Expanding Display Color Gamut Beyond the Spectrum Locus

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Abstract: Digital video and display media are at a "sweet spot" of growth with brighter and more colorful digital projectors and displays available seemingly every day. Much more is possible in achieving brighter and more vibrant colors, colors that may even transcend our typical experience in terms of dynamic range and an expanded gamut in the perceptual sense. If the full capabilities of these technologies to produce a fuller visual experience are to be realized, new processing and encoding methodologies are required. In this paper, the powers of adaptation and the CIECAM02 color appearance model are exploited to define perceptual gamut. The strategy of this methodology is, simply and in effect, to "push down" the white point of the display and demonstrate, both empirically and with a limited set of images, a striking gamut expansion in the perceptions of lightness, chroma, brightness, and colorfulness beyond the locus of pure, spectral color and the MacAdam Limits as observed with traditional display configurations.

Key words: perceptual gamut, display color gamut, high dynamic range displays

INTRODUCTION

Digital video and display media are changing rapidly with brighter and more colorful digital projectors and displays available seemingly every day. Much more is possible in achieving brighter and more vibrant colors, colors that may even transcend our normal experience in terms of dynamic range and an expanded, redefined gamut. The focus of this paper is on these media and the opportunity available in a theoretical sense for the expansion of their gamut to levels that begin to encroach on the bounds of visual perception, to levels not available through traditional gamut representations, to levels beyond the realm of object color and the spectrum locus of pure colors. This theory may see practical applications with forthcoming high dynamic range (HDR) display technology.

BACKGROUND

In his 1935 paper, Maximum Visual Efficiency of Colored Materials[1], MacAdam stated that "one of the most compelling objectives of pigment and dye chemists has been to "… produce colors of ever greater purity without the sacrifice of brightness." In the interest of insuring that reasonable expectations be set in this regard, MacAdam computed what are now known as the MacAdam Limits - the theoretical maximum color gamut of ideal materials that has since served to bound the problem addressed by subsequent workers in the sciences of colorimetry and color perception. These limits, in effect, bound the range of possible object colors, yet they represent only a portion of what we see everyday.

In a classic 1941 paper[2], Jones and Condit measured the brightness range of 130 nature scenes and determined an average brightness scale or contrast ratio of 160:1 with a maximum of 750:1 occurring in front, sunlit scenes with the principle object in the shade.

While these data were aimed at obtaining a strategy for correct photographic exposure, it is worthy to apply these results to current video image display technology. High quality, LCD displays are reported to achieve contrast rations of 300:1, and it could be said that such a display would reproduce certainly more than half of Jones' and Condit's scenes with identical range. However, under typical ambient viewing conditions, LCD display contrast ratios of 30:1 are more typical.

If current video display technology fails to serve us for the entirety of the Jones and Condit scenes, the technology surely fails to reproduce all aspects of our visual experience. Scenes beyond the range of Jones' and Condit's study are clearly a part of our everyday experience – a scene where our attention is on the shadowed portion of a building with direct sun in our field of view, the sun filtered through foliage or reflected off the ripples of water in a lake, a ray of sunlight shining through a cloudy October day illuminating colorful foliage, or the brilliance of a spot-lit dancer and her costume in the dark surround of a theater. The perceptions invoked by these scenes have been long known and, in the case of the spot-lit dancer, fully exploited by the theater's lighting director. Furthermore, 11th and 12th Century architects used light in the gothic cathedrals of France to invoke a perception that " … transcend[s] the statics of the building masses, the realities of this world" [3] and at Chartres, perhaps the most magnificent of these structures, to create " … a world of illusion, shaped by and for the heavenly light of the enormous stained glass windows."[3]

It is, then, the greater promise of display technology to take us perhaps even beyond our experience – an experience that is well within our ability to perceive and an experience that is offered by expanding the gamut of this technology in the perceptual sense.

HIGH DYNAMIC RANGE (HDR) DISPLAY TECHNOLOGY

At the time of this writing, the available digital video and display media technologies listed in their order of maturity are Cathode Ray Tube (CRT), Liquid Crystal Display (LCD), plasma, Digital Light Processing (DLP), Liquid Crystal On Silicon (LCOS), and Organic Light Emitting Diodes (OLED). It is the latter of these technologies that are capable of achieving a more volumetric gamut with some reported dynamic ranges of up to 3000:1 for plasma displays.

Perhaps the most compelling of these technologies that has recently stirred interest both in the research community and ultimately in consumer video applications is that introduced by Brightside Technologies, Inc. The technology was developed at the Structured Surface Physics Laboratory of the University of British Columbia characterized as a high brightness display or HDR display media technology.[4]

The technology was first introduced in the form of a DLP projector whose filter wheel and electronics are modified to produce only a modulated luminance channel which is further modulated in the three RGB channels of an LCD panel with backlighting removed. The result is a very bright image – 2,700 cd/m^2 compared to 300 cd/m^2 for high quality LCD displays – and a very low measured black level of 0.05 cd/m^2. Hence, contrast ratios of 54,000:1 are obtained compared to 300:1 reported for some LCD displays, and this technology is capable of nearly 5 orders of magnitude in dynamic range approaching, or perhaps even exceeding, the range of the fully adapted, human visual system. The following sections explore how the perceived color gamut of such displays can be described in terms of color appearance and how definition of the diffuse white point impacts the perceived gamut.

METHODOLOGY

A traditional representation of the gamut of a typical digital display device with RGB primaries in a CIE Chromaticity Diagram is shown in Figure 1 superimposed on the locus of pure, spectral colors. Such a representation does not give any insight into their respective appearance attributes, yet this representation is typically used in the display media industry as a point of comparison. Furthermore, in traditional applications, the display is characterized and its white point set to the maximum output of the display. By definition, such a display is configured to render only within the realm of object colors. Colors outside this realm are rendered by employing varies gamut compression strategies.

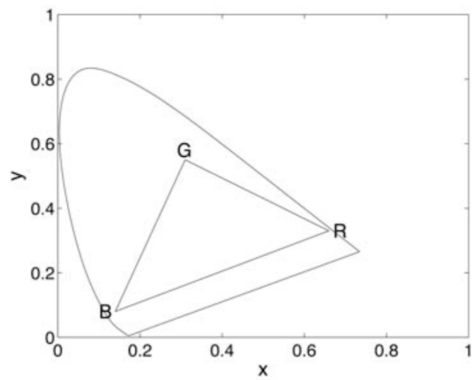

FIG. 1. The gamut of a typical digital display device in CIE Chromaticities superimposed on the locus of pure, spectral colors

In this paper, knowledge about the powers of adaptation and the color appearance modeling tool, CIECAM02, are exploited to define expanded perceptual gamut. The strategy of this methodology is simply to "push down" the white point in relative luminance and extrapolate a gamut expansion in lightness, chroma, brightness, and colorfulness. The flow chart shown in Figure 2 represents the methodology described fully in the following sections.

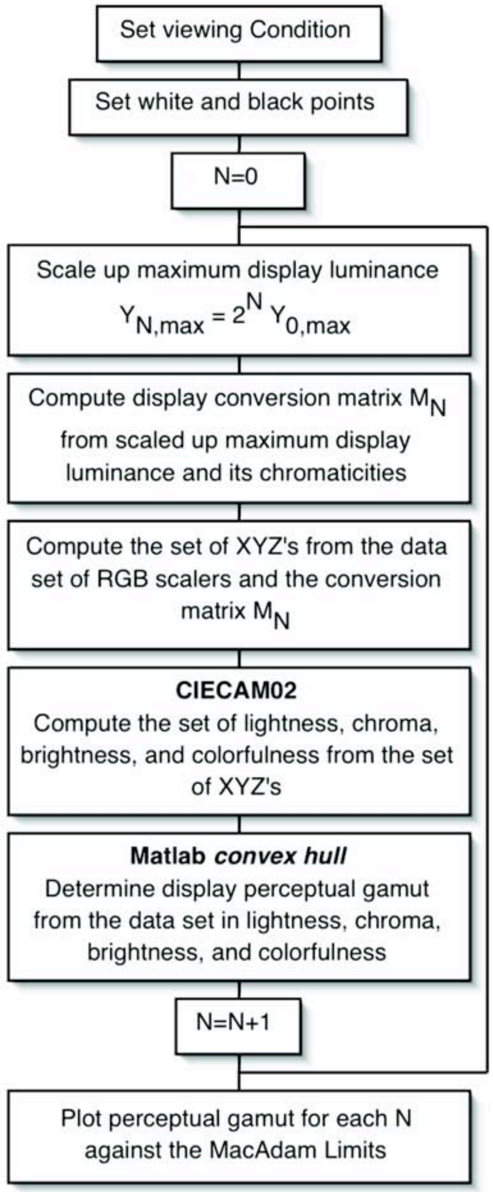

FIG. 2. Gamut expansion methodology

Display Assumptions

For convenience, a typical, baseline display was taken from Berns, Colorimetry of a Computer-Controlled CRT Display[6], having the following chromaticities with each channel's maximum output $Y_{0,max}$ scaled to sum to 100 cd/m^2 instead of 80 cd/m^2 as given in Berns[5].

TABLE I. Display primaries in tristimulus values and maximum output Y_{max}

	R	G	B
x	0.6340	0.3096	0.1508
y	0.3337	0.5878	0.0664
$Y_{0,max}$(cd/m^2)	21.83	71.73	6.45

The corresponding X and Z maximum tristimulus values are then given by:

$$X_{\max} = \frac{x}{y} Y_{\max} \qquad\qquad Z_{\max} = \frac{1 - x - y}{y} Y_{\max}$$

giving the following baseline conversion from display RGB scalars to tristimulus values along with the corresponding white point (XYZ_{white}) obtained by summing each of the channels maximum output in XYZ and the black point (XYZ_{black}) assuming a contrast ratio of 100:1.

TABLE II. The baseline display's maximum tristimulus values ($XYZ_{\max}$) for each of the RGB channels and the displays white point (XYZ_{white}) and black point (XYZ_{black})

	R	G	B	XYZ_{white}	XYZ_{black}
X_{max}	41.46	37.79	14.64	96.72	0.94
Y_{max}	21.83	71.73	6.45	100.00	1.00
Z_{max}	2.11	12.53	75.99	81.43	0.91

The conversion to tristimulus values from RGB scalars is then:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_0 \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix}$$

for M_0 the baseline conversion matrix given by:

$$M_0 = \begin{bmatrix} X_{r,\max} - X_{black} & X_{g,\max} - X_{black} & X_{b,\max} - X_{black} & X_{black} \\ Y_{r,\max} - Y_{black} & Y_{g,\max} - Y_{black} & Y_{b,\max} - Y_{black} & Y_{black} \\ Z_{r,\max} - Z_{black} & Z_{g,\max} - Z_{black} & Z_{b,\max} - Z_{black} & Z_{black} \end{bmatrix} = \begin{bmatrix} 40.52 & 36.85 & 13.70 & 0.94 \\ 20.83 & 70.73 & 5.45 & 1.00 \\ 1.20 & 75.08 & 89.72 & 0.91 \end{bmatrix}$$

Based on HDR display technology and the above assumptions, this baseline display is assumed to scale linearly as its dynamic range increases and its maximum output luminance correspondingly increases beyond its white point.

CIECAM02 Color Appearance Model Assumptions

CIECAM02 was implemented as prescribed in the CIE Technical Report[6], A Colour Appearance Model for Colour Management Systems: CIECAM02. Full adaptation was assumed (D = 1) under the following viewing conditions as given in the report.

TABLE III. CIECAM02 viewing conditions

Viewing Condition	Dark	Dim	Normal
Ambient Lighting	0 lux (0.0 cd/m^2)	38 lux (12.0 cd/m^2)	500 lux (159.2 cd/m^2)

The luminance L_A for the adapting field was taken to be one-fifth of the absolute value of the display white (100 cd/m^2) and the background luminance factor Y_b taken to be one-fifth display white as recommended[7].

MacAdam Limits

The MacAdam Limits in xy chromaticities, CIE Illuminant D65, and the 10^0 Observer, were computed as prescribed in MacAdam's paper[1] (see Figure 3). Lightness (J), chroma (a_c b_c), brightness (Q), and colorfulness (a_m b_m), were then computed from CIECAM02 under the above listed CIECAM02 assumptions.

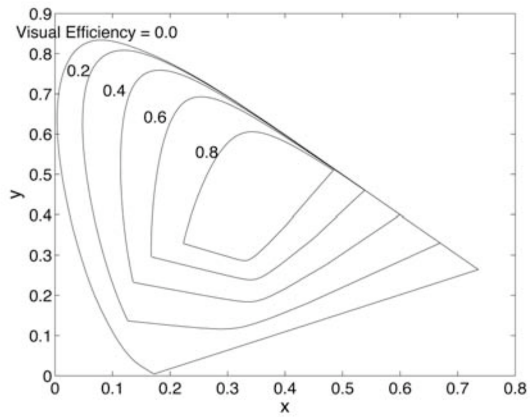

FIG. 3. MacAdam Limits of visual efficiency, CIE Illuminant D65, 10^0 Observer

Lowering the White Point

First, a data set of RGB scalars is constructed from 10,000 samples in RGB randomly sampled from a uniform distribution with the addition of a set of ramps in all possible combinations of R, G, and B. Then, the maximum luminance $Y_{0,\max}$ of the display is then scaled up by 2^N, $N = 0,1,2,...$ while retaining diffuse white point at a luminance of 100 cd/m^2. Based in the new value of $Y_{N,\max} = 2^N Y_{0,\max}$, a new conversion matrix M_N is computed according to the procedure given under Display Assumptions above. Assuming the display luminance between the diffuse white point and the black point is encoded in 8 bits to maintain contrast sensitivity, each $N = 0,1,2,...$ represents a hypothetical display with a diffuse white point luminance of 100 cd/m^2, a maximum luminance of 100, 200, 400, … cd/m^2, and the encoding of 8, 9, 10, … bits in luminance. In effect, rescaling the maximum display luminance by a factor of 2^N while retaining its original white point luminance is equivalent to lowering the baseline display's white point luminance by a factor of $1, \frac{1}{2}, \frac{1}{4}, \ldots$ for each $N = 0,1,2,\ldots$. With the diffuse white point always set at 100 cd/m^2, the additional display luminance is available for more accurate rendering of highlights and light sources, for example. This additional, available dynamic range also has a significant impact on the colorfulness of the display.

For each value of N, a set of tristimulus values XYZ are computed from the data set of RGB scalars according to the display conversion matrix M_N where:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_N \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix}, \ N = 0,1,2,\ldots$$

Lightness, chroma, brightness, and colorfulness are then computed from CIECAM02 from the set of tristimulus values under the assumptions stated above under the CIECAM02 color appearance model assumptions.

The MATLAB procedure *convhull* was invoked to delineate the respective gamut boundaries. Finally, the resulting gamut representations are plotted with the respective percepts computed from the MacAdam Limits.

RESULTS

In the following results under CIECAM02 dark viewing conditions (0 lux ambient illumination), N is taken up to the equivalent of 13 bits of luminance channel encoding with the intent of approximating the range of the fully adapted HVS. Such a display at 13 bits of encoding is equivalent to a display with maximum luminance of 3,200 cd/m^2, a contrast ration of 3,200:1, and a white point mapped to 1/32nd the maximum display luminance.

As a preface to the presentation of results, it should be noted that CIECAM02 is only strictly valid in the realm of object color perception and was never intended to predict color appearance outside this realm. The following results in perceptual gamut outside the realm of object color perception, then, are empirical extrapolations into a realm of "pseudo color" that presumably falls short of the luminous mode of perception. However, it could be said that human perception makes no such strict distinction – that the transition between object color perception and "pseudo color", if such a transition exists, is gradual and applying CIECAM02 to this region of perception would provide at least some insight into its effect.

Furthermore, the MATLAB procedure *convhull* presumes that the gamut being represented are strictly convex surfaces. Hence, some fine detail of the gamut may be lost in the following representations.

Lightness and Chroma

Figure 4 shows perceptual gamut in lightness (L) and chroma (a_c b_c) for N = 0, 1, 2, 3, 4, and 5 successive displays with the respective precepts computed for the MacAdam Limits at a maximum luminance of 100 cd/m^2 for diffuse white.

In the third plot, perceptual gamut in a_c b_c, the MacAdam Limits represented by the dashed line are, in fact, the locus of pure, spectral colors. Within 11 bits of luminance channel encoding or a white point of 1/8 the maximum display luminance, the gamut of the display virtually contains the locus of pure, spectral colors - what we know as maximum chroma. At 11 bits and beyond or white points of 1/8, 1/16, and 1/32, the CIECAM02 extrapolated colors exceed maximum perceived chroma and the MacAdam Limits in perceived lightness and chroma.

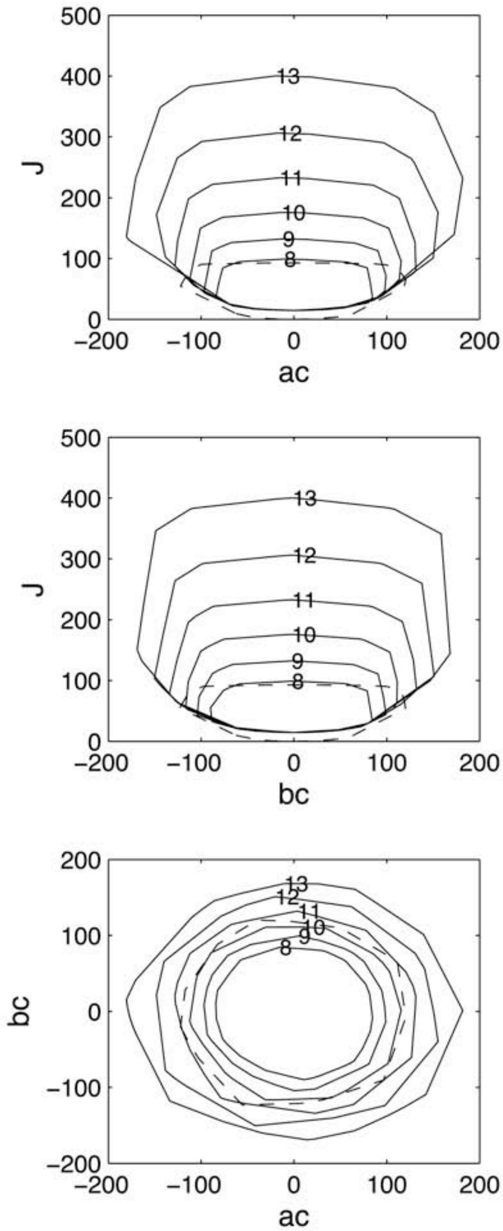

FIG. 4. The perceptual gamut in CIECAM02 lightness (J) and chroma ($a_c b_c$) of N successive displays of 8, 9, 10, 11, 12, and 13 bits of encoded luminance, each with half the preceding white point luminance relative to the display maximum, plotted against the MacAdam Limits (dashed line).

At first, this result may seem beyond reason until it is remembered that the locus of pure, spectral colors represents the color of a perfectly reflecting, monochromatic object and that this locus and its extension by the MacAdam Limits through to a perfectly diffuse, reflecting white object bounds the extent of all object colors. In this analysis, the luminance value of this perfectly diffuse, reflecting white object was constrained to 100 cd/m^2 as the diffuse white point of the display. By extension, all other possible object colors are constrained accordingly to lie within these limits. Hence, those colors made possible by raising the maximum luminance of the display beyond its diffuse white point necessarily must occur beyond the limits of object color and the locus of pure, spectral colors.

Brightness and Colorfulness

Figure 5 shows perceptual gamut in brightness (Q) and colorfulness (a_m b_m) of N = 0, 1, 2, 3, 4, and 5 successive displays as in the above.

In the third plot as in the case for lightness and chroma, perceptual gamut in colorfulness (a_m b_m) within 11 bits of luminance channel encoding or a white point of 1/8 the maximum display luminance virtually contains the locus of pure, spectral colors in colorfulness. At 11 bits and beyond, the CIECAM02 extrapolated colors are brighter and more colorful than those within the MacAdam Limits or at the locus of pure, spectral colors.

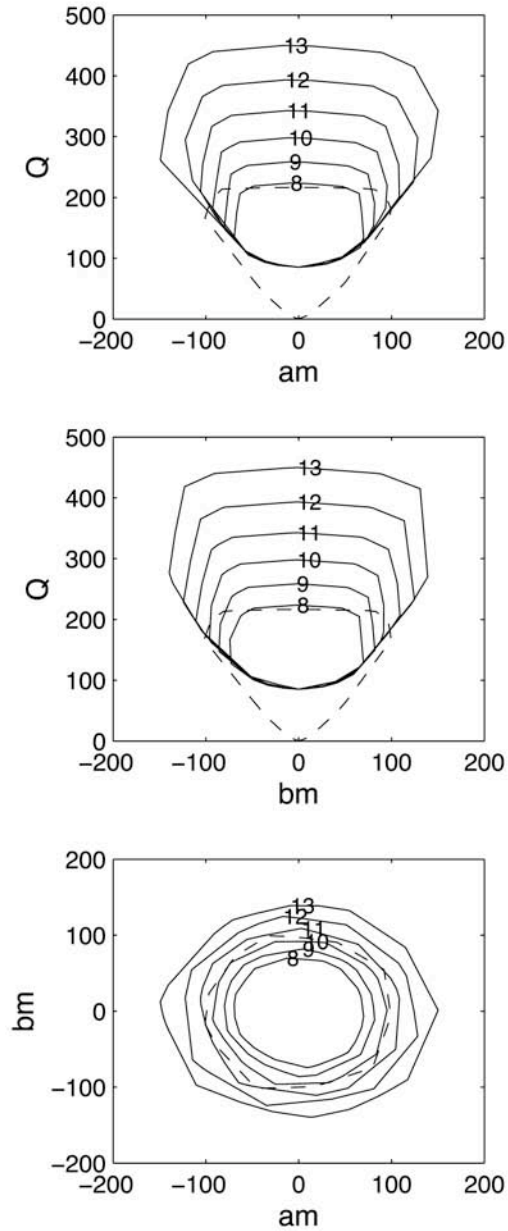

FIG. 5. The perceptual gamut in CIECAM02 brightness (Q) and colorfulness ($a_m b_m$) of N successive displays of 8, 9, 10, 11, 12, and 13 bits of encoded luminance, each with half the preceding white point luminance relative to the display maximum, plotted against the MacAdam Limits (dashed line).

Sample Images

The pairs of images in Figure 7, Grand Tetons, Neon, and the Stanford Memorial Church, are included only to illustrate the effect of "pushing down" the white point in relative luminance with due consideration given to the limitations of this media.

In each of the three images, a region was chosen as diffuse white – the patch of snow on the mountain in Grand Teton, the white paper in the foreground of Neon, and the skylight in the rotunda of the Stanford Memorial Cathedral. Each version of these images was rendered by mapping diffuse white to a white point 25% below the original 8 bit image (i.e. rendered as 6 bit images). On the left, those portions of the images with a luminance above the white point were clipped to 6 bits and represent the more traditional methodology of rendering the white point to the maximum luminance of the media – 6 bits of encoded luminance in this case. In the case of the Stanford Memorial Cathedral, it was necessary to segment that portion of the cathedral lit by the stained glass windows to achieve the desired effect.

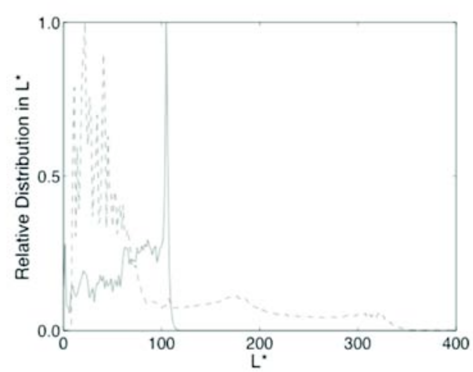

FIG. 6. Imaging mapping function – expanded gamut mapping (solid line) and a clipped mapping (dotted line) to diffuse white

On the right, those portions of the respective images with luminance above the white point - the sunlight trees, the neon sign, and the stained glassed window lit portions of the cathedral - were maintained at 100% of the original (i.e. a maximum display luminance four times the white point or a full 8 bits). Figure 6 illustrates the distribution of

Luminance L* for the Grand Teton - the clipped mapping (left) and extended gamut mapping (right) on the previous page.

The fact that these images appear dark as rendered for this paper is due to the limitations of the printed media and its dynamic range for illustrating this effect. Viewed in a dark surround on the Munsell Color Science Laboratory's High Dynamic Range (HDR) display which has a dynamic range approaching five orders of magnitude, the images do not appear dark, and those portions above their respective diffuse white when mapped to the full sixteen bits available in this display appear strikingly more brilliant[6] in the images on the right. These images appear more representative of what perhaps was actually seen in the original scene and demonstrate a significant, perceived gamut expansion in lightness, chroma, brightness, and colorfulness when compared to those versions on the left.

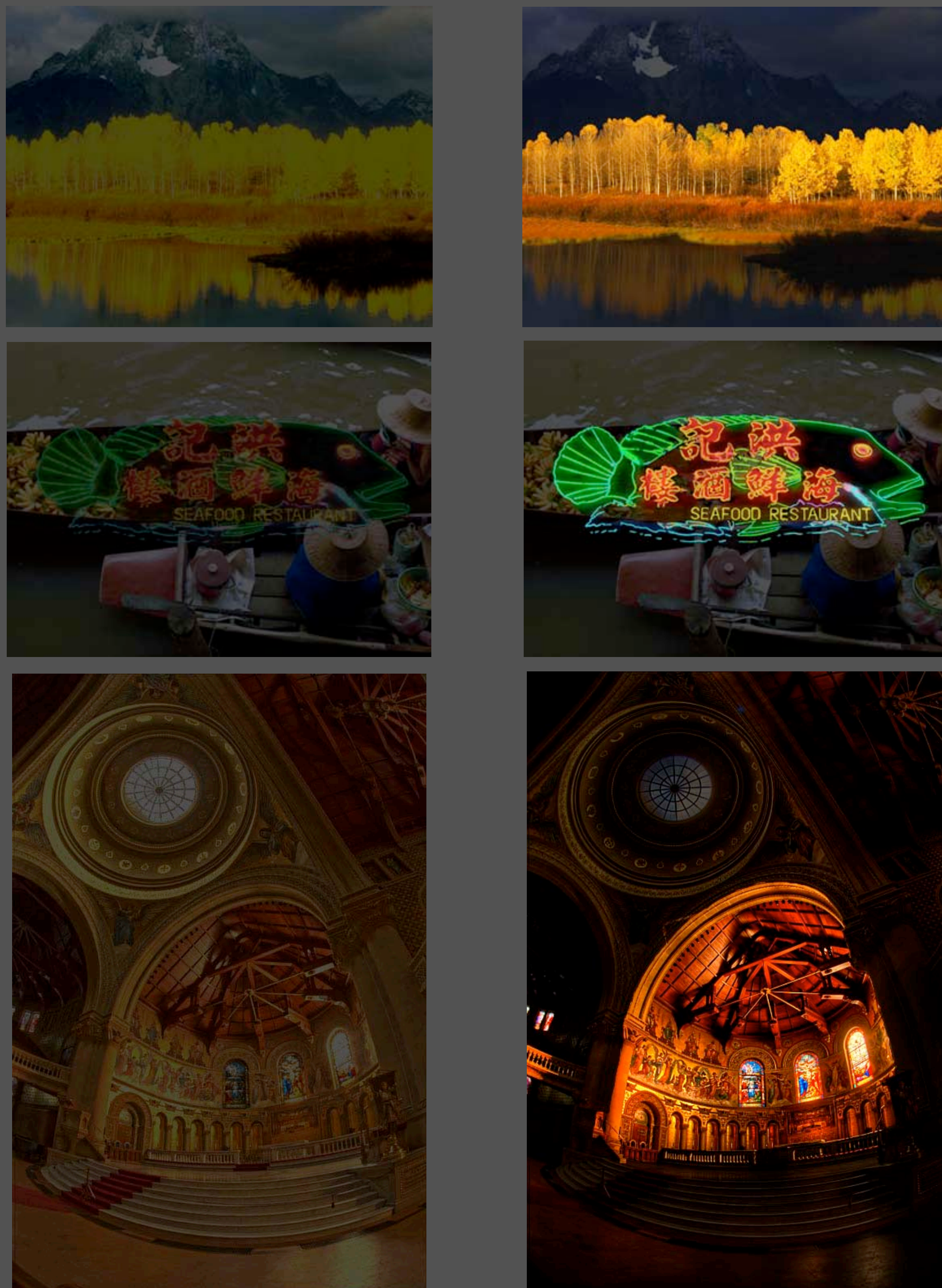

FIG. 7. The Grand Tetons, Neon, and the Stanford Memorial Church images clipped to the display's white point of the left and fully rendered on the right. The illustrations on the right allow for two additional bits of encoding beyond diffuse white (i.e. the display maximum luminance is four times that used to represent diffuse white.

Figure 8 plots the effect of viewing condition on the relative increase in the volume of perceptual gamut as the number of encoded bits in the luminance channel of the display is increased. Under normal viewing conditions, the relative gamut volume in lightness and chroma effectively doubles for each added bit of luminance. Under dim and dark viewing conditions as the surround becomes successively less bright and the display lower in perceived contrast, the effect diminishes correspondingly. In brightness/colorfulness, the increase in volume goes by the root of 2 instead and is similarly affected by viewing conditions.

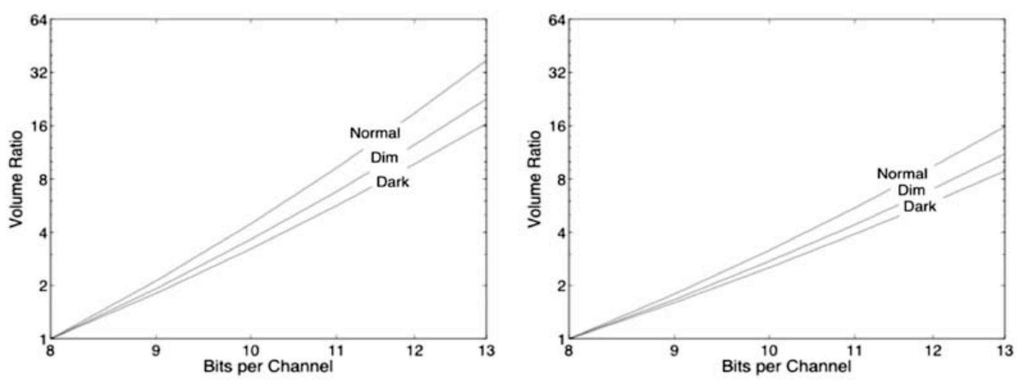

FIG. 8. Relative increase in perceptual gamut volume in lightness and chroma on the left and brightness and colorfulness on the right as a function of the number of bits encoded in display luminance for the CIECAM02 viewing conditions Dark, Dim, and Normal.

The above analysis was performed without consideration for the effect of viewing flare especially under normal viewing conditions as there is no viewing flare effect under dark viewing conditions and minimal effect under dim conditions. Figure 9 plots the effect of viewing flare on the relative increase in the volume of perceptual gamut as before under normal viewing conditions. Viewing flare is expressed as a percent ambient illumination (500 lux in this case) and is assumed to be characterized by CIE Illuminant A. Volume ratio is expressed relative to the gamut volume computed under zero viewing flare conditions.

As shown, the increase in gamut volume converges to the zero viewing flare case as more and more bits of luminance encoding are added beyond diffuse white – i.e. the display becomes brighter and brighter relative to its surround. At lower luminance encoding – i.e. as maximum luminance approaches diffuse white, the effect of viewing flare becomes more significant thereby countering the advantage of higher perceived contrast under normal viewing conditions as noted above.

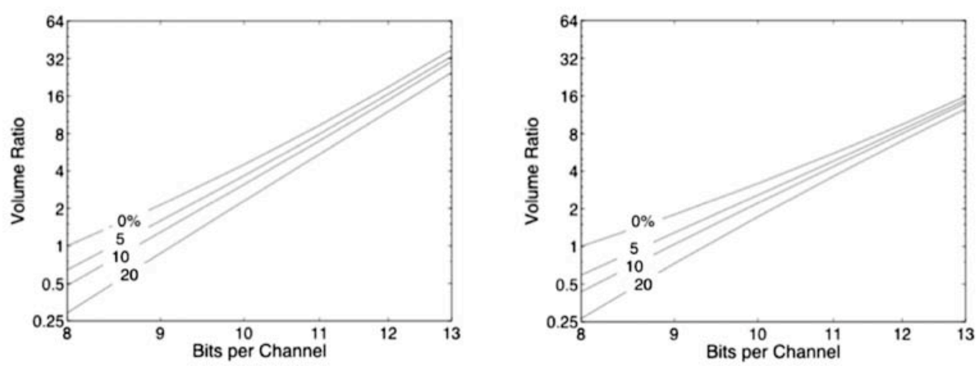

FIG. 9. Relative increase in perceptual gamut volume in lightness and chroma on the left and brightness and colorfulness on the right as a function of the number of bits encoded in display luminance for various levels of viewing flare under normal viewing conditions (500 lux).

CONCLUSIONS

A methodology that shows promise in producing a fuller visual experience provided by the capabilities of current and future display media technologies was demonstrated both empirically and in a limited set of images. In this methodology, knowledge of the powers of adaptation and CIECAM02 are exploited for expanding the perceptual gamut in lightness, chroma, brightness, and colorfulness beyond the locus of pure, spectral color and the MacAdam Limits by simply "pushing down" the white point of the display.

"Pushing down" the display's white point is equivalent to keeping the white point constant and increasing the maximum display luminance beyond its white point. In this sense, a maximum display luminance 4 to 8 times its white point results in a perceptual gamut in chroma and colorfulness that virtually contains the corresponding percepts of the locus of pure, spectral colors.

Each successive doubling of maximum display luminance relative to its white point requires an additional bit of encoded display luminance. For each additional bit, the perceptual gamut in lightness and chroma is increased by a factor of 2 and perceptual gamut in brightness and colorfulness by a factor of the square root of 2. The effect is somewhat more pronounced in normal surrounds, and successively less in dim and dark surrounds as perceived contrast correspondingly decreases. Finally, viewing flare serves to counter the more pronounced effect in normal surrounds as maximum display luminance approached diffuse white of the display.

The effect of "pushing down" the white point is not unknown and continues to be common practice in photographic systems where diffuse white is encoded at a density greater than the minimum available in transparencies or less than the maximum available in negative films in order to render those " … parts of the scene having luminance greater than that of the reference white (such as specular reflections …).[8]

Furthermore, returning to the stained glass windows at the Cathedral at Chartres, James Rosser Johnson notes in his treatise, <u>The Radiance of Chartres</u>[9], that "… the experience of seeing these windows … is a very complicated experience …” that spans many aspects of perception. Yet fundamentally, “when the spectator enters the Cathedral from the bright sunlight, … the visitor must step with caution until his eyes have made a partial dark adaptation … then the details of the interior will seem lighter and clearer while, at the same time, the [stained glass] windows become richer and more intense. [Conversely] … in a richly colored window [in lesser church or cathedral’s windows] with an intruding spot of light glass, the eye will adapt to the brightest intensity … thus failing to perceive the more muted and perhaps richer tones in the same field”. In both these cases, adaptation has played a powerful role - the former by adaptation to the darkness or lower, perceived diffuse white of the cathedral where the colors of the windows appear exceedingly brilliant and the latter by adaptation to a diffuse white as the maximum luminance in the field thereby underplaying the brilliance of the windows.

Hence, while the perceptual experience is certainly complex and affected by the many artifacts of the human vision system, the richness of this experience is largely and simply made possible by the broad extent of sensitivity of the fully adapted human vision system and its innate ability to adapt to its surround. And it is the challenge of display systems to reproduce this visual experience to its fullest extent.

FUTURE DIRECTIONS

While the methodology presented here seems simple on the surface, the implications of implementing such a methodology are not. “Pushing down” the white point is only feasible if contrast sensitivity is maintained throughout the full dynamic range of the display. Yet contrast sensitivity in an expanded perceptual gamut is only maintained if the image data are encoded to more than the 8 bits per channel. While such an expanded encoding is supported in professional, graphic arts markets today, it is not yet fully supported in today's consumer and commercial media markets with imaging standards (e.g. JPEG and MPEG), nor is it supported in the image capture, processing, storage, and display devices themselves and their respective interfaces. The promise of media capable of displaying the full range of the visual experience should be more than compelling enough to motivate media manufacturers to develop such new standards and devices as these technologies continue to develop.

Even more fundamental to the limitations of today's media support, the basis for this methodology and its compelling result is in our current knowledge of color - a knowledge rooted in the perception of object color even though our everyday visual experience is far richer. The work of Ralph M. Evans[10] in the middle of the 1900's in color perception, his new found perception of brilliance, and more recently, Nayatani's acknowledgement[11,12] of Evan's work which formed much of the basis of his NT color space - an almost unified theory of color appearance - may provide the necessary insight into this far richer experience and its application to display media technology.

The application of current knowledge, limited as it may be, and the work of Evans and Nayatani to the broader realm of the visual experience remains to be seen, and it is this that is of high interest. Through psychophysical testing and analysis using images rendered on an HDR display that comes close to the limits of the fully adapted HVS, perhaps a sounder basis will be formed – a basis for future display media and its capability to provide a full visual experience.

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BIOGRAPHIES

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Rodney L. Heckaman is a third 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 and retired after 32 years of service at the Eastman Kodak Research Laboratory.