Effect of DLP projector white channel on perceptual gamut

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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 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 where lightness contrast is important, it is necessarily less than ideal for viewing images or in home-theater environments where color is important.

Keywords — *Perceptual gamut, display color gamut, digital projector.*

1 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.

It is well known that adding white light to any color display media de-saturates its color. Yet, when confronted with a traditional gamut representation of such a media as a chromaticity diagram shown in Fig. 1 for a digital light projector (DLP), it is tempting to add a white channel to increase its luminance seemly without affecting its color gamut. This is good idea for those display applications where lightness contrast is important – applications such as the presentation of business graphics or textual information in a conference-room environment where viewing flare is a problem.

However, a chromaticity diagram tells very little of the perceptual or appearance aspects of viewing. In those applications where color is important, *e.g.*, digital video in a home-theater environment under dark viewing conditions, white-channel enhancement actually decreases the perceptual gamut of a projector. This paper addresses this effect where perceptual gamut is determined in the color-appearance attributes CIELAB and CIECAM02[3] lightness, chroma, brightness, and colorfulness and is tested psychophysically using real images.

2 Terminology

Chromaticity diagram[2]: A plot of the chromaticity coordinates x and y where x and y are obtained as the ratios of their respective CIE tristimulus values X, Y, and Z.

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z}.$$

CIELAB[2]: The CIE tristimulus values represent the relative amounts of primaries used to specify color matches under identical conditions of illuminant and are computed, in this case, from the color-matching functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$ for the 1931 CIE Standard Observer.

The CIE 1976 $L^*a^*b^*$ opponent-based color space with representation as lightness L^*, hue h_{ab}, and chroma $C_{ab}{}^*$.

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16,$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right],$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right],$$

$$h_{ab} = \arctan\left(\frac{a^*}{b^*}\right), \quad C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2},$$

where X_n, Y_n, and Z_n are the tristimulus values for reference white usually taken as a perfectly diffuse reflector.

Brightness and colorfulness[3,4]: While lightness and chroma are relative to an illuminated area that appears white (*i.e.*, reference white), brightness Q, and colorfulness M are absolute terms – brightness according to the appearance of an area that emits more or less light and colorfulness according an area that appears more or less chromatic.

The color appearance model CIECAM02 computes brightness Q and colorfulness M as a function of lightness J and chroma C, respectively. Chroma, as in the CIELAB representation, is computed as the distance from the origin to a point in opponancy space a_c and b_c analogous to a^* and b^*, and colorfulness to a_m and b_m.

Revised extended version of a paper presented at the 2005 Color Imaging Conference held November 7–11, 2005 in Scottsdale, AZ.

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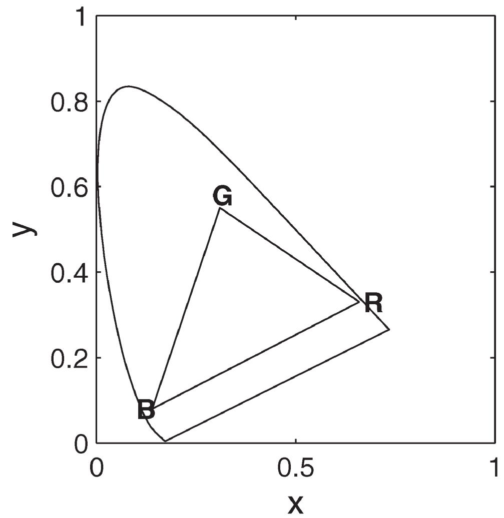

FIGURE 1 — Chromaticity diagram of the LDP gamut.

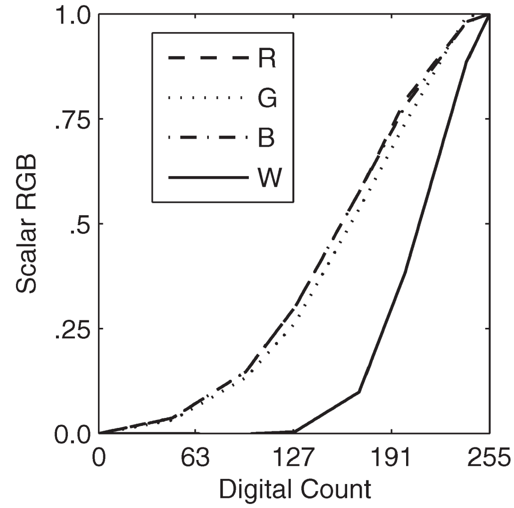

FIGURE 2 — Forward model lookup table in RGBW.

The model applies a von Kries-type chromatic adaptation transform and includes dependencies on illuminant-level adaptation, induction, and background relative luminance.[4]

3 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 with white-channel enhancement, the RGB luminance signal is first allowed to 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

$$\begin{aligned} Y_{combined} &= Y_{RGB} + Y_{white}, \\ X_{combined} &= X_{RGB} + X_{white}, \\ Z_{combined} &= Z_{RGB} + Z_{white}. \end{aligned} \tag{1}$$

In this representation, the InFocus LP650 was characterized in both modes using the Wyble[5] methodology presented at the IS&T/SID 12th Color Imaging Conference. Using this methodology, the forward model is characterized according to

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R' \\ G' \\ B' \\ W' \end{bmatrix} \tag{2}$$

for $R'G'B'W'$, the linearized scalars obtained by the LUTs determined from the characterization of the projector (Fig. 2) and M is the 3×5 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 3 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 darkened room.

4 DLP perceptual gamut

The representation of the gamut in a CIE Chromaticity Diagram for this DLP was shown in Fig. 1. As noted before, this diagram does not distinguish between the two modes of this

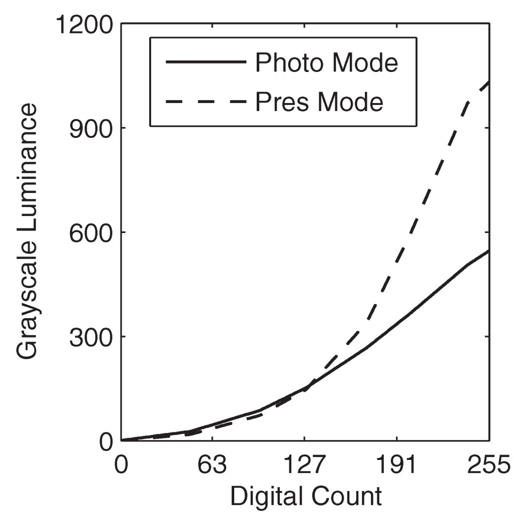

FIGURE 3 – Gray-scale illuminance with white-channel enhancement in Presentation Mode and without Photographic Mode.

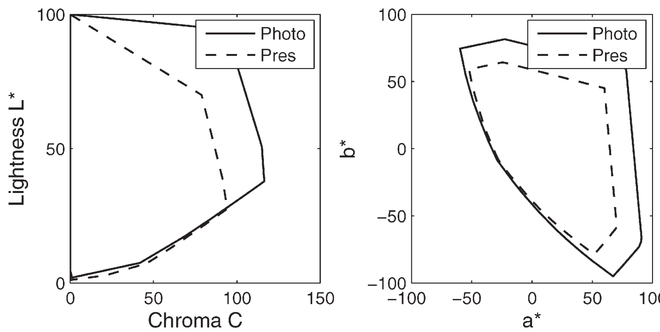

FIGURE 4 — DLP gamut in CIE lightness, chroma, and a^*b^* in Photographic Mode and Presentation Mode.

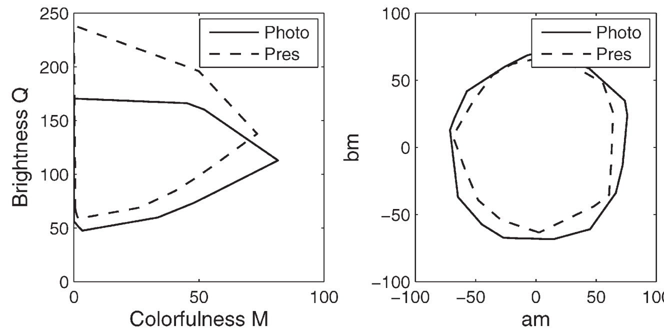

FIGURE 6 — DLP gamut in CIECAM02 brightness, colorfulness, and $a_m b_m$ in Photographic Mode (blue) and Presentation Mode (red).

projector, nor does it give any insight into their respective appearance attributes. Often, such a representation would be useful to suggest that the color gamut of the two modes is identical. Hence, the "Presentation Mode," being brighter, would be presumed to be "better."

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 Fig. 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 Fig. 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.

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

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.

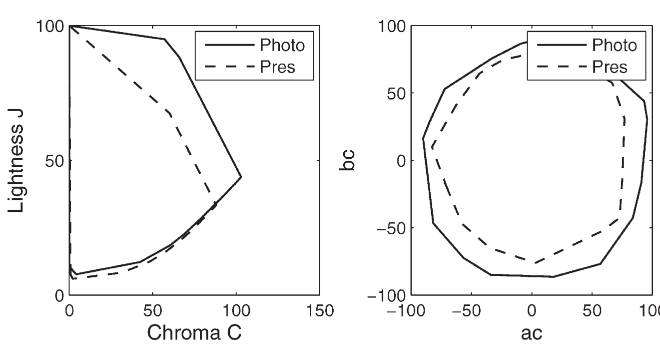

FIGURE 5 — DLP gamut in CIECAM02 lightness, chroma, and $a_c b_c$ in Photographic Mode (blue) and Presentation Mode (red).

Table 1 summarizes these conjectures in terms of the ratio of their relative gamut volumes. In colorfulness and brightness, the white-channel enhancement does not affect overall gamut volume as these appearance attributes are taken in the absolute sense but, in effect, this enhancement redistributes the volume from colorfulness to brightness. In lightness and chroma, the gamut volume in "Photographic Mode" is approximately 50% larger than that for the "Presentation Mode," and the effect of white-channel enhancement is to reduce gamut volume almost exclusively in chroma by approximately one-third.

5 Psychophysical testing

A psychophysical experiment was performed using the images shown in Fig. 7 to test the validity of the gamut analysis. The Street Scene was chosen for the pastel colors of the buildings. The Barn scene was chosen as a control because 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

TABLE 1 — Relative perceptual gamut volumes.

Gamut Representation	Volume Ratio – "Photographic Mode" to "Presentation Mode"
CIELAB lightness and chroma	1.53
CIECAM02 lightness and chroma	1.58
CIECAM02 brightness and colorfulness	0.92

FIGURE 7 — Test images.

chosen as high in chroma or colorfulness. The Woman image was 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-ft.-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 normal conference-room viewing conditions. Each image was simultaneously viewed on a Sony 23-in. 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 first trial was intended as a pilot and as training for the judges.

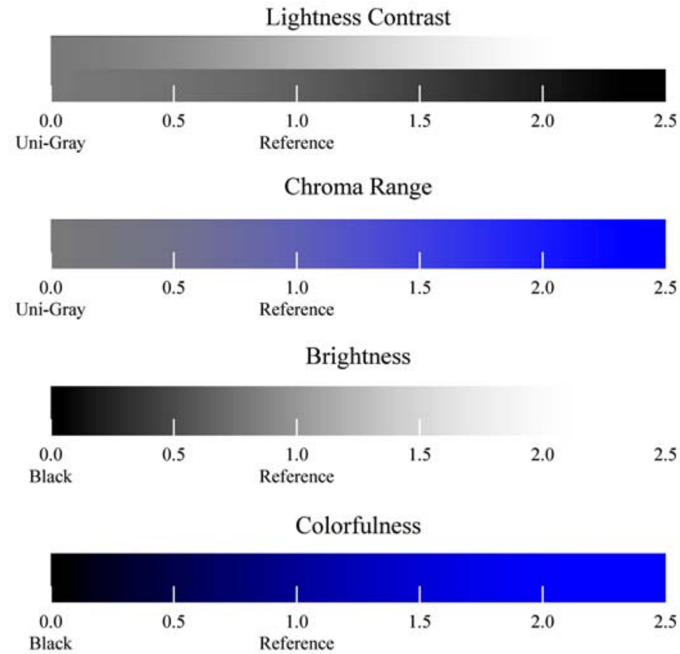

FIGURE 8 — Observer rating instructions – rating attributes.

Figure 8 below illustrates the instructions to the judges on the intent of the rating scales. Because lightness and chroma are intended as appearance attributes of individual objects in a scene, overall scene lightness contrast and chroma range were used. 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. While each judge was allowed their own scale, *i.e.,* the "rubber band" effect, the effect of the scale differences was removed by normalizing the scores on an individual basis. In all cases of scenes and judges, the respective standard deviations across both scenes and judges were consistent at 0.40 normalized scale value and normally distributed with a set of confidence intervals equally consistent between 0.13 and 0.20 in scale value.

6 Test results

The results of the second trial are presented in Fig. 9 for lightness contrast and brightness, chroma range, 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 bars represent 95% confidence intervals where a log ratio value of 0.00 for any attribute is interpreted to mean that the observers rated the image as equal in the respective attribute across both modes. A log ratio 0.30 is interpreted having a value in "Pho-

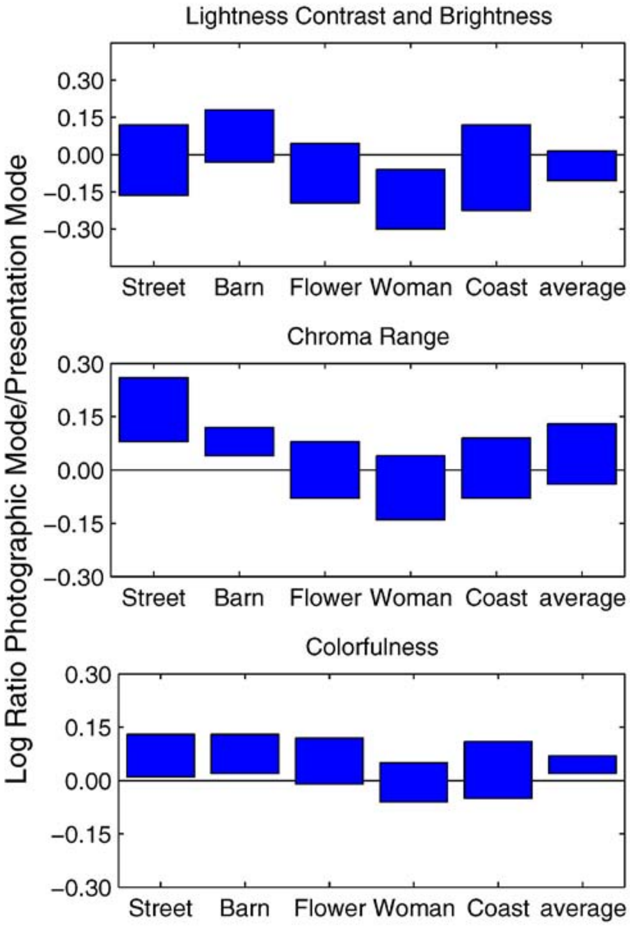

FIGURE 9 — 95% confidence intervals of the log ratio of each test image's rating in Photographic Mode over its rating in Presentation Mode for lightness contrast and brightness, chroma range, and colorfulness and the average log ratio over all the test images.

tographic Mode" twice that of "Presentation Mode," and a log ratio of –0.30 as half that of "Presentation Mode."

As predicted from the overall 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-point 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.

Clearly, the gamut analysis regarding colorfulness is confirmed as the average overall scenes are judged as more colorful in "Photographic Mode" – three of the five significantly so. Brightness, on the other hand, did not confirm the gamut analysis as being perceived brighter in "Presentation Mode."

The brightness results were 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."

7 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 under dark viewing conditions, but the local adapting fields were taken to be the average illuminance of each scene.

The ratio of the areas of each of the scene's gamut in the following appearance attributes were then computed along with maximum brightness (Max Q) and contrast (Max C) where MAX C was taken to be the difference between maximum and minimum lightness as predicted by CIECAM02.

1. CIELAB lightness L^* and chroma $C_{ab}{}^*$
2. CIELAB a^* and b^*
3. CIECAM02 lightness J and chroma C
4. CIECAM02 chroma in a_c and b_c
5. CIECAM02 brightness Q and colorfulness M
6. CIECAM02 colorfulness in a_m and b_m

The respective areas were computed for each of the attributes from the convex hull formed by a random sampling of 1000 pixels from each image. The following tables indicate the ratios of the respective gamut areas in the "Pho-

TABLE 2 — Gamut area ratios A_{Ph}/A_{Pr}.

	Street scene	Barn	Flowers	Woman	Coastal town	Average
CIELAB $L^*/C_{ab}{}^*$	1.52	1.62	1.39	1.36	1.39	1.46
CIELAB a^*b^*	1.54	2.05	1.62	1.98	1.78	1.79
CIECAM02 L/Q	1.31	1.27	1.31	1.21	1.26	1.29
CIECAM02 a_c b_c	1.21	2.33	1.24	1.05	1.05	1.38
CIECAM02 QM	0.90	0.88	0.91	2.70	2.70	1.62
CIECAM02 $a_m b_m$	1.21	1.33	1.27	0.97	0.97	1.15

TABLE 3 — Ratios in CIECAM02 maximum lightness contrast (Max *C*) and maximum brightness (Max *Q*).

	Street scene	Barn	Flowers	Woman	Coastal town	Average
Max C	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

tographic Mode" over that of the "Presentation Mode" (Table 2) and the ratios CIECAM02 maximum lightness contrast and maximum brightness (Table 3).

The above analysis was then correlated to the test results. It was found that the log ratio of predicted maximum lightness contrast from Table 3 (noted in red) correlates best with the lightness contrast test results, and the log of the square root of the area ratios in CIECAM02 $a_c b_c$ and colorfulness $a_m b_m$ in Table 2 (also noted in red) correlated best with the chroma range and colorfulness test results, respectively.

Figure 10 compares these respective predicted attributes (dots) with the test results represented by their 95% confidence intervals (bars). The predicted brightness attribute is not included as the majority of the judges rated it the same as lightness contrast (stated before).

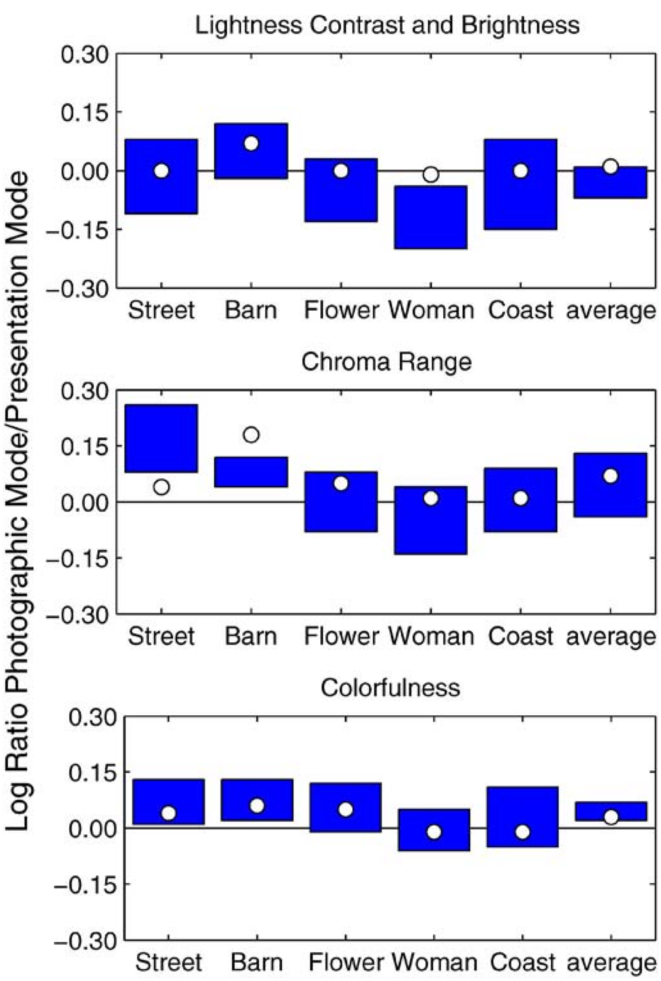

FIGURE 10 — CIECAM02 gamut analysis results for each image in lightness contrast and brightness, chroma range, and colorfulness (dots) compared to the psychophysical test results (bars).

With the exception of the contrary results in chroma range for the Street Scene and the Barn Scene, there is excellent correlation between predicted and test results.

The Barn Scene was addressed in the previous section in terms of its lightness contrast and the conjecture that judges had adapted to higher white point in the context of the Presentation Mode judgments. In this context, the predicted result falls in line with the judgments. However, in terms of chroma range, the higher predicted result may indicate that the judges had not been fully adapted in the chromatic sense, at least for this scene, thereby tempering their judgment.

On the other hand, a similar argument could be made for the Street Scene as it was the first scene viewed by the judges after they were sat in the viewing room and the room lights darkened. While this scene is mainly composed of pastel colors and thus less chromatic which would explain CIECAM02's tempered prediction for chroma range, the judges may have over-reacted on first viewing. In either case, the use of the Barn Scene as a control in the experiment only served to raise more questions in this sense than it answered.

8 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 in those applications where color is important.

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. This same analysis done under normal room lighting would certainly indicate less of a compromise in gamut volume due to viewing glare. Hence, viewing images or video under the best conditions is best done under low ambient illumination.

With due note of the exceptions addressed in the above that were mostly due to experimental error, the CIECAM02 color appearance model proved very useful in this analysis by producing results that correlated quite well with the psychophysical test results. The correlation between the judge's response to both chroma range and colorfulness and the model predictions in terms of the square root of the respective gamut areas in the opponent, chromatic channels is an intuitive result as is lightness contrast with predicted maximum contrast.

Finally, this analysis illustrates the utility of using perceptual gamut analysis and color appearance models such as CIECAM02 in the design of display media. Sole reliance on a CIE chromaticity diagram as a design tool can easily be both misleading and limiting. With rapidly developing display media technologies having higher and higher contrast ratios, much more is possible in expanding the perceptual gamut – the gamut of what we see that is mediated by surround and adaptation. Such possibilities cannot be realized with such a limited tool.

As an example, current media technology are reported to achieve contrast ratios of 3000:1, yet their white points are set to maximum display output. Hence, any portion of the scene that exceeds diffuse white are rendered at diffuse white. The setting sun or a ray of sun light on colorful fall foliage on a cloudy, Fall day do not appear as we remember. By simply moving down the white point of the display and controlling the surround as suggested in these perceptual analysis tools, such scenes can appear to us in their full, original glory.

Acknowledgments

The authors acknowledge the Macbeth-Engel Fellowship in color science for making this work possible.

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