COLOR APPEARANCE IN IMAGE DISPLAYS

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ABSTRACT

CIE colorimetry was born with the specification of tristimulus values 75 years ago. It evolved to improved metrics of color difference and basic metrics of appearance about 30 years ago. Within the last decade, CIE color appearance models have been published and used in a variety of applications. This paper describes the application of these ever-evolving color metrics to imaging applications and the further evolution into more comprehensive image appearance models. Also reviewed are several recent, ongoing, and planned research projects aimed at providing pieces of the puzzle that is image appearance.

Keywords: Color Appearance, Image Appearance, Modeling, Image Reproduction

1. INTRODUCTION

Color appearance models extend basic CIE colorimetry as embodied by XYZ tristimulus values and the CIELAB color space to enable prediction of appearance attributes (brightness, lightness, colorfulness, chroma, saturation, hue) across a wider range of viewing conditions (illumination color and level, surround, background, etc.). Research on the formulation and testing of color appearance models progressed to the point that CIE models could be published in the late 1990's (CIECAM97s) and significantly refined and improved several years later (CIECAM02). While better color appearance models will almost certainly be derived in the future, CIECAM02 provides a very effective method to predict color appearance for relatively simple patches of color on essentially uniform backgrounds and surrounds.

Colorimetry in its many forms from XYZ to CIECAM02 JCh has been successfully applied in the development and characterization of all types of image displays from photographic film, to the early development of color television, to color printing technology, to modern digital systems. However, image displays also present additional challenges since the color stimuli vary significantly in size and are arranged in complex spatial and temporal arrays (still and moving images). In many imaging applications, traditional colorimetric models are very helpful because the spatial and/or temporal variations in color are approximately replicated between original and reproduced images. However, in some cases it is necessary to reproduce colors across significant changes in spatial and temporal scale or to pull a color out of one context and reproduce its appearance in a completely different spatio-temporal context. In such cases, colorimetric models that do not explicitly account for more complex spatial and temporal properties of the visual system (and the stimuli) might not provide satisfactory results.

To address these more complex appearance issues, color appearance models have become part of a natural process of scientific evolution and been joined with models of spatial and temporal vision to create image appearance models. Such models allow the prediction of color appearance across much more complicated changes in viewing environments and have a number of applications including image and video quality metrics and the rendering of high-dynamic-range images and video. The iCAM framework illustrates one approach to image appearance modelling that has been developed recently and continues to be refined [Fairchild, 2005; Fairchild and Johnson, 2004].

In addition to reviewing the history of the development of colorimetry for image displays from CIE XYZ, to CIELAB, to CIECAM02, to image appearance models and presents some recent experimental results this paper briefly outlines some future directions for related research. Some of these specific research topics from the past, present, and future are listed below.

Previous research results reviewed include:

- Use of an image appearance model to predict perceived image quality attributes such as sharpness and contrast,

•Rendering of high-dynamic-range (HDR) images through the modelling of local adaptation to luminance and contrast, and

•HDR video rendering through modelling the time-course of chromatic adaptation.

Recent research on image color appearance and quality is also described as follows:

•Evaluation of HDR rendering accuracy and preference,

•Measurement and enhancement of perceived color gamut volumes,

•The effect of surround on image appearance,

•Adaptation to noise in image displays, and

•The derivation of orthogonal opponent-colors dimensions for image quality modelling.

Lastly, some research topics that are just underway and aimed at improving fundamental aspects of colorimetry for image displays are briefly introduced including:

•Improved HDR rendering techniques,

•An HDR photographic and color appearance survey,

•Spectral adaptation modelling,

•Transformability of primaries,

•Color difference modelling in color appearance spaces,

•The effects on image appearance of changes in image size and angular subtense,

•Perceived color gamuts and the perception of brilliance,

•Observer metamerism and a fully specified system of colorimetry, and

•An educational resource aimed at putting it all together for future scientists.

2. PREVIOUS RESEARCH

Fairchild and Johnson (2004) described a framework for an image color appearance model known as iCAM that extends traditional point-wise color appearance models by including spatially complex inputs for chromatic, luminance, and surround adaptation and spatio-temporal filtering for image and video quality applications.

The iCAM framework has been implemented and evaluated in a variety of ways for a range of applications. One of these applications has been as an image difference metric for image quality specification. Johnson and Fairchild (2000) successfully applied the model to the prediction of perceived sharpness in images while Calabria and Fairchild (2003) obtained similar results for the perception of overall image contrast.

Since the iCAM model inherently includes spatially localized light and chromatic adaptation (sometimes simply called local adaptation), it is applicable to the problem of rendering HDR images to low-dynamic-range displays such as typical self-luminous displays and prints. Johnson and Fairchild (2003) describe the details of this process using the iCAM framework.

Lastly, it is possible to use information about the time-course of chromatic adaptation to extend iCAM to moving images. A prototype of this process has been implemented to illustrate how a human observer would adapt as they moved their gaze around an HDR scene [Fairchild and Johnson, 2004].

3. RECENT RESEARCH

More recent research has looked at detailed aspects of image appearance modelling or more specific applications.

Kuang et al. (2005) examined the performance of various algorithms for rendering HDR images. This work compared image appearance approaches with those of image processing algorithms with no regard for colorimetry. Observers scaled image preference and the results showed that, even for preference scaling, a model based on reproducing image appearance performed quite well.

As an extension to that work, Kuang et al. (2006) performed similar experiments in which observers were asked to scale the accuracy of rendered HDR images in comparison to real-world HDR scenes constructed in a laboratory. In this case, the advantages of an image-appearance based model became even more prevalent.

Heckaman and Fairchild (2006) recently showed how image and color appearance models could be used to facilitate the creation of modern image displays with color gamuts that apparently exceed the limits of the spectrum locus of a chromaticity diagram without, of course, physically exceeding the spectrum locus. This bit of visual magic relies on judicious selection of the display's diffuse white point and taking advantage of HDR properties of forthcoming display technologies.

Liu and Fairchild (2004) have studied another aspect of how viewing conditions can significantly impact display color quality. In this case, they studied the effects of surround color and luminance in a specially constructed room that allows full 24-bit control of room illumination. They were able to repeat classic results on the effects on image contrast while at the same time obtaining more quantitative data and beginning explorations into other surround effects.

In the course of these studies on image appearance and quality, a new effect was observed. When observers view image content with a noise pattern (such as a halftone screen), they actually adapt to the noise and become less sensitive and aware of it and more sensitive to the image content of interest. This image noise adaptation is a special case of spatial frequency adaptation and was measured psychophysically by Fairchild and Johnson (2005) as well as modelled in terms of iCAM image differences.

A process common to all image quality/difference/encoding techniques is a transformation into opponent color dimensions that are assumed to be orthogonal. In other words, the image processing procedures carried out in these spaces assume there is no luminance information in the chromatic channels. Song et al. (2004) explored the reality of these spaces and derived a truly orthogonal opponent-colors space for image different and spatial filtering algorithms. This space is an important improvement to a variety of image appearance modelling applications.

4. ONGOING RESEARCH

As more has been learned about image appearance it has become clear that even more interesting problems are being uncovered. Such is the way of scientific inquiry. Of note is that many of the important questions have made a full circle back to fundamental questions of color science. In essence, as the applications of color science become more sophisticated the situations in which limitations of the CIE system are important come to light more often.

Nezamabadi and Berns (2005) have reported some preliminary results on the effects of image size and viewing distance on image appearance. In general larger images appear lower in contrast and chroma due to local adaptation. However, this depends on image size and distance, not just angular subtense and there is much more to learn on the topic.

Jiangtao Kuang is extending his evaluations of HDR rending algorithms to improve the image appearance aspects of the iCAM model for that application. The result should be an improved model for both image appearance and HDR rendering.

The author has initiated a project known as the HDR Photographic Survey in which high-quality HDR images will be obtained along with colorimetric and color appearance data from the original scenes. These images and data will be made publicly available to aid researchers in the field. See <www.cis.rit.edu/fairchild/HDR.html>.

Rod Heckaman is extending his work on perceived color gamuts through the construction of HDR displays and ongoing experiments on the psychophysics of gamut volume and Evans' concept of brilliance. This work should result in a more widespread understanding that color gamuts cannot be meaningfully expressed as two-dimensional areas on a chromaticity diagram.

The work on noise adaptation led the author to ponder the concept of spectral adaptation as an alternative to chromatic adaptation. The various mechanisms of the human visual system do have some sub-conscious access to spectral information, so a spectral model is not entirely unfeasible and would have some advantages in applications such as spectral image reproduction.

Color appearance modelling and color difference equations have been evolving on a very separate path over the past two decades with very sophisticated color appearance models such as CIECAM02 being successfully applied and very complicated formulae such as CIEDE200 being constructed on top of the CIELAB color space. Combining these two areas has become of more interest lately and an ongoing collaboration with Roy Berns appears to be making some headway toward deriving a simple color difference equation within a color appearance model that is simpler, more flexible and potentially more accurate than CIEDE2000.

Under Michael Brill's chairmanship, CIE TC1-56, Improved Colour Matching Functions, has put out a call for the systematic study of transformability of primaries. Together with Dave Wyble, a simple LED-based visual colorimeter with multiple primary sets is being constructed to contribute one set of tests. This is also an important verification for image appearance modelling since primary transformations are a very common practice color imaging systems.

That brings us to the topic of color matching functions, the main focus of this conference. Color matching functions are fundamental to image appearance modelling and have come under scrutiny recently as the spectral variance between image displays has increased the degree and variety of metamerism encountered. There is no question that a complete system of colorimetry that includes accurate mean color matching functions along with an accurate set of covariance color matching functions could be of great utility in a variety of imaging applications. Mitch Rosen is working with the author to revive and earlier model of color matching functions, modernize it with current knowledge of the visual system and use it to simulate a large population of observers for the purpose of estimating this full set of color matching functions that was proposed by Nimeroff half a century ago.

The concept of observer metamerism and individual adjustments to color matching functions comes back into play in image appearance modelling through some current work of Changmeng Liu in his investigations of surround effects. He noticed a systematic discrepancy between surround appearance and the display appearance when the CIE tristimulus values were matched. This is a case of severe metamerism since the surround was illuminated with high-intensity RGB LEDs and the display was a typical LCD monitor. In addition, the display was viewed centrally while the surround was mainly outside the fovea. These color differences were measured for a population of observers and found to be systematic beyond the level of inter-observer variability (which is high). Interestingly, the observed "error" in the predictions of the CIE color matching functions was easily corrected by making a multiplicative correction to the functions to account for the difference in macular pigment between the two matching fields. This work might well solve some other reported problems when trying to make color matches for large displays like those found in digital cinema applications.

Finally, the key to all this work is education and the inspiration of future generations of scientists. All of this work is culminating in the creation of a educational website and resource on science that uses color as a theme and is aimed at both satisfying students' curiosity about color and potentially inspiring them to pursue science further. It is called the Color Curiosity Shop and its progress can be observed at <whyiscolor.org>.

2. CONCLUSIONS

Image appearance modelling is a natural extension of color appearance modelling enabled by recent technology.

There are many questions of fundamental and applied color science that build together to address image appearance while also improving our fundamental understanding of colorimetry.

Many exciting scientific and technical challenges remain ahead to keep us occupied for the second 75 years of CIE colorimetry.

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