P-52.1: High, Wide, & Deep: Displayed Image Color Appearance and Perception

Mark D. Fairchild
Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science,
Rochester Institute of Technology, Rochester, NY 14623-5604 USA

Abstract
Color imaging technologies with higher dynamic range, wider color gamut, and greater bit depth require new and/or different ways of thinking about color. In particular, color appearance issues become more important. This paper discusses some recent research on the application of color and image appearance modeling to high-dynamic-range and wide-color-gamut imaging.

1. Introduction
A color stimulus is often specified by its CIE XYZ tristimulus values or xy chromaticity coordinates (plus luminance information). For example, the color gamut of an additive display is often represented as a triangle on a chromaticity diagram with its corners defined by the primary chromaticities. When displays are similar in other properties such as luminance level, dynamic range, white point, and surround luminance, such a stimulus specification might be a useful tool. However, specifying a stimulus for color is not the same as specifying the appearance of that stimulus and more sophisticated color metrics are required to make meaningful comparisons of color appearance across significant disparities in display properties (e.g. luminance) and viewing conditions.

While tristimulus values and chromaticity coordinates can be used to specify pairs of matching stimuli, information about the viewing conditions is required to specify the color appearance of those stimuli. Color appearance is defined by the perceptual attributes of color, brightness, lightness, colorfulness, chroma, saturation, and hue. Color appearance models aim to provide mathematical scales that correlate with these perceptual attributes. The CIELAB and CIELUV color spaces, that use information about the adapting white point in addition to tristimulus values provide a first order estimate of the relative attributes of color appearance, lightness, chroma/saturation, and hue. Recently, the CIECAM02 color appearance model has been developed to incorporate the influence of more attributes of the viewing conditions (such as absolute luminance) to allow approximate prediction of the absolute attributes of color appearance, brightness and colorfulness, in addition to lightness, chroma/saturation, and hue.[1] More recent research aims to extend color appearance models to ever more complex viewing conditions by incorporating properties of spatial and temporal vision with the ultimate goal of predicting image appearance and quality.

Given new display technologies with a much greater range of capabilities in terms of dynamic range and chromaticity gamut, there are new opportunities to better understand the perception of displayed images and the processing and encoding of image data to be displayed through the use of color and image appearance models. The aim of this paper is to introduce some recent research on the applications of color appearance modeling to display perception and suggest some ways that appearance modeling might aid in the design and development of new displays. Topics described include perceived color gamut volume, expansion of perceived color gamuts, rendering of high-dynamic-range (HDR) images through appearance models, observer variability in display perception, preferences in display gamut volume, and the creation of an HDR image database with corresponding colorimetric and color appearance data.

2. Results
2.1 Perceived Color Gamuts
Some projection displays have been designed with a white channel in addition to the traditional RGB channels in order to increase the brightness of the displayed images. In such a display, the

luminance of a full-white signal can be approximately twice that of the sum of the RGB primaries. While the chromaticity gamut of such a display is unchanged whether or not the white channel is activated, the relationship between the luminance of white and the luminance of the full-on primaries changes dramatically. This relationship is critical to defining the appearance of displayed images. In general, a brighter display will be more colorful. However, introducing that additional brightness in a white channel, without simultaneously increasing the brightness of the primaries, has the opposite effect; a brighter display actually appears less colorful.

This situation prompted a study to examine the color gamut volumes of such projectors in color appearance spaces. When the gamuts were expressed in lightness-chroma-hue color space, the gamut volume actually increased by a factor of about 1.5 when the white channel was turned off. This was due to the increased chroma of the primaries since they were in effect brighter relative to the display white point (actually they did not change, the white point brightness decreased). This relationship held in both the CIELAB color space and in CIECAM02 lightness-chroma gamuts. CIECAM02 brightness-colorfulness gamuts showed a more complex relationship since there was a trade-off between the added chroma when the white channel was turned off and the added brightness when it was turned on. Psychophysical experiments were carried out to measure observers' perceptions of gamut volume. The results correlated with the computed lightness-chroma gamut volumes in the sense that the perceived color gamuts were larger when the white channel was off. Details of this work can be found in reference [2].

2.2 Expanding Perceived Color Gamuts

The work described above illustrated how perceived color gamut volume can decrease if the white point luminance is increased relative to the luminance of the primaries. The opposite is also true as explored in references [3] and [4] through a computational analysis of just how large a perceived color gamut can become when the diffuse (or adapting) white point luminance is decreased relative to the luminance of the primaries. In fact, it is possible to ponder the possibility of creating a display with perceived chroma (or colorfulness) that corresponds to chromaticities falling beyond the spectrum locus with respect to traditional display specifications. The computational analysis shows that when the display white point luminance is approximately 15% of the sum of the RGB primary luminance levels that the colorfulness and chroma exceed this criterion. While this is impractical with current displays, the visual effect could certainly be used to advantage as the dynamic range, luminance, and bit depth of displays increases. What is required is to reserve some of the luminance of the primaries for special stimuli such as light sources, reflected highlights, and very saturated objects. When this is done, the perceived color gamut can be greatly enlarged without making any change in the location of the primaries on a chromaticity diagram. In other words, two displays with identical chromaticity gamuts can have vastly different perceived color gamuts depending on their overall luminance and relationship between their white-point luminance and maximum primary luminance levels. (It should also be noted that well-exposed photographic transparencies have been created for a long time that take advantage of this effect by placing the diffuse white at an exposure level producing slightly greater than the minimum density available. The effect is also witnessed when viewing stained glass windows from within a darkened room.)

2.3 HDR Scene and Image Perception

Increasing display dynamic ranges (and bit depths) will enable a variety of perceptual experiences for users, including perceived color gamuts well beyond current expectations. To best utilize such display technologies it is important to understand the perception of color in HDR scenes and reproduced images. One way this is studied is through the creation and testing of visual models of image appearance that can mimic the adaptation processes of the human visual system to produce approximately appearance-matched images for low-dynamic-range displays or prints. Examples of such work are the psychophysical evaluations and appearance modeling of Kuang et al.[5][6] They illustrated the comparative utility of visual models of local adaptation for tone mapping HDR scenes through short-term memory comparisons of in-lab HDR scenes with rendered images on traditional displays. They also used these results to improve an image appearance model for the interpretation of HDR scenes and evaluated the potential of a prototype HDR display system to serve as an accurate surrogate for actual scenes with positive results.

Models of spatially (and temporally) localized adaptation also provide the basis for the prediction of other image appearance and image quality effects. For example, the iCAM model that has been used for HDR tone mapping, is also capable of predicting perceived image differences (e.g., sharpness or contrast changes) and predicting an interesting visual phenomenon, adaptation to noise in images, that also has a potentially important impact on the perception of various image displays.[7]

2.4 The HDR Photographic Survey

The use of any new display capabilities requires the availability of images with the necessary content and encoding. For example, displays with expanded perceived color gamuts will require a method to encode the appropriate display values for a diffuse white as well as when to exceed those values for particular types of stimuli. HDR displays require HDR image data and methods to interpret the image data in terms of colorimetry and appearance. While HDR images are becoming readily available, there is still value in a public database of characterized images. One such database, *The HDR Photographic Survey*, was recently created and made available.[8] This resource includes a collection of approximately 100 high-resolution HDR still images stored in a 32-bit floating-point format (OpenEXR). Many of the images also include colorimetric data for scene elements and visual color appearance scaling (lightness, brightness, chroma, and hue) for those elements. It is hoped that this public-domain resource will be an aid to researchers developing and testing new display technologies and algorithms.

2.5 Observer Variability and Gamut Perception

Many higher-level color appearance phenomena impact perceived display quality. However it should also be kept in mind that lower-level differences in color vision also can have important effects on display perception. Specifically, differences in observer color matching functions can be large enough to introduce significant perceived color differences between metameric displays (displays with different sets of primaries) despite identical CIE colorimetry. A computational analysis was recently completed to illustrate the potential magnitude of such observer differences using displays with different primary sets and a recent CIE technique for computing different sets of color matching functions for various field sizes and observer ages.[9] The results illustrated that displays with narrow-band primaries, which are often used to expand the chromaticity gamut, are significantly more susceptible to large color differences due to observer variability. In other words, observers will agree with one another better for displays with broad-band (less saturated) primaries. This result points to one potential negative consequence of expanding display chromaticity gamuts. This ties in with the work described above since it is possible to achieve the enlarged perceived color gamut with less saturated primaries by increasing the display luminance. (This result was also recently confirmed in visual experiments on image preference as a function of gamut volume and luminance level. A smaller chromaticity gamut at higher luminance produces images visually equivalent to those displayed with a larger chromaticity gamut at a lower luminance level.[10]) In addition, with extended display dynamic range it is possible to expand the perceived color gamut through careful control of the relationship between the diffuse white-point luminance and the luminance of the primaries. Thus, it is possible to consider trade-offs between observer metamerism, display luminance, and diffuse white relative luminance in the design of desired perceived color gamuts for displays.

3. Conclusions

This paper presents a survey of several recent research projects on the interactions between color appearance modeling, color display design, and the complex perceptions of color gamut volume and image quality. It is hoped that this overview will provide insight into potential applications of color appearance and image appearance models in the specification, testing, and design of ever-improving and expanding display technologies.

While this short paper has focused on the work of the author and coworkers at RIT, there are many other important contributions to these topics from researchers around the world. A more full review would certainly include them and readers are encouraged to explore the literature cited and discussed in the references listed below to obtain a broader picture.

4. Acknowledgements

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5. References

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