different observation days. Versus Figure 9, the RIT MPD yields far superior observer metamerism with many patches yielding values less than 0.5. The Panasonic display, on the other hand, has improved very little versus the optimization of Experiment 1, showing values of 1.0 - 1.5 and higher. Both systems suffer penalties to standard observer color difference with a number of patches approaching a  $\Delta E_{94}$  of 4.0 on each.

Experiments 3 and 4 repeated the scenarios of Experiment 1 and 2, but this time the Panasonic display was replaced by the Necsel laser system. Statistics for optimized performance can be found in Figures 11 and 12. In Experiment 3, only 13 of the original 25 Color-aid patches were used and the participants completed observations across three days. Because there are no color gamut issues, each system achieved standard color errors versus reference that typically measured well below 0.5 and were generally well matched. However, for observer

metamerism, the laser system was markedly deficient with magnitudes for OM<sub>s</sub> near 5.0 for most patches. This is consistent with findings from reference [vii].

For Experiment 4, a hybrid presentation of display stimuli was implemented across two days of testing. Six of Experiment 3's Color-aid patches were selected and shown to the observers with the identical respective standard observer optimization of Experiment 3. The same six patches were then repeated, but with each display re-optimized to minimize observer metamerism. This served to confirm findings from Experiment 3 and permit direct comparison to the observer metamerism minimization, using a consistent group of observers. Calibration performance in Figure 12 reflects this approach, with patches 1-6 yielding statistics very similar to their counterparts in Experiment 3 and patches 7-12 (the repeats with minimized observer metamerism) generating superior  $OM_s$ .

Finally, Table 1 summarizes demographic data for the observers in each of the four experiments. Prior to participation, each observer was confirmed to be color normal using Ishihara color blindness plates.

	Experiment 1 Panasonic P3 min ∆E (1931)	Experiment 2 Panasonic P3 min OM <sub>s</sub>	Experiment 3 2020 Lasers min ΔE (1931)	Experiment 4 2020 Lasers min OM <sub>s</sub>
Male/Female	17 / 11	14 / 11	16 / 8	5/6
Age 17-24	19	19	16	7
Age 25-39	3	3	2	1
Age 40-60	6	3	6	3

Table 1. Experiment participants

### **Results**

In all four experiment variations, the rendered observer metamerism (as defined from the Sarkar CMF set) for displayed patches on the RIT MPD was superior to that of the three-channel systems for all but a small number of displayed stimuli. And in those few cases, the two systems were effectively the same. If the models are statistically sound, it would be logical for any single observer with unknown individual CMF to still preferentially select the MPD in forcedchoice comparisons across all viewed patches in a test session. Histograms for the number of observers versus individual percentage preference to the MPD in Figures 9-12 verify that the multiprimary display is indeed more likely to be chosen as a stimulus match to a Color-aid reference in any particular observation. Qualitatively, the larger the discrepancy between the MPD and three-channel  $OM_s$  average, the more the histogram trends to the right (or 100%) preference) to the MPD. For example, in Experiments 1 and 2 where the Panasonic spectra were less metameric than the laser spectra of Experiments 3 and 4, there are a few observers who preferred the SMPTE-431 device (histogram values less than 50%). In Experiment 3 where a minimization to the 1931 standard observer color difference was attempted for the laser, two observers showed 50% or less preference to the MPD, suggesting they might themselves be characterized very near the 1931 CMFs.



Figure 9. Measurements of 25 test stimuli for Experiment 1 across 4 test sessions; minimization of ΔE versus Color-aid reference stimuli on Panasonic P3 projector and RIT MPD
OM<sub>s</sub> for Panasonic versus RIT MPD (top row); histogram of observer preference to selection of RIT MPD in paired comparisons (bottom row)



Figure 10. Measurements of 25 test stimuli for Experiment 2 across 4 test sessions; minimization of OM<sub>s</sub> versus Color-aid reference stimuli on Panasonic P3 projector and RIT MPD OM<sub>s</sub> for Panasonic versus RIT MPD (top row); histogram of observer preference to selection of RIT MPD in paired comparisons (bottom row)



Figure 11. Measurements of 13 test stimuli for Experiment 3 across 3 test sessions; minimization of  $\Delta E$  versus Color-aid reference stimuli on Rec2020 Laser projector and RIT MPD OM<sub>s</sub> for Laser versus RIT MPD (top row); histogram of observer preference to selection of RIT MPD in paired comparisons (bottom row)



Figure 12. Measurements of 12 test stimuli for Experiment 4 across 2 test sessions; minimization of OM<sub>s</sub> versus Color-aid reference stimuli on Rec2020 Laser projector & RIT MPD OM<sub>s</sub> for Laser versus RIT MPD (top row); histogram of observer preference to selection of RIT MPD in paired comparisons (bottom row) Experiments 3 and 4 are particularly interesting in that several observers picked only the MPD, even for the cases where the laser and MPD showed identical matches to the reference stimuli, according to the 1931 observer. Each observer commented at the end of their session that there must have been something wrong with their observations in that the laser-based system never seemed a good match to the Color-aid reference.

Next, Figure 13 shows the preference in selection of the MPD in the forced-choice comparisons for every individual patch in Experiment 1. These results are plotted against four different observer metamerism indices to assess where correlation is strongest. The models compared include the straight observer metamerism magnitude according to the Sarkar (OM<sub>s</sub>), CIE2006  $(OM_c)$  and Heckaman  $(OM_b)$  CMF sets, respectively. Last in the figure is a plot of the MPD preference versus the Sarkar CMF observer variability index, OM<sub>s.var</sub> which is the calculated volume of error ellipsoids associated with the spread of observer match variability. For each plot point, the mean observer metamerism of the reproduced stimuli versus the Color-aid reference was computed for both the MPD and the associated three-channel display. Next, the net difference by which the three-channel system's index exceeded the MPD's index in each metric was used for the plot's abscissa values. Most plot values were thus positive as the threechannel system underperformed the MPD in all permutations for nearly all of the observed stimuli. As the magnitude of this deficiency increases, it would be expected that the MPD would be more likely selected as a better match to the Color-aid reference in the paired comparison. It might also be expected that the response function should be sigmoidal as the indices have been designed to reflect normal psychophysical threshold behaviors. Where there is no difference in observer metamerism index between the MPD and the three-channel system, the preference for the MPD should ideally be only 50%, representing the result of observer's randomly guessing.

Reviewing the three options for simple observer metamerism,  $OM_x$ , the CIE2006 and Heckaman CMF sets deliver very weak apparent correlation to MPD preference. The Sarkar set, though, does offer some reasonably consistent trending. Figure 14 shows all four experiment results plotted together with a sigmoidal curve fit as a function of  $OM_s$ . Sarkar-based observer variability,  $OM_{s,var}$ , is also a weak correlation, though this is somewhat expected as overall CMF population variability should not necessarily be directly relevant to the task of a forced-choice color match. Another weak correlation to the psychophysical results comes from comparison to the 1931 standard observer color difference values, evident for each experiment individually as well as in a combined plot, shown in Figure 15.

The 75% Just Noticeable Difference (JND) for preference to the MPD versus the three-channel systems compared in these experiments is a net  $\Delta OM_s$  of 2.4. Composite sigmoidal trend lines for  $OM_c$  and  $OM_h$  yield significantly less definitive trending and are not shown here. The present results suggest that the prediction of observer behavior is not as well correlated with CMF populations designed from those two vision models. No attempt was made to model MPD preference versus simple 1931 standard observer  $\Delta E_{94}$  as the signals in the domain of -1 to +1 color difference units are not monotonic. The reasonable predictions afforded by the Sarkar CMF set are encouraging, as this observer metamerism index holds strong potential for models of observer satisfaction with color matches in cross-media applications. However, there are also opportunities for further refinement of the vision models and metamerism indices to yield stronger correlation. Also encouraging is the significant preference for the RIT MPD to either of the three-channel systems in these color matching experiments. The design objective for the system is validated with these results.



Figure 13. Measurements of forced-choice selection preferences per color patch for Experiment 1 - minimization of  $\Delta E$  versus Color-aid reference stimuli on Panasonic projector and RIT MPD (scaled against OM<sub>s</sub>, OM<sub>c</sub>, OM<sub>h</sub> and OM<sub>s,var</sub>). In all cases, the numerical value shown on the x-axis is the net amount by which the color difference index for the three-channel display exceeds that for the MPD



Figure 14. Combined RIT MPD selection preference from all four experiment permutations as a function of  $\text{OM}_{\text{s}}$ 



Figure 15. Combined RIT MPD selection preference from all four experiment permutations as a function of  $\Delta E_{94}$  (1931 2° standard observer)

### Conclusions

Models of observer metamerism based on CMF definitions promoted by Sarkar et al. are predictive of observer preference for color matching in mixed-spectra forced-choice comparisons. Further, issues of observer metamerism and variability suggested for highly monochromatic stimuli as defined by ITU-R Rec. 2020 are real. Systems designed under these definitions are likely to deliver greatly exaggerated inconsistency of experience amongst cinema audiences. On the other hand, an intentionally-engineered multiprimary display, encompassing deliberate primary spectra design, can enhance the available color gamut and minimize observer metamerism in an optimized multispectral color management scheme.

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