A Pictorial Review of Color Appearance Models

Mark D. Fairchild and Lisa Reniff
Munsell Color Science Laboratory, Center for Imaging Science,
Rochester Institute of Technology, Rochester, New York

Abstract

Color-appearance models are simultaneously a topic of much recent research and a key link in the chain of color management systems. While the application and testing of color appearance models for device-independent color imaging applications has been previously presented, the visual significance of the differences between model predictions is not often displayed. This poster presents an array of images designed to illustrate key differences between various color appearance models. A total of 15 color appearance models (or variations of models) are presented and compared.

Introduction

CIE XYZ tristimulus values specify color matches between two stimuli evaluated in identical viewing conditions by an average observer. While CIE tristimulus values have proven their immense value for the prediction of color matches over the last 65 years, by themselves they tell us nothing about the appearance of the stimuli. Color appearance models extend tristimulus values by performing transformations on them based on additional information about the state of chromatic adaptation, mode of viewing, luminance level, background, surround, *etc*. A color appearance model allows a stimulus, in given viewing conditions, to be numerically described with correlates of perceptual attributes such as brightness, lightness, colorfulness, chroma, and hue. In cross-media color reproduction applications, color matches must be made across changes in illumination level and color, white point, surround, viewing mode, as well as other features of the viewing environment and images. Thus, tristimulus matches cease to be appearance matches and color appearance models (or at least portions thereof) are required. Figure 1 shows a flow chart of the general process of cross-media color reproduction. Figure 1 also illustrates the process followed in the generation of images for this poster and the process that must be implemented within color management systems.

The process begins with the colorimetric calibration and characterization of the device producing or acquiring the original image. This allows the device coordinates (*e.g*., RGB) of the original image to be transformed into a device-independent color space (*e.g*., CIE XYZ). The next step requires information about the viewing conditions and a color appearance model to transform from device-independent coordinates to a viewing-condition independent space that specifies the image appearance (*e.g*., lightness, chroma, and hue). At this point image editing, color preference adjustments, gamut mapping, and other such processes can be efficiently implemented. The process is then reversed for the output viewing conditions and device characterization to reproduce a matching image within physical limitations. (Note: If a chromatic adaptation transform is used to account for viewing conditions, the process can be completed, but the intermediate appearance correlates are never available.)

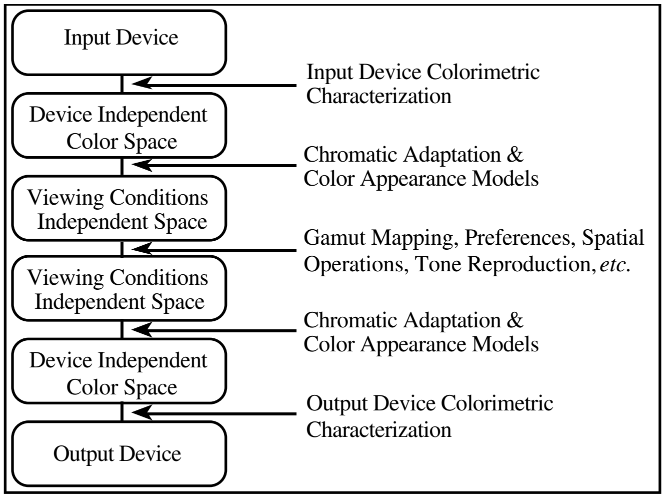

Figure 1. The process of cross-media color reproduction.

Technological advances in the last decade have accentuated the need for a useful color appearance model. While technology demands a model, science has yet to develop a single answer to this problem (and perhaps never will!). Thus the formulation, testing, and application of color appearance models have been active areas of research. While the equations and numerical results of tests are often presented and discussed, an intuitive visual appreciation of the differences between models is generally not provided. This poster provides a visual comparison of the predictions of 15 different color appearance models, chromatic adaptation transforms, or variations thereof, for three different changes in viewing conditions.

Models

A significant number of color appearance models and chromatic adaptation transforms have been formulated over the past century (most within the last 20 years) that can be applied to the problems of cross-media color reproduction. While it is impossible to include all of the models that have been published, a representative sampling of different types of models was selected including those most commonly used in current imaging applications. Some of the models can also be implemented with different interpretations of the viewing conditions. Multiple examples of these have been included to illustrate the function of the models.

The models presented include:

CIE 1931 XYZ (*i.e.*, no model at all)
CIELAB[1]
CIELUV[1]
LABHNU2[2]
von Kries[3]
Spectrally Sharpened von Kries[4]
ATD[5]
Nayatani *et al.*[6]
LLAB[7]
Hunt[8] [Discounting]
Hunt[8] [No Discounting]
Hunt[8] [Inc. Adaptation, No Helson-Judd Effect]
RLAB[9] [Discounting]
RLAB[9] [Partial Discounting]
RLAB[9] [No Discounting].

Viewing Condition Transforms

The first viewing condition explored is a change in white-point chromaticity from that of CIE Illuminant A to CIE Illuminant D65 at constant luminance. This, rather large, change in white point was chosen to better illustrate the significant differences between models. Also it is not unusual to encounter such large white-point changes in desktop color imaging applications (*e.g.*, 9300K CRT display and tungsten illumination for prints). All 15 transformations are presented for this white-point change.

The second viewing condition explored is a change in adapting luminance level from 100 cd/m^2 to 10000 cd/m^2 at a constant D65 white point. Many of the models do not predict changes with luminance level so they are all represented by a single image (CIE XYZ tristimulus match). The predictions of the models with luminance dependencies (ATD, LLAB, Nayatani, Hunt, RLAB) are presented and contrasted.

The final viewing condition evaluated is a change in the surround relative luminance from an average surround (typical for print viewing) to a dark surround (typical for projected transparencies). Again, this extreme surround change was chosen to accentuate the differences between the models. Many of the models do not predict changes with surround relative luminance so they will be represented by a single image. The predictions of the models with surround dependencies (LLAB, Hunt, RLAB) are presented.

In all cases, lightness-chroma matches were calculated rather than brightness-colorfulness matches. This is because brightness-colorfulness matches are of no practical value for color reproduction applications. Some models (ATD, LLAB) do not have explicit predictors for chroma. In these cases, the most appropriate approximation was used. The chromatic adaptation transforms (von Kries, *etc.*) do not include appearance correlates. Thus they were used simply as transformations to predict corresponding colors with the understanding that the data on which they are based consist of lightness-chroma matches. This can easily be proven to be true since the adaptation transforms do not include luminance dependencies.

The demonstration images were produced using a single image made up of a montage of two pictorial scenes with patches from the Macbeth Color Checker Chart pasted along the edge for comparison. All images were produced for hypothetical viewing conditions as defined above. To truly evaluate the performance of the various models, the original and reproduced images must be viewed in the appropriate conditions with sufficient adaptation time. Despite this limitation, the images are of significant value in comparing the relative characteristics of the various models and they certainly contribute to a better understanding of the models' formulations. All prints were made using a Fujix Pictrography 3000 digital printer. All calculations were performed with double-precision floating-point procedures to avoid quantization artifacts in intermediate images. In some cases the floating-point calculations were performed on the images themselves while in other cases, floating-point calculations were used to construct 24-bit precision three-dimensional LUTs used for image transformations via interpolation.

Psychophysical Tests

Given the important role of color appearance models in cross-media color reproduction, it is fair to ask which one should be used. Unfortunately, that question is not easily answered. A perfect color appearance model is not available and each model has advantages and disadvantages. There are two CIE technical committees (TC1-27 and TC1-34) actively evaluating various models. Both committees have published guidelines for coordinated research[10,11] and are currently collecting and evaluating additional data. These committees are unable to recommend a single color appearance model as superior for specific applications. However, recognizing the urgent industrial need, TC1-34 has been charged with formulating a single CIE color appearance model incorporating the best features of published models. This model will continue to be tested, and perhaps refined, as additional scientific data become available. However, it is hoped that a single CIE model will promote uniformity of practice and help solve some technical and commercial problems. TC1-34 hopes to publish this model during 1997.

A variety of psychophysical evaluations of color appearance models in cross-media image reproduction applications have been completed.[9,12-15] While the results cannot be briefly summarized and no single model works best in all experiments, general trends regarding each model have been found. These are briefly summarized below. There are many details behind these general summaries and the original references should be reviewed prior to making strong conclusions.

CIE XYZ: Tristimulus values are not a color appearance specification. Their use is limited to identical viewing conditions for original and reproduction.

CIELAB: CIELAB works surprisingly well, but shows some inaccuracies in the blue hues due to it's application of a von Kries-type adaptation transform to XYZ tristimulus values rather than cone responses.

CIELUV: CIELUV produces completely unacceptable performance due to its subtractive adaptation transform that often shifts colors out of gamut and distorts hues.

LABHNU2: LABHNU2 is similar to CIELAB in spacing, but incorporates an adaptation transform similar to that of CIELUV. It thus performs similarly to CIELUV.

von Kries: While the von Kries model is only an adaptation transform, it works quite well and can be used with CIELAB to improve it.

Spectrally Sharpened von Kries: This technique apparently predicts higher degrees of color constancy.[4] However, this does not necessarily correlate well with human visual observations for which color constancy is quite poor.

ATD: The ATD model can potentially work as well as the von Kries transform. It does not include appropriate appearance predictors (*i.e.*, lightness, chroma, and hue) and requires some interpretation beyond published equations.

Nayatani et al.: The Nayatani *et al.* model performs poorly for images due to its intrinsic prediction of a strong Helson-Judd effect, which is not observed.

LLAB: LLAB is a relatively new model that appears to have a very good adaptation transform. However, it includes predictors of lightness, colorfulness, and hue rather than lightness, chroma, and hue and is not analytically invertible. These factors limit it's usefulness.

Hunt: The Hunt model generally performs quite well. Although sometimes its complexity requires some careful specification of various parameters in order to obtain reliable results. Generally, its complexity is not warranted for imaging applications. It is also not analytically invertible.

RLAB: RLAB has worked quite well for imaging applications. However, it's adjustments for changes in surround relative luminance might be too strong for some changes in viewing conditions. This can be fixed by using smaller changes in the RLAB exponents.

Conclusions

The aim of this poster was to promote a better understanding of various color appearance models by displaying pictorial images illustrating various predictions. Unfortunately, cost and time constraints precluded the production of accurate color prints to be inserted into the proceedings.

Color appearance models do make significant contributions to the quality of cross-media color reproduction when used with care (like any process). Given the large and often confusing variety of choices available, a few simple recommendations might be useful. These are presented in order of increasing complexity and it should be noted that increasingly careful control of the viewing conditions is also required.

1. If possible, it is preferable to equate the viewing conditions such that simple tristimulus matches are also appearance matches.
2. If a white point change is necessary, CIELAB can be used as a reasonable first-order approximation of an appearance model.
3. If CIELAB is found to be inadequate, it can be enhanced by using a von Kries chromatic adaptation transform (on cone responses) to a reference viewing condition.
4. If a more flexible adaptation model is required (e.g. hard-copy to soft-copy changes) and/or their are surround changes, then the RLAB model can be used without too much added complexity.
5. Lastly, if a full range of appearance phenomena and wide range of viewing conditions (*e.g.*, very high or low luminances) must be addressed, then the Hunt model should be used. The Hunt model should be used if brightness and colorfulness predictors are required (*e.g.*, overall quality metrics for projected transparencies).

As a last note, it is expected that the forthcoming CIE color appearance model will be sophisticated enough to address the same issues as the Hunt model (perhaps more accurately) and also incorporate a simplified and compatible version that is similar, in concept, to RLAB.

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