Effects of display properties on perceived color gamut volume and preference

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Abstract — The effect of varying the color gamut of an extended-gamut LCD on color appearance and preference was measured psychometrically in two experiments at each of two separate laboratories over a representative set of 10 images each. The first experiment measured the effect of color gamut on appearance, and the effect on the appearance attribute colorfulness was shown to be relatively strong compared with other attributes as the volume of display color gamut is varied. Overall, colorfulness monotonically increased at constant sensitivity as the gamut area in *xy* chromaticities increased while tending to become less and less sensitive to increasing the gamut volumes in CIELAB and CIECAM02. In the second experiment, the overall preference indicated an optimal color gamut for the display gamut volume even though the results were shown to be highly scene dependent.

Keywords — *Color-gamut volume, display gamut, color appearance, image preference, sunjective judgment.*

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1 Introduction

The term "wide-color-gamut display" has been well known to consumers since wide-color-gamut displays were introduced into the marketplace by several manufactures. As a result, consumers can enjoy rich color in their homes, particularly in the home-theater media experience because the gamut of cinema film is wider than that of a conventional video signal (BT.709[1]) used in television today.[2] Moreover, displays with four to six primary colors and devices such as organic LEDs have been developed that also extend the color gamut.[3–5] Hence, a display with a wide color gamut is an advantage in consumer markets.

Although Fedorovskaya *et al.*[6] and Shimada *et al.*[7] investigated the color appearance and image quality when varying the chroma of images or color gamut of a display, their investigations do not correspond to the extended gamut and large-screen displays of today. The current studies of Laird and Heynderickx[8] and Hisatake *et al.*[9] also indicate that the preferred gamut or optimal limit of chromaticities were smaller than that of the wide-gamut display from observers' preferred saturation in natural images. Yet, while these displays express vivid, clear colors colorimetrically and photometrically, there is little research on how humans perceive these extended-gamut displays. Clearly, such research is important to the design of such displays.

2 Purpose

The effect on color appearance and preference of varying the color gamut of an extended-gamut LCD was measured psychometrically in two experiments at each of two separate laboratories (Group-A, Sony; Group-B, RIT) over a representative set of 10 scenes. In the first experiment, we measured the effect of changes in color gamut on perceived gamut volume, colorfulness, light contrast, and chroma range was measured over a series of representative images using the method of paired comparison. The results were analyzed to determine which area or volume related metrics in *xy* chromaticity diagram, *u′v′* uniform chromaticity diagram, or the appearance attributes of CIELAB and CIECAM02 lightness and chroma and brightness and colorfulness predict best the results. In the second experiment, a psychophysical measurement using the method of paired comparison was performed to determine observer preference as a function of color-gamut volume for each of ten representative scenes. The results utilized a cluster analysis to clarify the dependencies on image preference.

3 Methodology

3.1 Display

In both experiments, the display was an extended-color-gamut LED-backlit flat-panel LCD. The specifications of this display are summarized in Table 1. The gamut of the

TABLE 1 — Display specifications.

Feature	Specification
Screen size	40 in.
Maximum luminescence	458.9 cd/m^2
Contrast ratio	1350 : 1
Gamut area against NTSC on $u'v'$	120%

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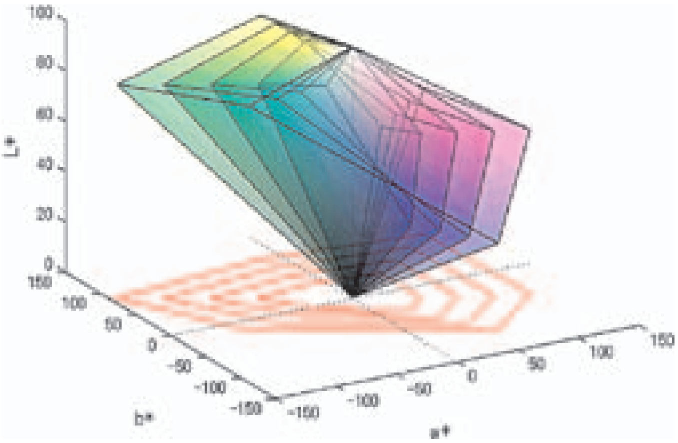

FIGURE 1 — Color gamut for the simulated primaries plotted in CIELAB.

display is 120% that of the NTSC[10] gamut on the $u'v'$ chromaticity diagram (see the outside triangle of Fig. 2).

3.2 Scenes

Ten scenes with a color chart were used in this experiment for Sony (Group-A, see Appendix A). The scenes were selected for their overall lightness contrast and colorfulness. The N1RGB, N2RGB, S6RGB,[11] N2A,[12] Barn, Goal, and Swim scenes were chosen as representing a high degree of colorfulness over a wide range of hue. The Fog and Beach scenes were chosen for their lower colorfulness and overall contrast, the coast scene for its high contrast, and the N1RGB and Goal scenes for their flesh tones. Similar scenes were selected for the experiment at RIT (Group-B, see Appendix B).

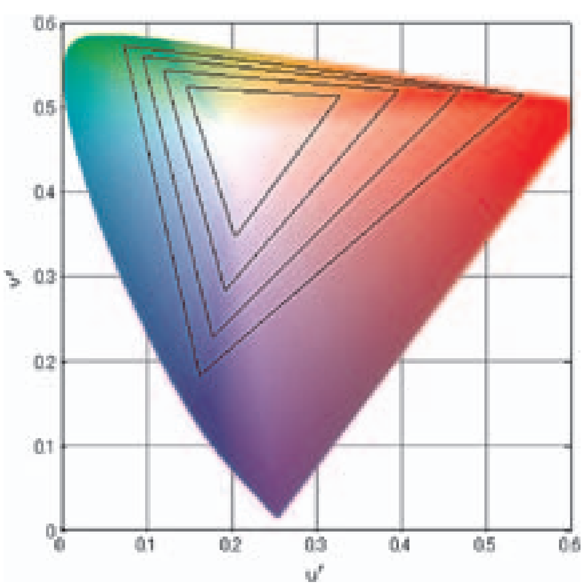

FIGURE 2 — Color gamut for the simulated primaries plotted on a $u'v'$ chromaticity diagram. The outside triangle indicates the full gamut of the display in this experiment.

APPENDIX A

3.3 Setting of test images

Four versions of each scene were rendered to each of four sets of simulated display primaries with gamut volume factors of 1.0, 0.8, 0.6, and 0.4 times the full-color gamut of the display in CIELAB a^*b^* at Group-A and 1.0, 0.89, 0.77, and 0.63 at Group-B, respectively. All the versions were constrained to maintain both the display's white point and hue within the ability of CIELAB to maintain perceptual hue. Therefore, the lightness in each version of any given scene was rendered equally. Figures 1 and 2 illustrate the gamut for each of the Sony's simulated primaries in CIELAB and

APPENDIX B

an $u'v'$ uniform chromaticity diagram. Each polygon from the outside to inside (1.0–0.4) corresponds to succeeding versions of simulated gamut reduction.

3.4 Viewing conditions

The viewing conditions in both laboratories are summarized in Table 2. For Group-A, the visual angles of the display screen were 25° and 14° in the horizontal and vertical meridians, respectively. The room was illuminated by D65 fluorescent lamps measured at 300 lx at the table on which the display was placed.

TABLE 2 — Viewing conditions at both laboratories.

Condition		Group-A	Group-B
Visual angle of display screen	Horizontal	25°	40°
	Vertical	14°	23°
Viewing distance		2 m	1.25 m
Illuminant		D65 fluorescent lamps	Diffuse studio lamps (150 W)
Illuminance		300 lx	10 lx

For Group-B, the visual angle of the display screen was 40° and 23° in horizontal and vertical meridians, respectively. A uniform gray wall behind the display in a darkened room was illuminated uniformly to eliminate or at least minimize viewing flare. The illumination off the wall was measured to be 94 cd/m^2 at a correlated color temperature of 3150K. Its illuminance was measured to be approximately 10 lx in the room.

3.5 Psychophysical measurement

3.5.1 Experiment I: The relationship between color appearance and the color gamut of the display

In Experiment I, the color appearance of the test images was measured using the method of paired comparison for all the images for each scene. All six possible pairs for each scene were presented. The observer was asked to evaluate relative colorfulness, perceived gamut volume, lightness contrast, and chroma range of one member of the pair (the test image) compared with the other member (the reference image) by rating how much more or less the attribute of the test image compares with the reference image. Each observer evaluated a total of 60 – six per scene times ten scenes.

3.5.2 Experiment II: The effect of display gamut volume on image preference

In Experiment II, a psychophysical experiment was performed to determine observer preference as a function of color-gamut volume for each of ten representative scenes rendered as in the above. All six possible pairs of the four versions of each of the Group-B images were displayed. For Group-A, all 36 possible pairs of the nine versions of each of the Group-A images were presented since the gamut volume factor used nine versions of the 0.25 steps from 1.0 to 0.8 as the experiment for precise decision on image preference. The observers were asked to simply select which image they prefered. Nine observers in Group-A and 20 observers in Group-B participated in the experiments and distributed in age from young adults to the elderly, both expert and non-expert.

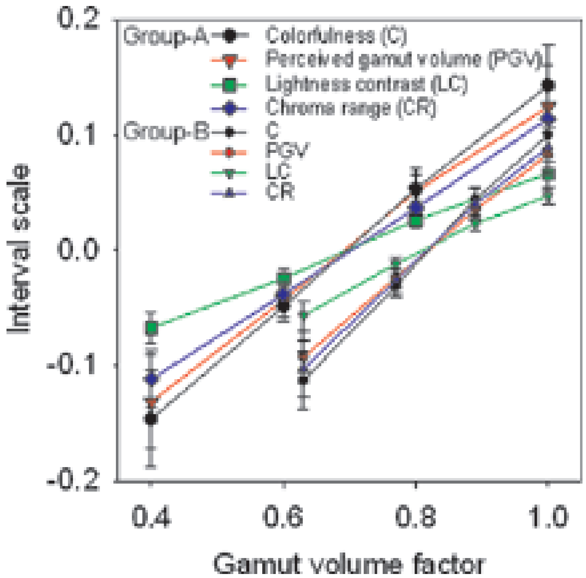

FIGURE 3 — The average interval scale results for 29 observers in the experiment for both Group-A and B as a function of the gamut volume factor. Each symbol corresponds to each attribute on the left top in this figure.

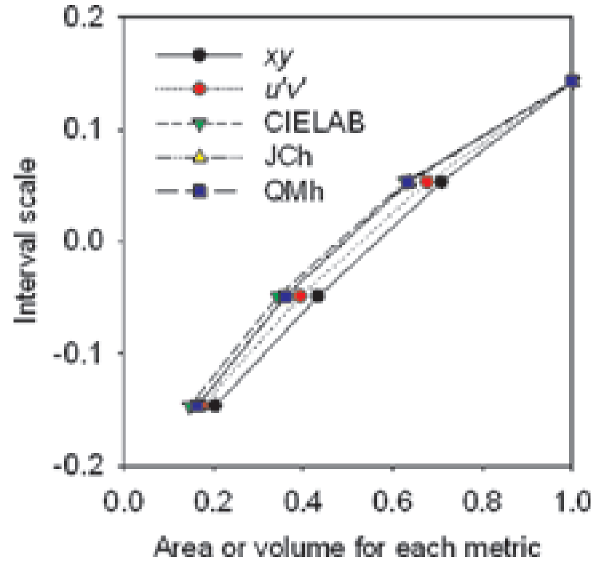

FIGURE 4 — Interval scales of colorfulness for the average overall Group-A scenes and observers as a function of the psychophysical metrics corresponding to the symbols of the area in *xy* chromaticities, the area in a *u′v′* chromaticities, the volume in CIELAB color space, and the volumes in JCh and QMh of CIECAM02 for each of the simulated gamuts. Each symbol indicates each metric of the left top in this figure.

4 Results and discussions

4.1 Experiment I

Scheffé's analysis[13] of variance for paired comparisons was utilized to calculate the interval scale (z-score) for all the images. The resulting interval scales were treated as the sensory criteria in each version of the gamut volume factor. Figure 3 shows the overall average of resulting interval scales in the experiments for both Group-A and B as a function of the gamut volume factor. Each symbol corresponds to the respective appearance attribute in the figure's legend, and the horizontal bars indicate the standard deviation over all the scenes and observers. As shown in Fig. 3 for both laboratories, colorfulness is the most sensitive to changes in color-gamut volume compared with the other appearance attributes in both laboratories. Although the lightness is the same for all the images in each scene, perceived lightness contrast decreases according to color-gamut volume – seemly the effect of Helmholtz–Kohlrausch.

4.2 Relationship between colorfulness and psychophysical metrics

Figure 4 shows the interval scale for colorfulness averaged over all the Group-A scenes and observers as a function of several gamut area or volume metrics describing the simulated gamut. The horizontal axis for each symbol indicates the relative area on a *xy* chromaticity diagram, the relative area on a *u′v′* chromaticity diagram, the relative volume in CIELAB color space, and the relative volumes in both CIECAM02 lightness and chroma (JCh) and brightness and colorfulness (QMh).

The interval scales plotted on the vertical axis increase monotonically and linearly with the relative area of the color gamut in *xy* chromaticities and with a slight decrease in sensitivity with the relative volume of color gamut in CIELAB. For the *u′v′* chromaticities in Fig. 4, the effect is between these two, and for CIECAM02 lightness and chroma and brightness and colorfulness, the effect is similar to the CIELAB results. In other words, colorfulness increases monotonically with area in *xy* chromaticities while it becomes increasingly less sensitive with increasing volumes in CIELAB and CIECAM02 color spaces. In this regard, it is suggested that the area in *xy* chromaticities does not explain the whole story, and that it only works well in this case because the lightness value is preserved.

Figure 5 shows the interval scales for colorfulness for each scene based on all Group-A observers as a function of the computed color-gamut metric relative to the full gamut of the display. Those computed metrics include the actual scene's area in *xy* chromaticity diagram (a), its area in *u′v′* chromaticity diagram (b), and the volume in CIELAB (c). The legend of Fig. 5(a) provides the scene symbol corresponding to those Group-A scenes shown in Appendix A.

In Figs. 5(a) and 5(b), the interval scale for colorfulness of the Beach scene rapidly increases with the areas in *xy* and *u′v′* chromaticities while the Fog scene becomes less and less sensitive even though both these scenes are lower in saturation. The interval scale for S6RGB (color chart), roughly representative of those scenes considered to be uniformly colorful, tends to be less sensitive with the changes in the areas in *xy* and *u′v′* chromaticities. In Fig. 5(c) with the exception of S6RGB (the color chart), the sensitivity (slope) of perceived colorfulness is consistent scene-to-scene with a slight loss in sensitivity while the relative volume in CIELAB increases. Conversely, the sensitivities across all scenes in chromaticity are clearly not consistent.

The *xy* chromaticity diagram is based on the results of the color-mixing experiment instead of color appearance. The *u′v′* chromaticity diagram is developed to improve the uniformity of the color difference on the *xy* diagram from the MacAdam ellipsis point of view. These two representations are colorimetric while the CIELAB and CIECAM02 color spaces are according to color appearance in human perception. Hence, from a perceptual point of view, gamut volume in color-appearance metrics (*i.e.,* CIELAB and those of CIECAM) provide a more consistent and valid measure of display performance than those based on colorimetric measures; particularly as the scenes chosen for this experiment represent a fairly wide variety of types.

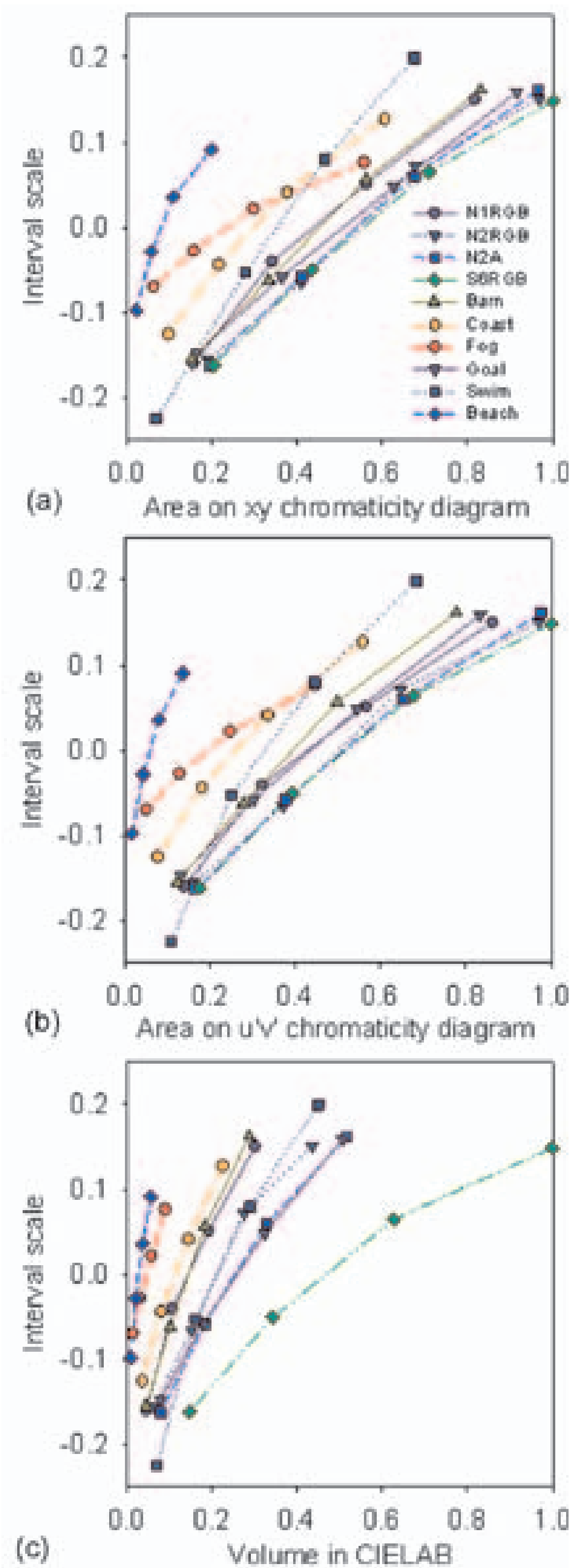

FIGURE 5 — Interval scales of colorfulness as a function of the computed color gamut for each scene relative to the full gamut of the display in the relative area in (a) *xy* chromaticities, (b) *u′v′* chromaticities, and (c) relative volume in CIELAB. Each symbol in the legend of (a) corresponds to the Group-A scenes in Appendix A.

4.3 Experiment II

Under the *a priori* assumption that Thurstone's Law of Comparative Judgments, Case V, holds, the paired comparison results were analyzed by the observer and by the scene using an interval scale (*z*-score) methodology that first computes the average proportion each image version was preferred over all comparisons, then their respective standard normal deviates or interval scale values from the tables for a normal distribution.

Figure 6 shows the average interval scale of preference as a function of the gamut volume factor over all the scenes and observers for Group-B. In addition, the corresponding 95% confidence intervals are shown as computed according to the method prescribed by Montag.[14] As shown, observers exhibited a significant overall preference for a color-gamut volume factor of beyond 0.89 with some, but not statistically significant, maximum preference at the

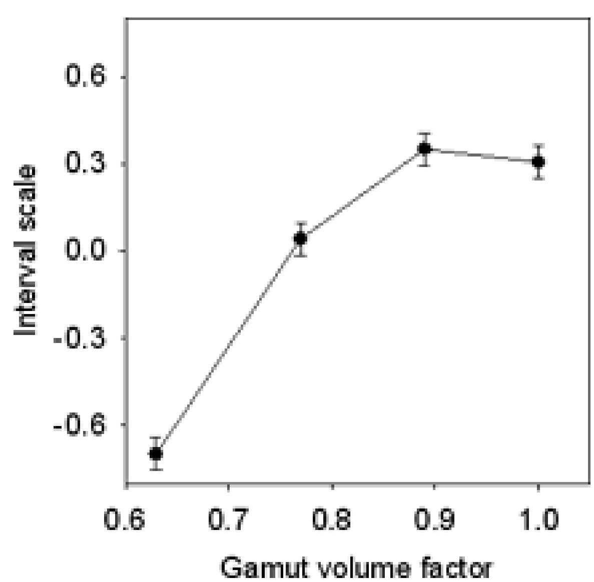

FIGURE 6 — The average interval scale results for overall 20 observers and 10 scenes for Group-B as a function of the gamut volume factor. The horizontal bars represent the 95% confidence intervals.

gamut volume factor of 0.89. This corresponds to the results from Laird and Heynderickx[8] and Hisatake *et al.*[9] indicate that the gamut for the observers' preferred saturation and optimal limit in natural images is not wider than those of the displays used in their studies. That is, the sensitivity of image preference reaches a peak with increasing color-gamut volume even though the sensitivity to colorfulness still increases as shown in Fig. 3.

4.4 Dependencies from principal component analysis (PCA)

The set of interval scale values for each version of the scenes was represented as a linear combination of orthogonal vectors (principal component analysis, PCA) which are, in turn, assumed to be normally distributed across observers and scenes. For four versions of each scene, then, there is a four-plex of vectors with their respective coefficients each accounting for a certain proportion of the variance in interval scale value. The average of those coefficients whose combination with the four-plex of vectors account for the bulk of variance are then subjected to a nearest-neighbor cluster analysis to find groupings of like results across scenes and observers.

4.5 Scene dependency

A cluster analysis performed on the scene-by-scene Group-B results averaged over all observers provides interesting insight. Table 3 shows the results. Across the top in columns are listed each of the ten scenes. On the side in rows, a level number in the hierarchy of the clustering is listed where, in a hierarchical clustering methodology such as this,[15] the scenes are first grouped according to their similarity where similarity, in this case, as a measure of how close they are in space of the coefficients of the four-plex of vectors found from the PCA analysis. Hence, at Level 1, the Flowers (FL) scene and the Color Chart (CH) are first grouped as most similar as shown in red in Table 3 (Group 1). The next most similar scene, the Barn (BN) scene, is added to the red group at Level 2. At Level 3 or next in the degree of similarity,

TABLE 3 — Scene-by-scene preference cluster hierarchy. Each row indicates the scene in Group-B and each column represents the level of the hierarchy in clustering.

		Scene in Group-B									
		FL	CH	BN	WA	TE	FG	SS	PA	MU	LA
Level in clustering	1	red	red								
	2	red	red	red							
	3	red	red	red			green	green			
	4	red	red	red	red		green	green			
	5	red	red	red	red		green	green		blue	blue
	6	red	red	red	red	red	green	green		blue	blue
	7	red	red	red	red	red	red	red		blue	blue
	8	red	red	red	red	red	red	red	red	blue	blue
	9	red	red	red	red	red	red	red	red	red	red

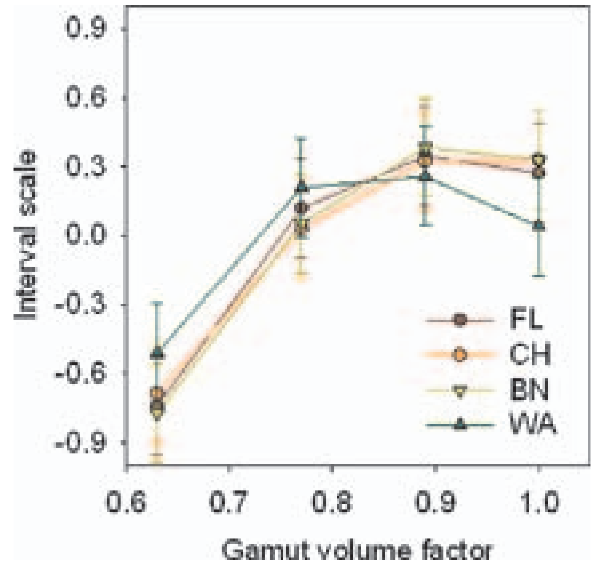

FIGURE 7 — Preference results for Group 1 highly colorful scenes [Flowers (FL), Color Chart (CH), Barn (BN), and Water (WA)]. The horizontal and vertical axes indicate the gamut volume factor and the interval scale, respectively. Each symbol corresponds to the bottom right in this figure.

another group (green) is formed consisting of the Fog (FG) and Sunset (SS) scenes (Group 2). At Level 4, the water (WA) scene is added to the first grouping as next most similar, and at Level 5, a new group (blue) is formed consisting of the Musicians (MU) and Lady (LA) scenes (Group 3).

Ultimately, as similarity decreases, all groups are merged into a single cluster as shown in the Table as Level 9. Obviously, a single cluster is of little interest. Hence, the next task at hand is to pick the level of most interest – in this case, Level 5 where the most groups, and hence the most interesting case, are formed. At this level, the Grand Teton (TE) and Pastel (PA) scenes are not members of any group.

The interval scale results for the Group 1 scenes are shown in Fig. 7. It is noted the Group 1 scenes are distinguished by their high degree of colorfulness, yet their ratings at a color-gamut volume factors of 0.77, 0.89, and 1.0 are virtually indistinguishable with overlapping confidence intervals. However, there is the notion that the rendering of these scenes would better serve preference at less than full gamut; particularly the Flower scene which appears artificial at full gamut (gamut volume factor = 1.0).

The Group 2 scenes consist of two outdoor scenes, one of a sunset over water and the other, a foggy lakeside scene in pastels. Their interval scale results are shown in Fig. 8, and unlike Group 1, their preference increases monotonically with increasing gamut volume and, unlike the Group 1 scenes, their preference benefits from ever-increasing color gamut of the display. The sunset scene at least seems intuitive as the experience of an actual sunset is extreme in colorfulness – certainly beyond object color perception. Yet, why the foggy scene is rated similarly is not so intuitive.

Group 3, consisting of the Musicians and Lady scenes, are clearly distinguished as representing flesh tones, and the interval scale results shown in Fig. 9 indicate a statistically

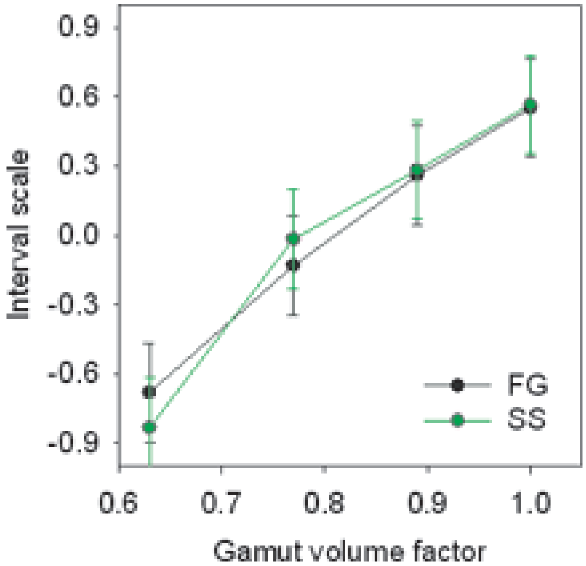

FIGURE 8 — Preference results for Group 2 scenic scenes [Fog (FG) and Sunset (SS)]. Each axis is the same for Fig. 7. Each symbol corresponds to the bottom right in this figure.

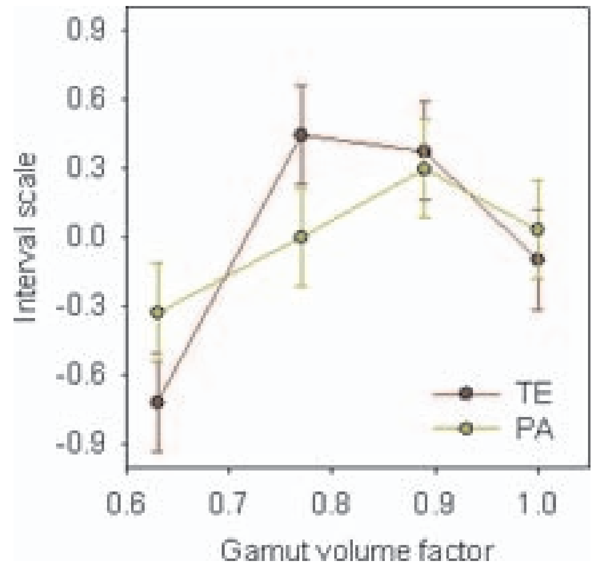

FIGURE 10 — Preference results for Grand Tetons (TE) and Pastel (PA). Each axis is the same as for Fig. 7. Each symbol corresponds to the bottom right in this figure.

significant preference for larger gamut volumes, and when viewing these scenes as rendered in the smaller of gamut volumes, the perception of grayness becomes apparent in the flesh tones – obviously not considered a desirable trait. Hence, similar to Group 2, these scenes benefit from ever-increasing gamut at least within the scope of this experiment.

Of the remaining scenes not considered as apart of any group at this level of hierarchical clustering, Grand Tetons (TE) and Pastel (PA), with interval scale results shown in Fig. 10, the preference for the Pastel scene is indistinguishable across the range of volumes tested considering the confidence interval – an expected result as the de-saturated colors are proportionately less affected by a shrinking gamut of the display. Unexpectedly, as noted in the above, the Fog scene does not exhibit the same result. The results for the Grand Teton scene are unexpected. Such a scene naturally occurs on dark cloudy days when rays of sunlight illuminate only a stand of colorful, fall foliaged trees. The resulting intense color sense they provoke is totally compelling when experienced. Yet, the observers' preferences are in conflict with this experience as they tended to prefer a much less intensely colored rendition. One possible explanation is that this scene was segmented and composited to create this effect which may have lent an artificial look to it, most apparent at higher gamut volumes of the display.

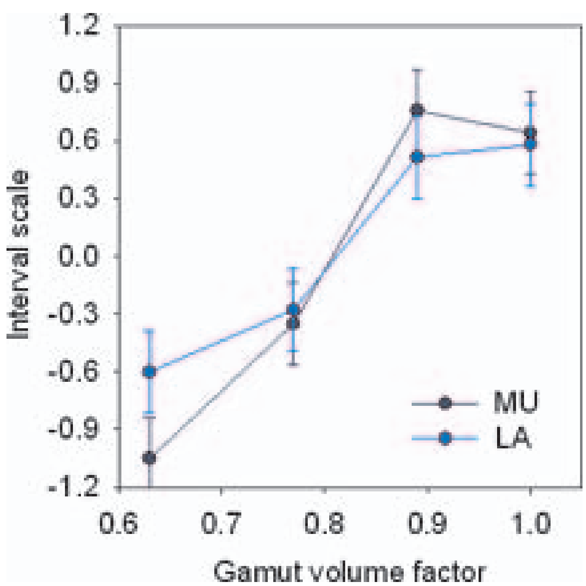

FIGURE 9 — Preference results for Group 3 flesh tones [Musicians (MU) and Lady (LA)]. Each axis is the same as for Fig. 7. Each symbol corresponds to the bottom right in this figure.

4.6 Observer dependency

A nearest-neighbor cluster analysis performed on the observer-by-observer results across all scenes revealed that all the observers' judgments essentially were in concert with each other. That is, no consistent clusters developed out of the observer group in both laboratories. This result is contrary to initial expectations that some observers would prefer the most colorful version of the images whereas others would prefer a more natural version having less colorfulness. Of course, each observer in the group was considered expert. Hence, as a group, they may tend toward more natural preferences, and their judgments confirm this notion.

4.7 A more precise determination of image preference

Figure 11 shows the average interval scale of preference as the function of gamut volume factor (1.0–0.8) more pre-

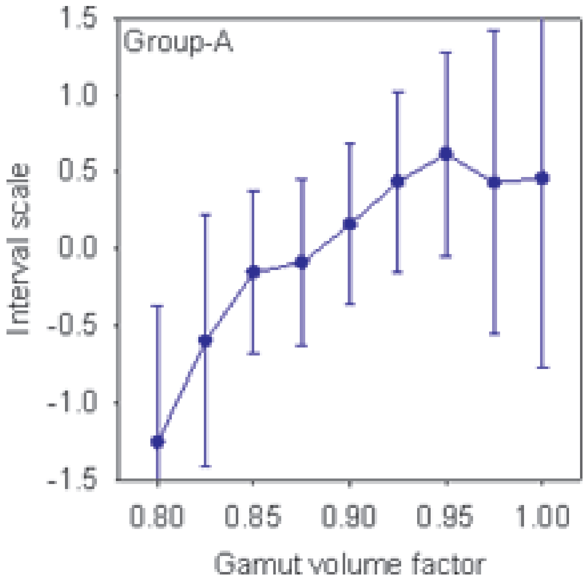

FIGURE 11 — The average interval scale results for nine observers and ten scenes for Group-A as a function of the gamut volume factor for precise decision on image preference. The horizontal bars indicate the standard deviations over the observers and scenes.

cisely defined across smaller intervals over all the scenes and observers for Group-A. The horizontal bar indicates the standard deviation over all the observers and scenes. As shown in this figure, the tendency is similar to the average results of Fig. 6 for Group-B and it indicates that preference is virtually indistinguishable above a gamut volume factor of approximately 0.925.

5 Conclusion

Overall, a methodology for the determination of perceived color-gamut volume and scaling of observer preference as a function of perceived gamut volume was established in the context of previous work in this area by Fedorovskaya *et al.*[6] The methodology was refined and validated over a series of two experiments that measured color appearance and preference as a function of color-gamut volume in terms of psychophysical and appearance metrics.

In Experiment I, the results of two different laboratories demonstrated that the effect of the perception of colorfulness is relatively strong compared with other color appearance attributes in images where the volume of display color gamut is varied. On the average, the interval scales for the perception of colorfulness monotonically increases at constant sensitivity as the gamut area in *xy* chromaticity diagram increases while it tends to become less and less sensitive as gamut volume in CIELAB and CIECAM02 increases. Additionally, an appearance based color space is more useful in explaining the effect of varying the color gamut of a display to color appearance since a chromaticity diagram does not reflect changes in lightness range in the color-gamut volume.

In Experiment II, the results for the measured observer preference as a function of color gamut at constant hue and lightness contrast show that image preference as a function of color-gamut volume is scene dependent. At reasonable color-gamut volumes of 0.8–1.0 times that of a full-gamut display, the perception of highly colorful scenes are less sensitive to reductions in gamut than certain outdoor scenes (*e.g.*, sunsets) and increase scenes with a sizable portion of flesh tone. Hence, while the overall preference results would indicate an optimal color gamut that the sensitivity on image preference reaches a peak when increasing the gamut volume of the display even though the sensitivity to colorfulness still increases, such a conclusion would only produce an average result. Scenes that are already quite colorful would be unaffected, yet the opportunity for rendering really compelling outdoor scenes and flesh tones are squandered away.

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