Brighter, More Colorful Colors and Darker, Deeper Colors Based on a Theme of Brilliance

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Abstract: A methodology for achieving brighter, more colorful colors and deeper, darker colors based on Evans’ zero gray (G₀) [described in The Perception of Color] and his concept of brilliance as a percept in color vision was demonstrated and tested psychometrically in media produced under current digital video and digital cinema standards—basically the sRGB set of primaries. Objects or surfaces in a scene represented in sRGB as having gray content in the Evans sense are rendered as original. Flesh tones are preserved. Those features not having gray content—a highly colorful arrangement of flowers, a clear blue sky, and the glossy red lipstick of a beautiful lady—are made brighter, more colorful and deeper, darker when rendered in a set of primaries that emulate, for example, the xvYCC-encoded standard and whose colors extend beyond those of sRGB—an expanded gamut, if you will. In all but the most-aggressive application, versions of scenes where this methodology was applied were consistently preferred over the sRGB version across 10 representative scenes and 17 observers.

Key words: image rendering; gamut mapping; brilliance; gamut expansion

INTRODUCTION

In his 1935 article, maximum visual efficiency of colored materials,1 David MacAdam stated, “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.” Yet, to this day, as digital video and digital cinema media technology shows the real promise of going well beyond MacAdam’s maximum visual efficiency in the perceptual sense, attempts to implement such technology through brighter, more colorful primaries than those standard in the industry have been met with the hue and cry of unnaturalness.2 Have we been so conditioned to these standards—most of us since childhood—that we consider video and cinema as a separate reality from what we see every day? This article asserts that perhaps not—that perhaps it is instead a matter of rendering. That certain features of a scene—specifically object or surface colors, flesh tones—should be rendered as original while other features such as a blue sky on a crisp winter’s day, a sunset, or a colorful arrangement of flowers are clear candidates for brighter, more colorful or deeper, darker renderings.

BACKGROUND

In Part II of their 1996 article,3 Natural Color System (NCS), Härd, Sivik, and Tonquist partitioned the NCS space into nuance (Fig. 1) by the primary percepts of blackness, whiteness, and chromaticness and the secondary attributes of grayness, clearness, and deepness (Fig. 2). The secondary attribute, grayness, is noted as influenced by Evans’ earlier studies4 of what he termed brilliance. To Evans, brilliance is a percept that takes on the appearance of gray that diminishes to zero (G₀) as the luminance of a chromatic stimulus approaches that of its surround. Beyond G₀, the stimulus appears fluorescent as it progresses from the surface mode of appearance below G₀ to the luminance mode where its brightness exceeds that of its surround. The appearance of brilliance to Evans is mutually exclusive—either gray or fluorescent—and further, that G₀ is directly related to the relative chromatic strength of colors.

Just prior to the Härd, Sivik, and Tonquist 1996 article, Nayatani5 stated his belief that the function G₀ is fun-
damental and influenced by this belief, he proceeded in defining his Nayatani Theoretical Color Space. Figure 3 illustrates one equi-hue plane in this space with loci of equal grayness (gr) from a value of zero that corresponds to Evans’ $G_0$ to a value of 100 at Nayatani’s reference gray ($G_r$). Furthermore, as grayness decreases in the region above the $G_r$-$B$ line from the point $G_r$, where $gr = 100$, color becomes brighter and more colorful as illustrated by the upper overlain arrow in Fig. 3. As grayness decreases in the region below the $G_r$-$B$ line, color becomes deeper and darker.

It should then be possible to demonstrate brighter, more colorful colors and darker, deeper colors in such a way as to preserve those colors said to be in object or surface mode—i.e., having gray content ($0 < gr \leq 100$). Those colors without gray content ($gr \leq 0$) are then candidates for expansion in chroma and lightness according to a sigmoidal-like expansion as function of their grayness value that preserves smoothness across the transition from zero gray. In this way, object or surface colors and specifically flesh tones are preserved, yet colors such as those in a sunset or colorful fall foliage are made brighter, more colorful and those of a deep, dark blue sky on a crisp winter’s day made even deeper and darker.

**METHODOLOGY**

As a demonstration of some practical interest, sRGB was chosen as the source set of primaries and a set of extended primaries that emulate the xvYCC-encoded standard as the target set. The opportunity for brighter, more colorful colors of deeper, darker colors in a full grid of sRGB scalar values was computed according to Nayatani’s relationships between grayness $gr$ and NCS chromaticness $C$, whiteness $W$, and blackness $S$:

$$gr = 2\min(W, S)$$  \hfill (1)

where NCS chromaticness $C$ and blackness $S$ were derived by necessity from the set of 24 NCS aim color patches and their corresponding CIE XYZ values in illuminant A, the CIE 1931 observer, for the NCS notation. Whiteness was computed from $W = 100 - C - S$, the normalization relationship for the NCS notation.
NCS Chromaticness and Blackness Derived from CIELAB LCh

The given NCS primary attributes and their corresponding CIE XYZ values were first chromatically adapted to the D65 illuminant consistent with the sRGB and target primaries, and their corresponding CIELAB LCh values computed for each of the aim color patches in each of the 24 NCS hues\(^9,10\) using a similar methodology as Derefeldt and Sahlin.\(^10\) These data for each NCS hue were regressed against their given NCS chromaticness \(C\) and blackness \(S\) giving the functions in polynomial form

\[
S_n = f_n(C, L) \quad \text{and} \quad C_n = g_n(C, L)
\]

for \(n = 1, 2, \ldots, 24\) NCS hues [see Figs. 4(a) and 4(b), for example].

Because the space of constant NCS hue is a warped space in terms of CIELAB hue \((h_{ab})\), CIELAB hue was regressed within each of the NCS hue sets giving the additional polynomial form \(h_{ab,n} = h_n(C, L)\) for \(n = 1, 2, \ldots, 24\) shown in Fig. 4(c) for the purpose of interpolating NCS chromaticness and blackness for each of the computed CIELAB LCh values in the sRGB grid. Additionally, the mean and standard deviation in CIELAB hue for each of the 24 planes of constant NCS hue was computed. These statistics are then treated as a standard normal probability density function for computing the most likely plane that any given CIELAB LCh will fall closest for interpolation purposes.

Interpolation of NCS Chromaticness and Blackness in an sRGB Grid and the Computation of Grayness

First, CIELAB LCh values were computed for each point in an \(18 \times 18 \times 18\) uniformly spaced grid in sRGB scalar values. Then, from the hue statistics referred to in the above, the maximum probability that each of the CIELAB hue values in the grid is a member of the 24 NCS hues is computed. Once the most likely plane \(k\) of constant NCS hue is determined for any given CIELAB LCh value in the sRGB grid, the corresponding NCS chromaticness \(C_m\), blackness \(S_m\), and hue \(h_{ab,m}\), \(m = k − 1, k, k + 1\), are computed from their corresponding fitted functions \(S_m = t_m(C, L)\), \(C_m = s_m(C, L)\), and \(h_{ab,m} = h_m(C, L)\). From the resulting three space of \([S_m, C_m, h_{ab,m}]\), the value \([S, C]\) is obtained using one-dimensional linear interpolation in the hue \((h_{ab})\) component of the given CIELAB LCh value. Figure 5 illustrates this mapping process for NCS chromaticness [and analogously for NCS blackness]. Now, having NCS chromaticness and blackness for each point in the sRGB grid, grayness value \((gr)\)
can be computed from Eq. (1) and the normalization relationship for NCS notation.

**Expansion in the Target Set of Primaries**

Once grayness $gr$ is available for each grid point in the sRGB cube, an expansion factor $a$ is computed for each point where:

$$a = \frac{100}{C_0} \frac{gr_0}{C_0} \frac{gr}{gr_0} \frac{g}{C_18/C_19}$$

for $gr < gr_0$, $\eta$ a parameter greater than 1, and $gr_1 = -60$ chosen as a practical or realistic minimum gray value within the extent of the sRGB primaries. Figure 6 plots this expansion factor $a$ as a function of gray value for test values of $\eta$ and $gr_0$.

**FIG. 5.** Linear interpolation in mapping CIELAB LCh to NCS chromaticness $C$ and blackness $S$.

**FIG. 6.** Lightness and chroma expansion factor $a$ as a function of the grayness ($gr$) of the source sRGB primaries for various parameter values of $\eta$ and $gr_0$.

**FIG. 7.** An equi-hue plane in the target set of primaries showing the result $L_{out}C_{out}$ of an expansion of an input value in $L_{in}C_{in}$.

**FIG. 8.** An equi-hue plane in the target set of primaries showing the result $L_{out}C_{out}$ of an expansion of an input value in $L_{in}C_{in}$.
FIG. 9. Locus of equi-gray levels in CIELAB for the NCS hue R overlain by the extent of the sRGB primaries (dashed) and the xvYCC target set.

FIG. 10. Locus of equi-gray levels, \( gr < 0 \), for the sRGB primaries in CIELAB.

Figure 7 illustrates the expansion method in an equi-hue plane of the target set of primaries showing the result \( L_{out}C_{out} \) of an expansion of an input value \( L_{in}C_{in} \) with

FIG. 11. The Flowers image. (a) gray value. (b) direction of expansion. (c) original sRGB version. (d) targeted version.
appropriate hue along the line passing through the lightness value $L_{Gr}$ of Nayatani’s reference gray (Gr) and the coordinates of the input. $L_{max}$ is the maximum chroma at that hue and $L_{C_{max}}$ its corresponding lightness computed from the target set of primaries, and $z$ the expansion factor computed from the above. The result, as illustrated, is a brighter, more colorful color. When the input lightness value $L_{in}$ is below $L_{Gr}$, the result is a deeper, darker color.

Like Evans’ $G_0$, the lightness value $L_{C_{max}}$ at maximum chroma is a strong function of the chromatic strength of colors, and both mediate whether a color is made brighter, more colorful or deeper, darker and to what degree depending on their relative position to reference gray ($L_{Gr}$).

Figure 8 plots the loci of equi-gray values for the NCS hue Y to illustrate these dependencies. The radial lines originating at reference gray ($L_{Gr}$) indicate the direction of expansion, whether deeper, darker or brighter, more colorful. The magnitude of the expansion varies according to the gray value of the input color and the extent of the target set of primaries relative to sRGB. Y as shown and to a certain extent G are low in chromatic strength and have a relatively high lightness values $L_{C_{max}}$ at maximum chroma. Hence, they most likely would be made deeper, darker but to a smaller extent.

Blue and red (shown in Fig. 9), on the other hand, are high in chromatic strength with more moderate lightness values $L_{C_{max}}$, and they would be equally likely made brighter, more colorful to a larger extent or deeper, darker to a lesser extent.
Results of Applying the Methodology in the sRGB Gamut

Figure 10 plots loci of equi-grayness for gr <= 0 (less than zero gray content) in CIELAB as computed from the sRGB grid and, as such, illustrates the potential in sRGB for expanding colors and making them brighter, more colorful or deeper, darker. For example, those regions in white would approach maximum chroma when expanded in the target set of primaries per the above, and those regions enclosed by the innermost shell (gr = 0) would retain their original quality as having gray content. As can be seen, sRGB provides ample opportunity for making brighter, more colorful colors or deeper, darker colors in the targeted primaries in this context.

Imaging Examples

This methodology was applied to a number of images to test the hypothesis that outside the region of gray content (e.g., object color and flesh tones), brighter, more colorful colors and deeper, darker colors are possible. The parameters $\eta = 4$ and $gr0 = 0$ were chosen as a more than adequate demonstration of the methodology.

Figure 11(a) illustrates the range of grayness value for the Flowers image. Gray to white is intended to represent decreasing degrees of gray content ranging from a value of 100 at reference gray to a value of zero (white). The shades of red represent decreasing degrees of less than zero gray content and, hence, prime candidates for expansion. Figure 11(b) illustrates the direction of expansion—brighter, more colorful in red or deeper, darker in blue according to the methodology presented in this article.

Note the flower in the upper center of the arrangement. The outer portions of its petals are brighter, more colorful (red) as noted in Fig. 11(b), whereas the inner portions of the petals are deeper, darker (blue). Figure 11(d) illustrates the result in the targeted primaries when compared with the original in Fig. 11(c). Under certain viewing conditions, the noted flower actually appears fluorescent.

Figure 12, the image of the Lady, is presented as an example of where this methodology distinguishes flesh tone as having gray content [Fig. 12(a)] and, hence, kept as original. Figure 12(c), rendered to the targeted primaries and when compared with the original [Fig. 12(c)], indicates a modest brightening, more colorful region in the lips but little or no effect on the flesh tones.

PSYCHOPHYSICAL TESTING

The question now arises of whether the specific aims of this method are met and accepted by observers. Whether object or surface colors, particularly flesh tones, would be rendered as original, whereas other features such as a blue sky on a crisp winter’s day, a sunset, or a colorful arrangement of flowers rendered brighter, more colorful or deeper, darker. The method is then tested against these aims using psychophysical methods to determine its effect on the perception of colorfulness and brightness and observer preference in real scenes.

Test Methodology

Colorfulness, brightness, and preference were scaled psychophysically by 17 observers over six versions of 10 scenes using a fully characterized, Sony, prototype, 40" LED backlit, LCD display with an expanded xvYCC-encoding under ambient viewing conditions with minimal viewing glare. The 17 observers consisting of a variety of demography in age—from 20 to 64, sex, expert and nonexpert, and cultural background—American, Chinese, Japanese, and European. Of the 10 representative scenes tested (see the Appendix)—six from sRGB renderings of M. D. Fairchild’s HDR photographic survey\textsuperscript{11} chosen for their overall lightness contrast and colorful-
ness. Three scenes—Flowers, Coast, and Lady—were chosen as a point of comparison to previous studies in this area. The scene Rachel was chosen along with the Lady scene as representative of flesh tones.

Image Preparation

In addition to the sRGB sourced version, the remaining five versions ranged from very aggressive to more moderate applications of this methodology of brighter, more colorful and deeper, darker color renderings according the methodology defined in the above for each of the expansion factors $\alpha = f(\text{gr}, \text{gr}_0, \eta)$, plotted in Fig. 6. The version $[\text{gr}_0, \eta] = [0, 2]$ is quite aggressive throughout the range of source grayness values—from $0 \leq \text{grayness} \leq 100$, where gray content is present and below grayness $\leq 0$, where gray content is absent. Hence, it would be expected that this version of each of the scenes would not support the aim of preserving object colors—particularly flesh tones. Conversely, it would be expected that the versions of the scenes for $[\text{gr}_0, \eta] = [80, 4]$ would easily remain true to this aim expanding only those source values absent of gray content. The remaining versions, $[\text{gr}_0, \eta] = [50, 2], [0, 4], \text{and} [40, 4]$, would be expected to fall between offering progressively increasing expansion in the areas absent of gray content and decreasing expansion in the areas having gray content.

The Psychophysics

Colorfulness and brightness of the expanded versions of the scenes were scaled using a ratio scale relative to the source sRGB version. In each case, the sRGB version was displayed on the left and the tested version on the right. Observers were asked to enter the percent more or less colorful (brighter) the image on the right was than the image on the left. Preference was scaled using the method of paired comparison. All possible pairs or each version of each scene were displayed randomly, and observers were asked simply to pick which version they preferred.

**Colorfulness and Brightness Results.** The overall results for colorfulness and brightness for each of the five versions are reported in Fig. 13. The results are averaged over all scenes and observers and reported as the percent increase in colorfulness and brightness from the sRGB version. The error bars around each reported average or mean are the 95% confidence intervals (CIs) in each mean.

The most aggressive expansion factor $([\text{gr}_0, \eta] = [0, 2])$ produced images perceived as 9% higher in average colorfulness and a little less than 6% higher in average brightness than the sRGB version and could be said to be significantly higher in each attribute than the remaining versions with greater than 95% CI. The remaining versions were perceived 4–6% higher in average colorfulness and 2–4% higher in average brightness than the sRGB version again with greater than 95% CI.

**Preference Results.** Overall preference is plotted in Fig. 14 in terms of each version’s $Z$ score averaged over

![Image of two versions of a scene](a)

![Image of two versions of a scene](b)
all scenes and observers with error bars in terms of their corresponding 95% CIs. At least on average, the most-aggressive application of expansion factor ([gr0, η] = [0, 2]) is significantly less preferred than all other versions including the source sRGB version. All the remaining versions, again on average, were significantly (with 95% CI) more preferred than the source sRGB version.

In the most-aggressive application ([gr0, η] = [0, 2]), two likely causes of its poor preference showing are illustrated in Fig. 15, where the aim of preserving flesh tone was not adhered to and observers are presumably reacting unfavorably, and Fig. 16 where contouring is visible in the sky—a direct result of the more-aggressive application.

On an image-by-image basis averaged over all observers, the preference relationships between versions holds up generally in the same way that the overall results. In both scenes having flesh tone—Rachel and Lady, flesh tones are preserved in the less-aggressive applications of the methodology ([gr0, η] = [50, 2], [0, 4], [40, 4], and [80, 4]). In all cases, the mean preference of the less-aggressive applications of the methodology can be said to be either significantly or at least equally preferred over the source sRGB version with 95% CI.

Cluster Analysis. On a scene-by-scene basis, image dependencies should be expected. More colorful scenes (e.g., the Flowers scene) would be expected to behave differently to the application of this methodology than outdoor scenes (e.g., Pecks Lake) or scenes predominantly of flesh tone (e.g., Lady) and so on. Furthermore, groups of observers that prefer more natural-looking scenes against those preferring more colorful or stylized applications of the method should be expected. To test these hypotheses, a k-Means cluster analysis was performed on mean colorfulness, brightness, and preference on both a scene-by-scene basis and an observer-by-observer basis. In neither case were any reliable clusters identified in a consistent hierarchy. Hence, it is suggested that the overall results depicted in Figs. 13 and 14 are representative of the results achieved by this methodology at least over the scenes tested and the observers at hand.

CONCLUSIONS

Overall, a methodology for achieving brighter, more colorful colors and deeper, darker colors based on Evans’ G0 and his concept of brilliance was tested in varying degrees of application in a representative set of scenes in terms of their preference against each scene’s source sRGB original—in essence, that which is produced under current digital video and digital cinema standards. For all but the most-aggressive application of the methodology, its principle aim was substantiated. Each scene having gray content in the Evans/Nayatani sense were rendered close to original and, most importantly, flesh tones were preserved. Furthermore, all but the most-aggressive application of the method was either significantly preferred or at least equally preferred over the source sRGB original version both when averaged across all scenes and on a scene-by-scene basis.

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APPENDIX: TEST SCENES


FIG. A2. Coast.

FIG. A3. Delicate Arch.

FIG. A4. Flamingo.

FIG. A5. Flowers.

FIG. A6. Golden Gate.

FIG. A7. Lady.

COLOR research and application