The Effect of DLP Projector White Channel on Perceptual Gamut

Rodney L Heckaman, Mark D. Fairchild, and David R. Wyble, Munsell Color Science Laboratory, Rochester Institute of Technology, Rochester, New York, USA

Abstract
The effect of white channel enhancement as implemented in the Texas Instrument DLP digital projector technology is evaluated theoretically using both the CIELAB and the CIECAM02 color appearance models and experimentally through psychophysical testing using real images. Both theory and the test results confirm a compression of perceptual gamut in both chroma and colorfulness as a result of the added white channel. Hence, while this technology is ideal for viewing graphics and text under ambient conference room conditions, it is necessarily less than ideal for viewing images or in home theater environments.

Introduction
Since its introduction in a 1998 paper by Kunzman and Pettit,[1] Texas Instruments (TI) DLP digital projector technology with white channel enhancement to achieve brighter images has become pervasive in their intended markets. Yet in the TI implementation, it is presumed that high brightness is achieved at the expense of chroma as the addition of a white channel reduces saturation. Colors, in effect, would appear to be washed out.

The purpose of this paper is then give credence to this presumption by determining the effect of white channel enhancement on the perceptual gamut of a projector utilizing this technology. Perceptual gamut is determined in the color appearance attributes CIELAB and CIECAM02[3] lightness, chroma, brightness, and colorfulness and tested psychophysically using real images.

DLP Characterization
The InFocus LP650 implements the TI DLP technology and was ideal for this application as it incorporates two modes of viewing – the “Presentation Mode” with white channel enhancement and the “Photographic Mode” where the white channel is disabled. Hence, the effect of white channel enhancement can be determined by comparing the respective volumes of perceptual gamut in these two modes.

In the TI implementation, the RGB luminance signal is first allowed too increase until its maximum is reached, then a portion of the luminance is shifted to the white segment of the filter wheel in three discrete levels according to:

$$Y_{combined} = Y_{RGB} + Y_{white}$$

$$X_{combined} = X_{RGB} + X_{white}$$

$$Z_{combined} = Z_{RGB} + Z_{white}$$

The InFocus LP650 was characterized in both modes using the Wyble[2] methodology presented at the IS&T/SID 12th Color Imaging Conference. Using this methodology, the forward model is characterized according to:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R' \\ G' \\ B' \\ W' \end{bmatrix}$$

for $R'G'B'W'$ the linearized scalars obtained by the LUTs determined from the characterization of the projector (Figure 1) and M the 3x5 rotation matrix incorporating the $R'G'B'W'$ contributions and their respective black residuals. Seventeen (17) step ramps were judged sufficient for the purpose of computing gamut.

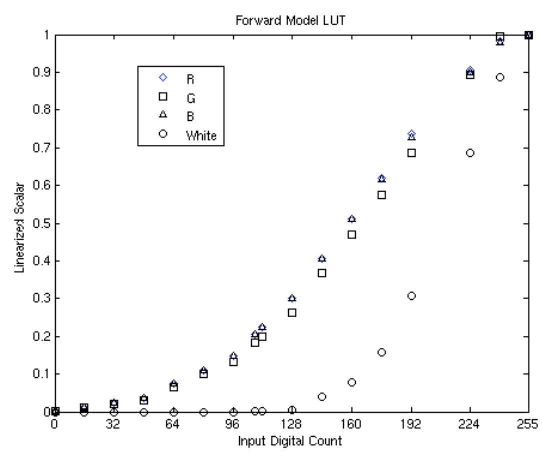

Figure 1. Forward Model Lookup Table

Figure 2 illustrates the resulting differences in absolute projector screen illuminance under dark viewing conditions (little or no viewing flair) between the "Photographic Mode" and “Presentation Mode”. In terms of full-on/full-off contrast ratio, the InFocus LP650 was measured off the screen to be 430:1 in “Photographic Mode” and 788:1 in “Presentation Mode” in a completely darken room.

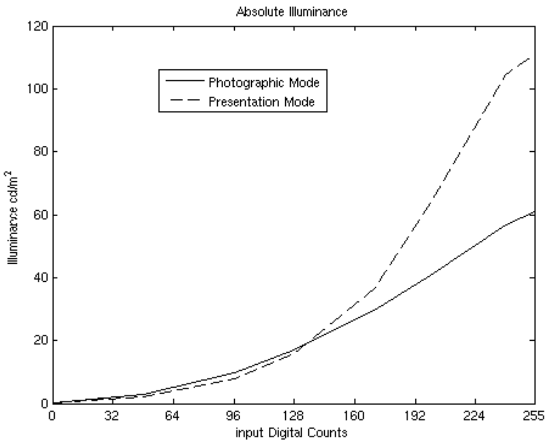

Figure 2. Gray Scale Illuminance

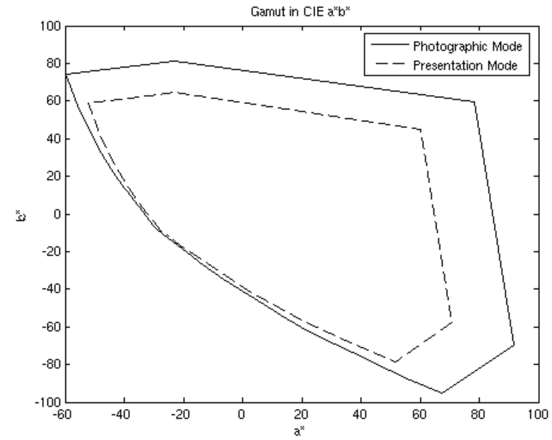

Figure 4. DLP Gamut in CIELAB

DLP Perceptual Gamut

The representation of the gamut in a CIE Chromaticity Diagram for this DLP is shown in Figure 3. This diagram does not distinguish between the two modes of this projector, nor does it give any insight into their respective appearance attributes. Often, such a representation would be useful to suggest that the gamut of the two modes are identical. Hence, the "Presentation Mode", being brighter, would be presumed to be "better".

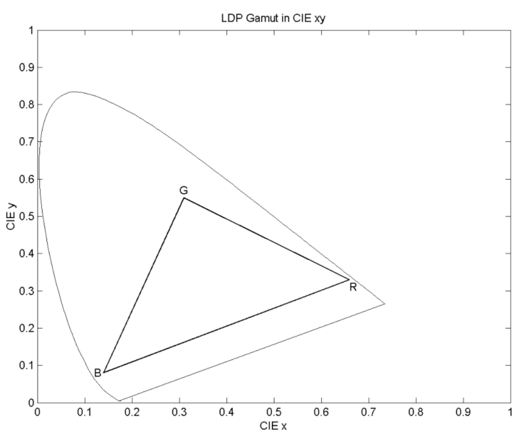

Figure 3. DLP Gamut in CIE Chromaticities

In terms of CIELAB, the effect of white channel enhancement is to raise the white point from a X_m,Y_m,Z_m, of 54.2, 61.1, 76.2 cd/m^2 in "Photographic Mode" to 101, 111, 132 cd/m^2 in "Presentation Mode". The effect is illustrated in Figure 4 where chroma in the L*Ch representation is mapped cylindrically to one plane. The volume of perceptual gamut in Chroma is compressed as a result of an enhanced white channel, yet lightness contrast is relatively unaffected for neutrals.

The effect is similar when gamut is computed using CIECAM02 as shown in Figure 5. Adaptation was taken to be complete (D=1) under dark viewing conditions with adapting fields L_A and Y_b taken to be one-fifth the respective white point illuminance values for each mode. As before, chroma is mapped cylindrically to one plane.

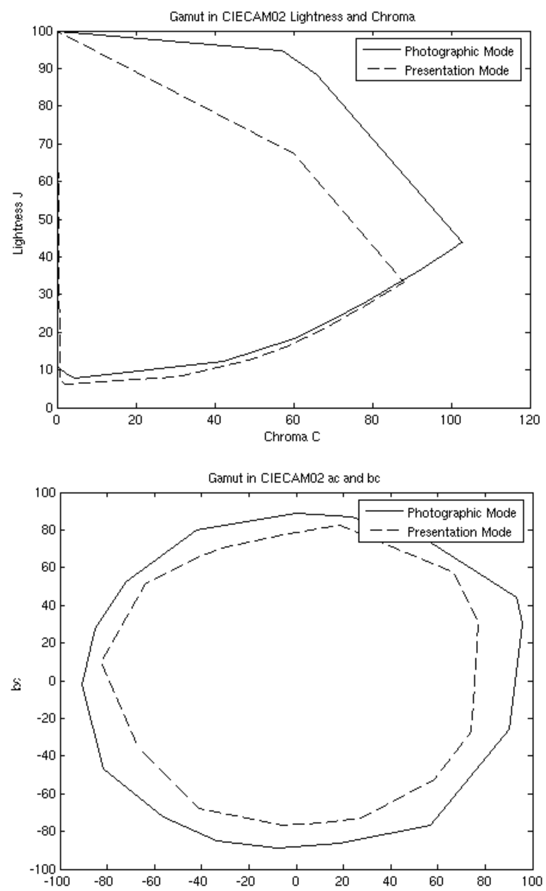

Figure 5. DLP Gamut is CIECAM02 Lightness and Chroma

Finally, the predicted effect of white channel enhancement on brightness and colorfulness is obtained using CIECAM02 as illustrated in Figure 6. The volume of gamut has been expanded in brightness by white channel enhancement and colorfulness compressed to a similar extent as chroma.

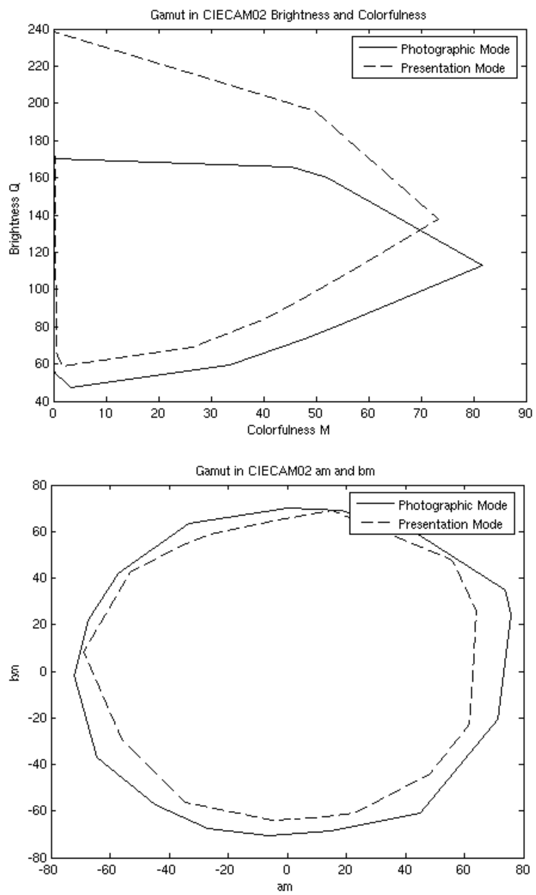

Figure 6. DLP Gamut in CIECAM02 Brightness and Colorfulness

These gamut representations predict that the effect of white channel enhancement is to compress the chroma portion of gamut while affecting lightness to a much lesser amount. The effect on brightness and colorfulness is to expand the gamut in brightness yet compress colorfulness. Table 1 summarizes these conjectures in terms of the ratio of their relative gamut volumes.

Table 1: Relative Perceptual Gamut Volumes

Gamut Representation	Volume Ratio – "Photographic Mode" to "Presentation Mode"
CIELAB LCh	1.53
CIECAM02 LCh	1.58
CIECAM02 QM	0.92

Psychophysical Testing

A psychophysical experiment was done using the images shown in Figure 7 to test the validity of the gamut analysis.

Figure 7. Test Images (Street Scene, Barn, Flowers, Woman, and Coastal Town)

The Street Scene was chosen for the pastel colors of the buildings. The Barn chosen as a control as its luminance values are below the point where the white channel comes into play, and presumably this image should rate the same in each projector mode. The Flowers image was chosen as high in chroma or colorfulness. The Woman chosen as high in contrast, low in chroma, and for the flesh tones. Finally, the Coastal Town was chosen as high in contrast with high chroma components in the sunset.

The images were projected onto an 8-foot wide screen in the Grum Learning Center of the Munsell Color Science Laboratory under dark viewing conditions in both Presentation and "Photographic Mode". The judges were dispersed in the room according to norm conference room viewing conditions. Each image was simultaneously viewed on a Sony 23 inch CRT color monitor that served as a reference or anchor point.

Two trials were completed by 27 expert judges who were asked to scale lightness contrast, chroma range, brightness, and colorfulness relative to the reference monitor on an absolute scale – first in "Photographic Mode" then, leaving the room and returning, in "Presentation Mode". The scale was anchored at 1.0 representing the reference monitor and 0.0 representing uni-gray for lightness contrast and chroma range and black for brightness and colorfulness. The first trial was intended as a pilot and as training for the judges.

Test Results

The results of the second trial are presented in the following figures, Figure 8 for lightness contrast and chroma range and Figure 11 for brightness and colorfulness. The data are presented in terms of the ratio of scale value given to each attribute in "Photographic Mode" to that given in "Presentation Mode".

The data points represent the mean ratio over all judges and the bars 95% confidence intervals. An average ratio value of 1.0 for any attribute is interpreted to mean that the observers rated the image as equal in the respective attribute across both modes. A ratio 2.0 is interpreted having a value in "Photographic Mode" twice that of "Presentation Mode", and a ratio of 0.5 as half that of "Presentation Mode".

While each judge had their own rating scale – i.e. the "rubber band" effect, the effect of these differences in scale was removed by taking this ratio. In all cases of scenes and judges, the respective standard deviations across both scenes and judges were consistent at around 0.40 and normally distributed resulting in a set of confidence intervals that were equally consistent between 0.13 and 0.20 in scale value.

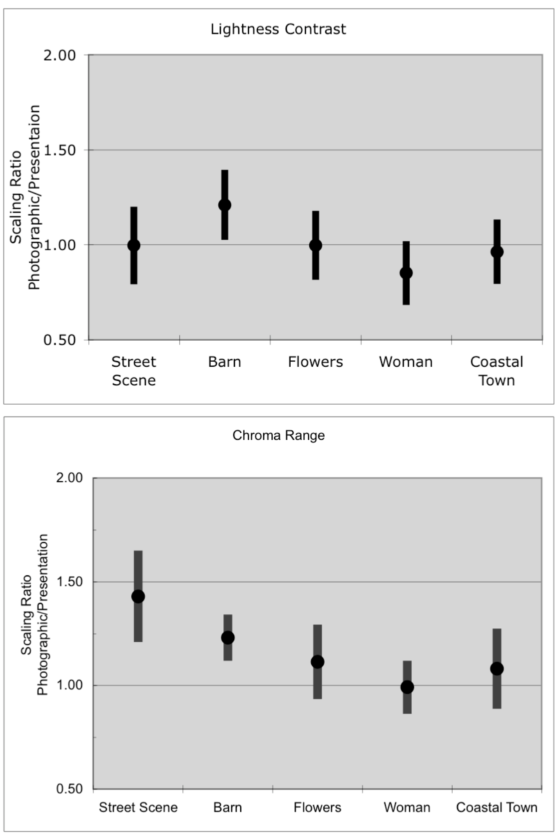

Figure 8. Observed Average and 95% Confidence Intervals for Lightness Contrast and Chroma Range

Figure 10 illustrates the scaling results for lightness contrast and chroma range. The average lightness contrast over the five (5) scenes confirms the predictions from the gamut analysis. The range of chroma is compressed by the addition of the white channel while lightness contrast is largely unaffected. However, taken individually, the Barn and the Woman scenes were judged contrary in lightness contrast although the Woman scene not significantly so.

Taken out of the context of this evaluation, the Barn scene should have been rated equal in lightness contrast as its maximum luminance was taken to be less than that where the white channel is invoked. Hence, an observer would have no clue about the relative white points disparity between the two modes.

However, in the context of this test, the judges were adapted via the remaining scenes in the series and affected accordingly. The higher white point in "Presentation Mode" then had the effect of compressing the contrast of the Barn scene. The resulting response of the judges in "Photographic Mode" that the Barn scene was perceived to be a factor of 1.2 times that of the "Presentation Mode" illustrates the power of adaptation.

Figure 9 illustrates the results for brightness and colorfulness scaling. Clearly, the gamut analysis regarding colorfulness is confirmed as all scenes are judged, on average, as more colorful in "Photographic Mode" – three of the five significantly so. Brightness, on the other hand, does not confirm the gamut analysis as being perceived brighter in "Presentation Mode".

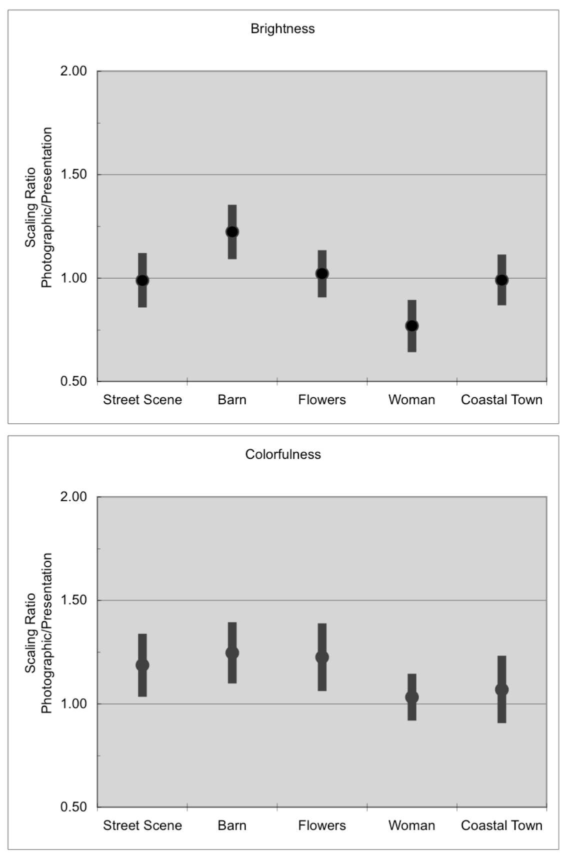

Figure 9. Observed Average and 95% Confidence Intervals for Brightness and Colorfulness

The brightness results when compared to those in Figure 8 are virtually the same as the lightness contrast results, and it is presumed that the majority of the judges rated these two attributes the same – a common occurrence when observers are asked to judge brightness. On closer analysis, a minority of the judges rated brightness higher in “Presentation Mode”. The effect of their ratings singled out the Woman scene, the brightest scene in the series, as significantly brighter in “Presentation Mode”.

Theory and Practice

In order to reconcile the perceptual gamut analysis with the test results, lightness, chroma, brightness, and colorfulness were computed for each scene in the test series using CIELAB and CIECAM02 as before. Again, adaptation was taken to be complete (D=1) under dark viewing conditions, but the adapting fields L_A and Y_b were taken to be the average illuminance of each scene.

The areas of each of the scene’s gamut were computed along with maximum brightness and contrast. Contrast was taken to be the difference between maximum and minimum lightness as predicted by CIECAM02. The following tables indicate the results in ratios of the respective parameter values in the “Photographic Mode” over that of the “Presentation Mode”.

The above analysis was then correlated to the test results. It was found the predicted contrast from Table 4 correlated best with the lightness contrast test results, and the square root of CIECAM02 chroma ($a_c b_c$) area and colorfulness M ($a_m b_m$) area in Table 3 with the chroma range and colorfulness test results.

The Figure 10 compares the respective predicted attributes (dots) with the test results represented by their 95% confidence intervals (bars). The brightness attribute is not included as the majority of the judges rated it the same as lightness contrast. In general, there is excellent correlation between predicted and test results.

Table 2: Gamut Area Ratios A_{Ph} / A_{Pr}

	Street Scene	Barn	Flowers	Woman	Coastal Town	Average
LCh	1.52	1.62	1.39	1.36	1.39	1.46
a*b*	1.54	2.05	1.62	1.98	1.78	1.79
JC	1.31	1.27	1.31	1.21	1.26	1.29
a_c b_c	1.21	2.33	1.24	1.05	1.05	1.38
QM	0.90	0.88	0.91	2.70	2.70	1.62
$a_m b_m$	1.21	1.33	1.27	0.97	0.97	1.15

Table 3: Square Root of the Gamut Area Ratios $\sqrt{A_{Ph} / A_{Pr}}$

	Street Scene	Barn	Flowers	Woman	Coastal Town	Average
LCh	1.23	1.27	1.18	1.17	1.18	1.21
a*b*	1.24	1.43	1.27	1.41	1.33	1.34
JC	1.14	1.13	1.15	1.10	1.17	1.14
a_c b_c	1.10	1.53	1.11	1.03	1.03	1.17
QM	0.95	0.94	0.95	1.64	1.64	1.27
$a_m b_m$	1.10	1.15	1.13	0.99	0.99	1.07

Table 4: Ratios in Contrast and Maximum Brightness (max Q)

	Street Scene	Barn	Flowers	Woman	Coastal Town	Average
Contrast	0.99	1.17	0.99	0.98	0.99	1.02
Max Q	0.73	0.78	0.77	0.72	0.73	0.74

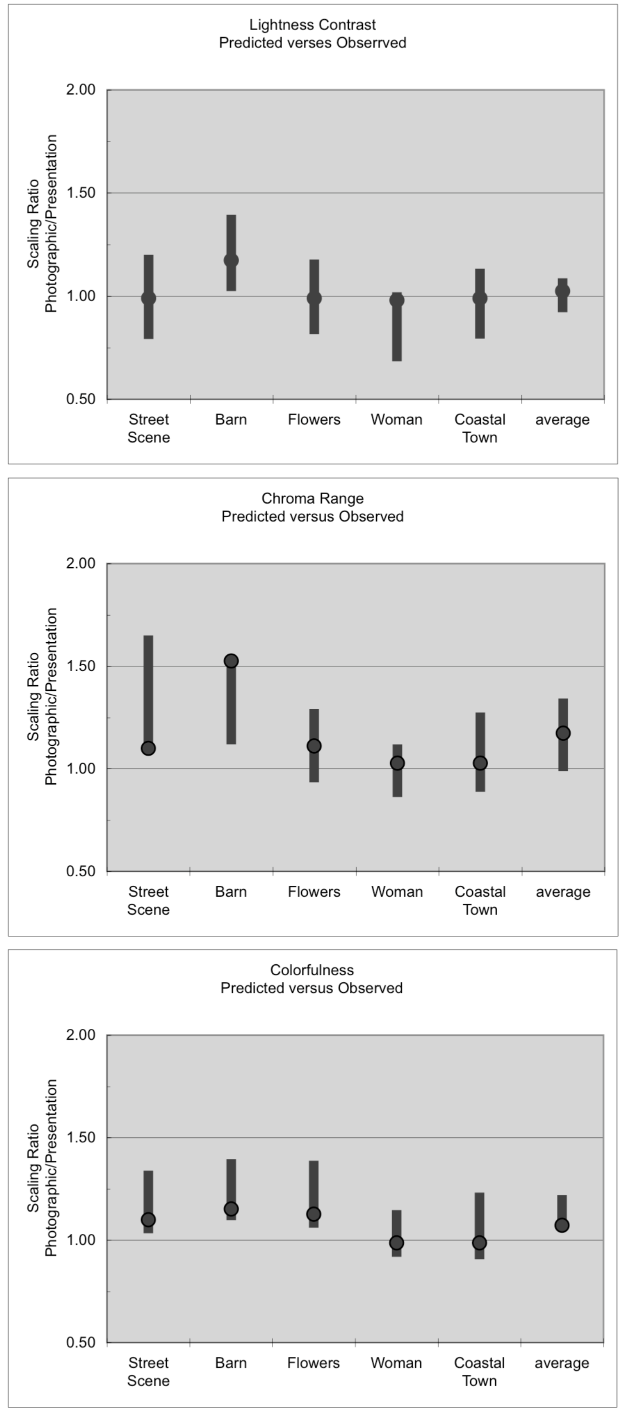

Figure 10. Predicted (dots) versus Observed 95% Confidence Interval (bars)

Conclusions

Under typical conference room viewing conditions with ambient room lighting, the InFocus LP650 "Presentation Mode" is intended to provide higher brightness to overcome viewing glare from ambient light. It seems the makers of this projector recognized that this mode of viewing compressed the color gamut and implemented the "Photographic Mode" without white channel enhancement to provide a full volume of gamut.

The analysis and testing reported on in this paper confirms the maker's astute recognition and the original presumption of this paper – that the addition of a white channel as a feature of the DLP technology produces a compressed gamut in chroma and colorfulness. And while the white channel enhancement is in answer to the problem of viewing glare in a typical conference room, those consumers who choose this technology for video applications such as home theater or viewing images may necessarily be compromised in their ability to achieve brighter, purer colors.

As a final note, the CIECAM02 color appearance model proved very useful in this analysis by producing results that correlated quite well with the psychophysical test results.

Acknowledgements

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2. David R. Wyble and Mitchell R. Rosen, Color Management of DLP Projectors, IS&T/SID 12th Color Imaging Conference, 228-232, (2004)
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Author Biography

Rodney L. Heckaman is a second year PhD student and Macbeth-Engel Fellow in Image Science, Munsell Color Science Laboratory, Rochester Institute of Technology. His work focuses on Perceptual Gamut, Brilliance, and surround with application to High Dynamic range displays. He graduated in 1968 from the Ohio State University in Engineering Physics with postgraduate work at the University of Rochester's Institute of Optics and Harvard University in Finance.