Mapping Standard Image Content to Wide-Gamut Displays

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Abstract

Wide-gamut display technology has provided an excellent opportunity for producing more visually pleasing images. However, through several studies, including Laird and Heynderickx[2], it has been shown that linearly mapping standard sRGB content to the gamut boundary of the wide-gamut display may not produce optimal results. Therefore, several algorithms were developed and evaluated for observer preference, including both linear and sigmoidal expansion algorithms, in an effort to determine a single, versatile gamut expansion algorithm (GEA) that can be applied to current display technology and produce the most preferable images for observers. The outcome provided preference results from two displays, both of which resulted in large scene dependencies. Overall, the sigmoidal GEAs (SGEA) were competitive with the linear GEAs (LGEA), and in many cases, resulted in more pleasing reproductions. The SGEAs provided an excellent baseline, in which, with minor improvements, could be key to producing more impressive images on a wide-gamut display.

Introduction

With current display technology, expanding the colorfulness of images is no longer a challenge. However, through recent research[1] observer preference does not necessarily increase monotonically with color. Heckaman et al., reported consistent results that observers enjoyed increased colorfulness and lightness contrast. However, this effect was dependent on the scene at hand. Laird and Heynderickx[2] attributed this scene-dependency to the naturalness of an image. In addition, they concluded from their results that the optimal color reproduction method does not appear to be the most colorful version. More specifically, Laird and Heynderickx established perceptually optimal boundaries for extended gamut displays, which for the most part, were only slightly wider than the EBU standard. From this, it appears the mechanism in which current image and media content is mapped to a display with extended primaries needs to be restrictive, in some respect, to avoid unpleasing results. Therefore, multiple gamut expansion algorithms (GEAs) were considered such that the sRGB content is expanded in the most preferable manner.

Purpose and Methodology

Various gamut expansion algorithms were developed and evaluated, in determining the most pleasing algorithm that maps images under current standards to wide gamut technology. This was conducted through psychophysical experimentation and analysis, which entailed evaluating observer preference across each of nine GEAs, including two baseline algorithms, with a paired comparison experiment, on two unique displays.

Scenes

There was a total of ten scenes (Appendix A) chosen for their colorfulness, lightness contrast and range of hue. More specifically, the coast scene was chosen for its wide range in lightness, the lady and musician scenes were used for their flesh tones, the flowers and PW837_rgb images had a high degree of colorfulness, and there were several scenes chosen for their natural content such as the water and coast scenes. Thus, a variety of images were chosen to encompass a range of colorfulness, lightness contrast, overall saturation attributes, as well as features of interest such as flesh tones, natural content, and image complexity.

Display

A SONY prototype, 40 inch, LED backlit, LCD display with three extended primaries was used as one of the wide-gamut displays for this evaluation. This display was characterized to a mean CIEDEab of 1.0 with a standard deviation of 0.67 using the standard illuminant D65, the 1931 standard-observer and measurements from a LMT C 1210 Colorimeter. Ten-step RGB ramps were measured and incorporated into the display look-up table (LUT) as a conversion between RGB linear scalars and RGB display digital counts. Due to the linear-dependencies between the three primaries, the LUT provided satisfactory results.[1]

The second display incorporated into the psychophysical evaluation was a Samsung HLT5087S 50" Slim LED Engine 1080p DLP HDTV. Although several characterization procedures were implemented, the evaluation was performed using the simple model characterization, or characterizing with three 1D-LUTs, similar to above. Since this display was designed for commercial purposes, non-linear processing had been imposed by the company such that it could not be completely accounted for within the characterization. As colorimetric accuracy was not the intent of the study, a simple model enabled control of the images displayed despite lacking a complete understanding of the processing introduced within the display's infrastructure.

Experimental Conditions and Observations

The preliminary experiments conducted at the Rochester Institute of Technology's Munsell Color Science Laboratory entailed twenty unique observers for each experiment, both male and female, ranging in age, demographic backgrounds, ethnicities, and expertise. The observers sat two meters from the display, which was placed in front of a uniformly gray background, illuminated by two Buhlite 150 watt, diffuse studio lamps. Viewing flare was minimized as the only light source was placed behind the display. Using a Spectrascan PR650 Spectrophotometer, the illumination off the wall was measured to be 94cd/m^2 and at a correlated color temperature of 3150˚K.[1] The images were displayed on a uniform mid-gray background, separated by approximately 2˚ of visual angle. The Sony display maintained 25˚ by 14˚ of visual angles; the Samsung maintained 32˚ by 22˚ visual angles, and both were viewed perpendicularly.

Stimulus Preparation

As was established by Fedorovskaya et al.[3], color is the main perceptual attribute that affects image quality. Therefore, both linear (LGEA) and sigmoidal (SGEA) gamut expansion techniques were applied to multiple images, such that expansion of the chromatic content was of primary focus.

LGEA

The LGEA applied to the image operated in CIELAB space, and was based on Eqn. 1:

$$Lab_{out} = [1\ k_{a*}\ k_{b*}]*Lab_{in} \quad (1),$$

where k_a* and k_b* are equal. By multiplying a* and b* by the same scaling factor, hue was preserved. Therefore, this expansion did not result in undesireable hue shifts. The resulting CIELAB expanded values represented the original lightness values, with expanded (a*,b*) coordinates.

When applying this LGEA to multiple images, the scaling factor was determined based on a ratio of the input gamut to the destination gamut. To avoid the effects of lightness and hue dependent maximum chromatic values, the ratio between the gamut boundary was calculated based on the appropriate lightness and hue angle combination. For a series of ten lightness blocks, and seventy-two hue slices, each comprised of five degrees of hue angle, the corresponding maximum chroma was obtained and used to form a LUT relating hue angle, lightness and maximum chroma. These data points were then linearly regressed to provide the direct relationship between lightness and chroma, ignoring any outliers.

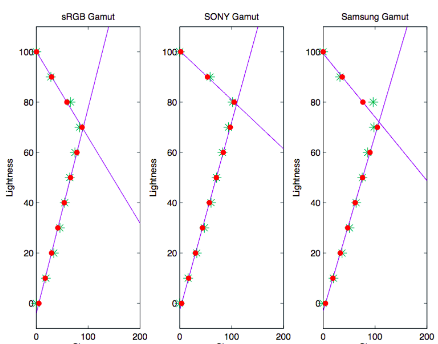


Figure 1. Maximum chromatic values (for hue 75˚) computed for given lightness values for both the input (sRGB) gamut and destination (SONY and Samsung) gamuts. (Green: calculated values, red: theoretical)

Using the linearly regressed data, a LUT was used to relate the three attributes of both gamuts, and hence, was used to establish the ratio between the two at every pixel of the image. This ratio defined the scaling factor used for each of the three LGEAs.

Three different scaling factors for each ratio, were incorporated into the chroma expansion. The distance between the ratio, at each hue, and the original image itself (or a value of one) was split into three equidistant sections, resulting in three expanding constants for every pixel.

$$[SF1_i \quad SF2_i \quad SF3_i] = \left[\left(\frac{Rato_i - 1}{3}\right) + 1 \quad \left(\frac{2(Ratio_i - 1)}{3}\right) + 1 \quad Ratio_i\right] \quad (2)$$

The scaling factors (SF), at pixel i, were therefore, one-third, two-thirds and one times the calculated distance between the ratio of maximum chromatic values to the original input value (one). Equation 2 mathematically represents these constants.

An example is provided for clarity purposes.

$Ratio_i = 1.2$, *therefore*

$$[SF1_i \quad SF2_i \quad SF3_i] = \left[\left(\frac{1.2 - 1}{3}\right) + 1 \quad \left(\frac{2(1.2 - 1)}{3}\right) + 1 \quad 1.2\right]$$

Thus, for pixel i,

$$[SF1_i \quad SF2_i \quad SF3_i] = [1.067 \quad 1.133 \quad 1.2]$$

In the occurrence that the maximum chroma of the output display was less than the corresponding maximum input chroma, all three scaling factors were constrained to one in order to prevent chromatic reduction from occurring at applicable pixel.

Maintaining constant lightness, the chromatic values for each pixel of an image were expanded by each of the three scaling factors.

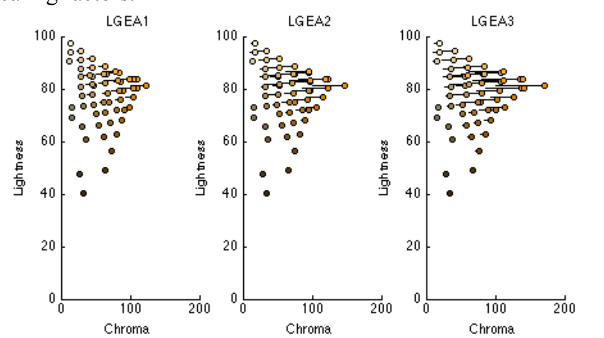


Figure 2. *All three LGEAs represented for sRGB digital counts that corresponded to a hue angle between 75 and 80. The lines extend from sRGB chroma values to expanded chroma. These transformations are representative of simulated data points for the Sony display.*

The effects of the three scaling factors (LGEA1, 2 and 3, each comprised of the appropriate scaling factor) are apparent in Figure 2. The left-most plot, LGEA1, represents the lowest expansion and the right-most plot, LGEA3, represents the greatest expansion. After the transformations, these expanded CIELAB values were converted to display digital counts using the inverse transformation matrix, and were incorporated into the psychophysical experiments.

SGEA

In addition to linearly expanding the chrominance of multiple scenes, a sigmoidal transfer function was sought out, as an attempt to minimize any negative results of the linear expansion. It has been found that colors of low chroma should not necessarily be manipulated as those of high chroma[6]. MacDonald et al. depict the values of low chroma as a core gamut, in that within the core gamut a one-to-one mapping exists but outside of that core, expansion will occur in accordance to the sigmoidal transfer function at hand.

The sigmoidal transfer functions incorporated into this study were based on the cumulative normal distribution.[7]

$$S = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-(t-u)^2}{2\sigma^2}} dt \quad (3)$$

Eqn. 3 represents the general equation form, where only the positive values of the function were incorporated into the study.

The chromatic expansion for the SGEA required once again, linearly interpolating the maximum chromatic input and output data at each hue slice, for given lightness values, at each pixel in the image. After obtaining the maximum chroma values for every pixel, three cumulative normal distributions (Figure 3) of varying standard deviations (Table 1) were applied to the data to form the sigmoidal transfer functions.

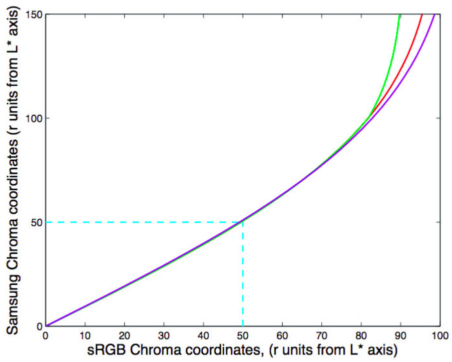


***Figure 3**. The three sigmoidal curves applied to this study are based on Eqn. 3. The red curve represents SGEA1, the blue curve represents SGEA2 and the cyan curve represents the third SGEA.*

Table 1. Curve characteristics of the sigmoidal functions represented in Figure 3.

Algorithm	Corresponding to Curve(Fig3)	Mean	Std Dev	Over Interval
SGEA1	Red	0	1.5	[0:3]
SGEA2	Blue	0	1.6	[0:3]
		0	1.5	[0:2]
SGEA3	Cyan	0	1.2	[2:3]

As stated in Table 1, the red and blue curves are single, unique functions, whereas the cyan curve is a combination of two sigmoidal functions. This combination results in a steeper expansion and lower input chromas.

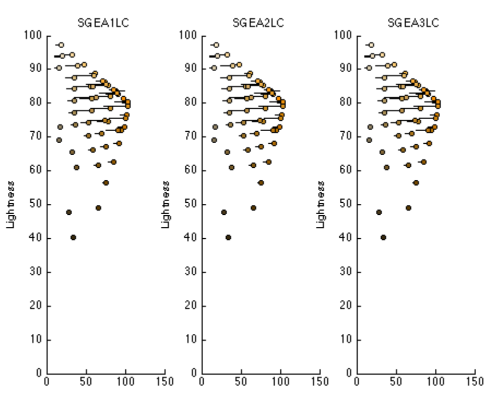


***Figure 4.** The transformations of chroma values as a result of each of the three sigmoidal transfer functions (Sig1-left, Sig2-center, Sig3-right). The lines extend from the original sRGB chroma values to the expanded values based on the Sony display. Note: the color of the data points correspond to the appropriate hue angle.*

After applying these three curves to sRGB digital counts, the resulting chromatic expansions, for those values between a hue angle of 75 and 80, are represented in Figure 4. This demonstrates the closeness between the three sigmoidal algorithms. Of course, the transformations depended on the hue as well, and therefore, there will be variations among each plot corresponding to the SGEA applied. For the hue interval in Figure 4 (between 75 and 80) the values for each point's chroma does not extend past a chroma of 105, which corresponds to a lightness of 80 units.

In addition, each of these curves were varied based on multiple reference points. Chae-Soo et al. utilized various anchor points in their gamut compression algorithms, and concluded mapping errors could be reduced when anchor points are incorporated[5]. Therefore, in accordance with their anchor points, where the center of gravity was on the lightness axis, lightness values of both 50 and 0 units were proposed for this evaluation in addition to maintaining a constant lightness.

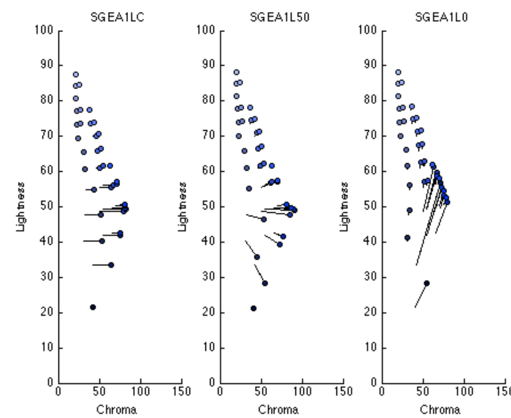


***Figure 5**. The transformations of sRGB values, corresponding to the Sony display output values, for hue angles between 270 and 275. A different hue was chosen for this comparison, to demonstrate the effect the reference point of L*=50 had on both high and low lightness values. The most left plot is constant lightness, the center extends from L*=50 and the right plot extends from L*=0.*

The reference points are denoted as LC, L50 and L0, referring to the anchor point in which the expansion is extending from. LC represents expansion while maintaining constant chroma, and L50 or L0 represent expansion extending from either a lightness value of fifty or zero units.

Both Figures 4 and 5 serve to demonstrate the possible sigmoidal expansions. The effect of the reference point of L* equal to zero was not fully understood until applied to the images, however. The potential effect the SGEAs with expansion from a lightness of zero is evident in Figure 5, as a few low lightness, low chromatic values were extended to dramatically higher lightness values with only relatively higher chromatic values. Therefore, the resulting appearance at these points is substantially desaturated. After examining the scenes visually and observing the significant artifacts as a result of this algorithm, the reference point of L* equal to zero was removed from the psychophysical analysis. Thus, in the end there were six different sigmoidal algorithms psychophysically analyzed:

SGEA1, 2, and 3 all evaluated at both constant lightness, and extending from a lightness value of 50.

Controls

Serving as a baseline to compare the above algorithms to, there were two controls included in the psychophysical experiments. One baseline was a true-color representation, such that the sRGB image content was mapped to the display by accounting for the difference between the display and sRGB primaries. In this manner, the original sRGB content is mapped to a smaller gamut within the wide-gamut display, avoiding any potential expansion that ordinarily would occur. This baseline is denoted as the “sRGBOrig”.

The second control (denoted as “sRGBExp”), directly maps the sRGB digital counts as input digital counts to the display. In this manner, the image underwent any inherent expansion required. As a result, the data is linearly stretched to fill the destination gamut. The overall preference of this algorithm will indicate if complex, versatile GEAs are necessary, or if simply displaying the original digital counts on the extended gamut display produces pleasing images already.

Data Analysis

The psychophysical experiment was performed for twenty observers on both displays, where the observers were not the same individuals for each display. With twenty observers, the mean standard deviation for each image, across all observers, was 0.09 interval scores. The results portrayed clear trends among observer, however, scene dependency was still evident as in past research.

With great variation in the image content, image dependencies became clear. A cluster analysis was performed on the images to define any relationships among image, however, no explainable clusters resulted. Therefore, by evaluating the overall results, for each individual image, the importance of each attribute became clear. These results are displayed in Figure 6 for the Sony display, Figure 7 for the Samsung display.

The most profound result, quite evident in Figures 6 and 7, was the degree to which the sRGB expanded method (or the method that linearly stretched the data to the display) was disliked. This effect is clearest for the Sony display, although this method did not perform well for the Samsung either. In addition, the second baseline where the sRGB data was displayed without expansion performed poorly. Therefore, these results confirm that the development of a GEA is pertinent to the success of extended gamut displays.

The general categories incorporated into the study by Heckaman et al[1], were analyzed here as well. Therefore, scenes of high colorfulness (mainly the flower scene), flesh tones (including both the musician and lady images) and natural scenes with a large range in lightness contrast (the coast scene) will be individually evaluated for trends within these categories. The significant image dependencies become very apparent in Figure 6 and 7. This was expected, as the images are comprised of different primary attributes, since a variety of images was desired. Still, some trends are stable across images. The expanded sRGB control, represented by the dark cyan-colored bar at the most left position for each image, was least preferred across the images. In addition, the “sRGBOrig” version never performed significantly better than any other version.

For the lady scene (Figure 5), which was comprised predominantly of flesh tones, LGEA1 and LGEA2 performed well on the Sony display, while observers preferred LGEA2 significantly more on the Samsung display. In addition, the SGEA1L50 method performed well on the Sony, which did not occur on the Samsung. This image, for both displays, resulted in clearer trends than the Musicans scene. Across both flesh tone scenes, and both displays, the LGEAs performed better than the SGEAs. However, for these images it was predicted that maximum chroma would not be optimal, which is shown through these results.

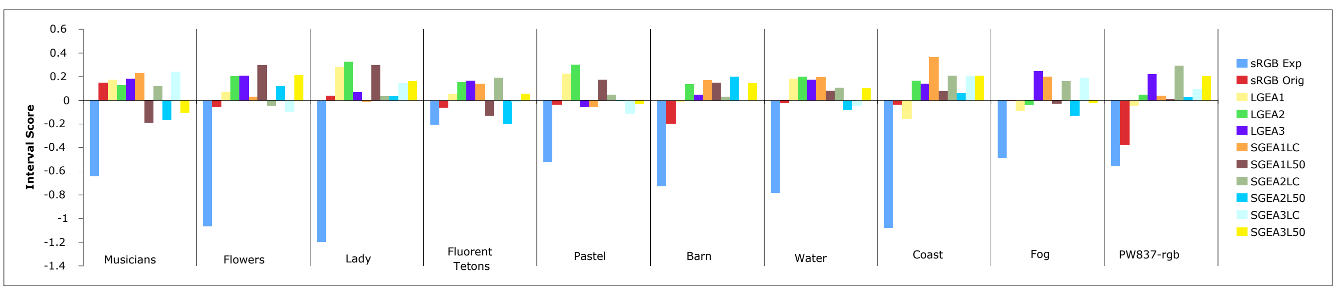


Figure 6. *Sony display results for all of the images evaluated psychophysically, with the results for each algorithm within the image dataset. The interval scores are represented for each algorithm as a separate bar, where the legend describes the color each algorithm corresponds to.*

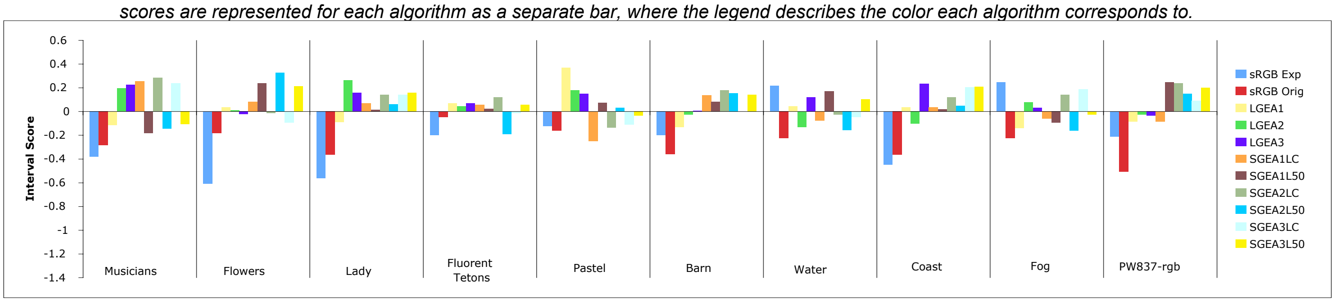


Figure 7*. Samsung display results for all of the images evaluated psychophysically, with the results for each algorithm within the image dataset. The interval scores are represented for each algorithm as a separate bar, where the legend describes the color each algorithm corresponds to.*

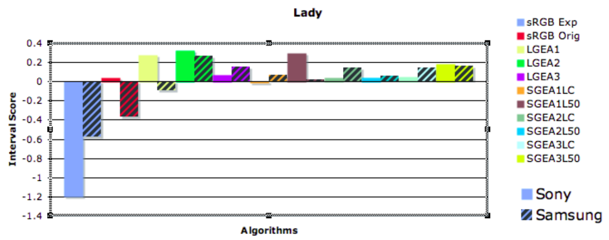


Figure 8. *The Lady image is represented as a bar plot, where each bar represents a different algorithm for each display (the Sony display is represented by the solid bars; the Samsung by striped bars). The units are interval scores, which directly correlate to overall observer preference. These data are representative of the average observer's response.*

The observed trends in the SGEAs could be a result of the expansion calculation, as hue and lightness dependencies were accounted for. In other words, as demonstrated in Figure 4, it was possible for values of low chromatic content to be drastically expanded, or not expanded at all, provided the corresponding hue and lightness combination allowed for either situation. In the former case, although the sigmoidal functions were designed to maintain chroma values for flesh tones, in actuality the flesh tones could have been expanded more than expected. If this was the case for the lady and musician scenes, (the SGEAs expanded the values to higher chromas than both LGEA1 and LGEA2), then possibly the resulting values were higher than the observer's threshold for colorfulness of flesh tones, which explains the negative interval scores.

In addition, if the lightness and hue combinations representing flesh tones were not expanded at all, this too could have a negative impact on observer preference. Although flesh tones needed to remain true to the observer's memory, if there was truly no expansion, these regions could perform similarly to the sRGB unexpanded version.

The SGEA function, SGEA2LC performed much better for a more colorful image.

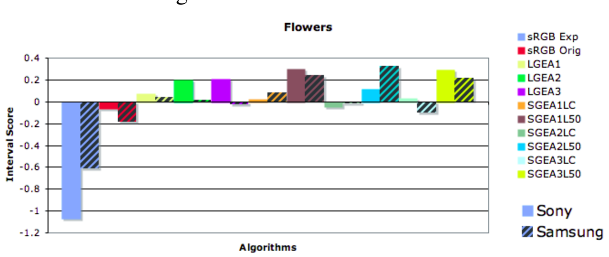


Figure 9. *The flower scene preference results for each of the eleven algorithms, and both Sony and Samsung displays, are displayed for the average observer.*

Interestingly enough, the flower scene displayed almost exactly opposite results from that of both the musician and lady scenes. Here, where the original data were already very chromatic, all three sigmoidal expansion methods, extending from a lightness value of fifty, expanded the image data in the most preferable manner. This result was more significant for the Samsung display, as none of the linear expansions were preferable.

SGEA1L50 and SGEA2L50, the optimal algorithms for the flower scene, are represented by the red and blue curves, respectively, in Figure 3. These curves, as compared to SGEA 3, resulted in the least amount of clipping in the sRGB values. SGEA3 clips the sRGB content at a lower chroma value, so that the expansion is more drastic. Given the already colorful content of the flower scene, possibly this other curve resulted in undesirable results due to these characteristics of the sigmoidal functions.

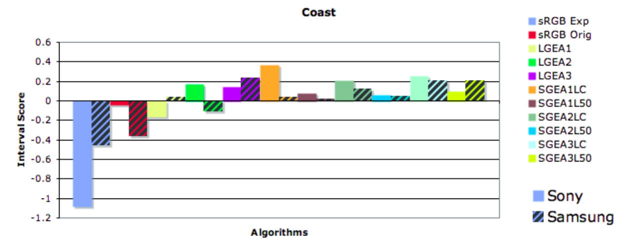


Figure 10. *The last of the three groups from Heckaman et al. [1], natural content with a wide range of lightness contrast, the coast scene is represented in terms of interval scores of preference, averaged over nine observers. Each of the eleven algorithms, on both displays, is represented by its own bar.*

In the coast scene, the results were much more dispersed. The main, significant observations were that the two controls were least preferable, and the SGEAs extending from a reference point of a lightness equal to 50 resulted in undesirable reproductions on the Sony display. This reference point, as compared to maintaining constant lightness, resulted in a few artifacts due to the large change in lightness compared to change in chroma (indicated for a few values in Figure 5). These artifacts resulted in reproductions that were less sharp than the original, and thus, were not chosen over the majority of the other images.

Conclusions

Upon analyzing the preference results based on ten scenes, eleven algorithms and two displays, averaged over twenty observers, one of the main conclusions regarded the high degree of scene dependency the algorithms maintain. Although the SGEAs are a step in the right direction, there is still improvement necessary so that a more wide-spread, easily applicable, algorithm is developed that produces preferable reproductions for a wide variety of image content.

Still, all three SGEAs performed well across all images. For images of a high degree of colorfulness, SGEAs extending from L* equal to 50 produced pleasing reproductions, while maintaining constant lightness for high contrast images performed well too. The scenes chosen for flesh tones, however, were consistent in that a slight increase in color, resulting from the LGEAs, was ideal across observers. The SGEAs are a good basis for improving linear expansion, and with a few minor alterations, could be the optimal reproduction method for mapping images under current sRGB standards to wide-gamut displays.

By comparing two unique display technologies, the applicability of the results becomes evident. Although there are some differences between the displays, most often they correlate with one another. Therefore, by continuing research in the development of a gamut extension algorithm, and possibly adjusting a few of the methods incorporated in this study, a GEA applicable to multiple display technologies will be attainable.

Many recent studies have provided solid evidence that viewers enjoy more color within their display. With the technology flourishing, the need for an optimal algorithm is becoming more apparent. This study has provided an excellent basis for this desired algorithm, and with relatively minor tweaking, will be capable of providing viewers world-wide with more satisfying images.

Appendix A: Images

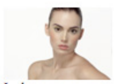

Barn


Coast


Flowers


Fluorent Tetons


Fog


Lady


Musicians


Pastel


PW837_rgb


Water

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Author Biography

Stacey received her B.A. in Mathematics from Ithaca College in 2006 and is a recent graduate from the Rochester Institute of Technology with a M.S. degree in Color Science. Her research has focused on gamut mapping algorithms for wide-gamut display technology.