37.2: Evaluation of CIE Luv and CIE Lab as Perceptual Image Representations

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Abstract

We present data to show that the conventional white point normalization used to transform an image representation from CIE XYZ tristimulus coordinates to CIE Luv or CIE Lab coordinates fails to incorporate the effect of observer adaptation on color appearance. Two image regions that have the same $L^*u^*v^*$ or $L^*a^*b^*$ coordinate values, when seen in different viewing contexts, can have quite different color appearances.

Introduction

One method of representing color image information is to transform the physical representation of an image into a perceptual representation. Ideally, this transformation would satisfy two important properties. First, it would allow us to predict the color appearance of an image region directly from the perceptual coordinates of that region. Second, it would allow us to evaluate the similarity of the color of two image regions directly from the distance between their perceptual coordinates.

When the viewing context is held fixed, the transformation from a physical description to CIE XYZ tristimulus coordinates satisfies the first property. Indeed, the CIE XYZ tristimulus representation has been used successfully as a perceptual image representation in color reproduction applications. When the original and reproduced images have the same size and are viewed under similar conditions, location-by-location matching of the image CIE XYZ coordinates leads to high-fidelity color reproduction (see e.g. Schreiber, 1986). On the other hand, the fact that two image regions have the same XYZ tristimulus coordinates does not imply that they have the same color appearance when seen in different contexts.

It is well known that the CIE XYZ tristimulus representation does not allow easy evaluation of the magnitude of color differences (MacAdam, 1942; Brown and MacAdam, 1949; Wyszecki and Fielder, 1971). The CIE Luv and Lab uniform color spaces were designed designed to overcome this drawback of the XYZ tristimulus representation (CIE, 1976; Robertson, 1977) and have achieved widespread acceptance as methods for deriving a similarity metric from the XYZ tristimulus representation. For any fixed viewing context, the three Luv or Lab coordinate values ($L^*u^*v^*$ for Luv, $L^*a^*b^*$ for Lab) of an image location are computed from the XYZ tristimulus coordinates. Because the visual system adjusts its sensitivity to the ambient viewing conditions, part of the computation involves a white point normalization. The normalization was designed to incorporate these changes in sensitivity, so that the magnitude of differences in Luv or Lab coordinates could predict color differences under a variety of viewing conditions.

A number of authors have suggested that the white point normalization implies that we can use the CIE uniform color spaces spaces in a way that goes beyond their original intent as uniform color spaces. For example, Lindbloom (1989) has suggested that the three-dimensional representation provided by CIE Luv may serve as a color appearance representation. The suggestion is that the white point normalization incorporates the effect of viewing context on color appearance, so that the $L^*u^*v^*$ coordinate values directly predict the color appearance of an image region. If correct, use of it would allow us to design color image reproduction techniques without the restriction that the original and reproduced images be seen under identical conditions.

As part of a series of experiments on color appearance, we have compared the color appearance of stimuli presented in different contexts. Our data permit us to test the hypothesis that the CIE Luv or Lab transformations yield a color appearance representation. In this paper, we compare our cross-context matching data with predictions generated by the assumption that two lights with identical $L^*u^*v^*$ or $L^*a^*b^*$ coordinate values will have the same color.

Experimental Procedures

Each experimental session began by training a subject to remember the color appearance of a *standard object*. The standard object, which we simulated on a monitor, was a rendering of a simulated flat, matte surface seen under uniform illumination. The standard object was presented as one of a collection of flat matte surfaces, all illuminated by a common *standard illuminant*.

Our experimental measurements consist of color matches that subjects set to the remembered color appearance of the standard object. Subjects used a button box to control the light emitted from a *test object* presented on the monitor. In a control condition, subjects set matches when the test object was seen under the standard illuminant. These measurements confirmed that subjects could set veridical memory matches. In our experimental conditions, we changed

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the simulated illuminant. The change in simulated illumination took place slowly over several minutes so that the visual system had plenty of time to adapt. Subjects then adjusted the light emitted from the test object to set a memory match. When the simulated illuminant was changed, the CIE XYZ tristimulus values of subjects' matches were substantially different from the standard object tristimulus values. This is not surprising, given that we manipulated the viewing context. Since the subjects' memory standard remained fixed throughout a session, the difference in tristimulus values is a measure of the effect of viewing context on color appearance. Our experimental method and basic results are described in detail elsewhere (Brainard, 1989; Brainard and Wandell, 1990; Brainard and Wandell, 1991).

We can evaluate whether the white point normalization in the Luv or Lab transformations predict the effect by comparing the Luv or Lab coordinates of the standard object with the corresponding coordinates of subjects' matches. To make the comparison, we proceeded in three steps. First, we computed the Luv or Lab coordinates of the standard object under the standard illuminant, using the tristimulus coordinates of the simulated standard illuminant as the white point. Second, we computed the Luv or Lab coordinates of the matches set by subjects in the test illuminant condition. For these computations, we used the tristimulus coordinates of the test illuminant as the white point. Third, to evaluate the magnitude of the difference between the actual match and the predicted match, we computed the Euclidean distance, ΔE^*, between the two sets of Luv or Lab coordinates. If CIE Luv or CIE Lab serve as predictors of color appearance, these ΔE^* values should be small.

Both CIE Luv and CIE Lab representations make rather unsatisfactory predictions. To illustrate the magnitude of the prediction error, Figure 1 shows the cumulative distribution of the CIE Luv and Lab ΔE^* prediction errors for our data set. The median prediction error quite large in both cases: approximately 20 ΔE^* units for CIE Luv and 12 ΔE^* units for CIE Lab.

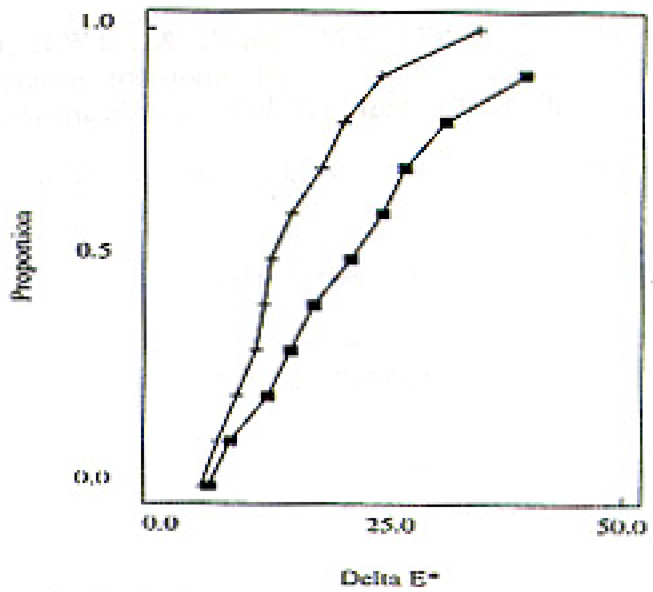

Figure 1: Prediction errors. The graph shows, for each ΔE^* values on the horizontal axis, the cumulative proportion of prediction errors for our data set that were less that the criterion value. The squares show the cumulative proportions for the Luv predictions. The crosses show the cumulative proportions for the Lab predictions. To find the median ΔE^* prediction error, we start on the vertical axis at the 0.5 value on the vertical axis and trace left to one of the curves. We then trace down to the horizontal axis to find the median value. The median Luv prediction error is 20.5 ΔE^* units, while the median Lab prediction error is 11.9 ΔE^* units. For clarity of scale, the Luv plot is truncated at proportion 0.90. The Luv ΔE^* datum for proportion 1.0 is 86.0.

Discussion

Although CIE Luv and CIE Lab transformations are useful for creating useful similarity metrics for color representations, they both contain substantial inaccuracies when we use them to represent color appearance. Lights with common CIE Lab or CIE Luv coordinates but presented in different viewing contexts do not match in color appearance. The errors are rather large, suggesting that neither can serve as a standard for representing color appearance.

Currently a number of rather complex models of color appearance are under study (Hunt & Pointer, 1985; Nayatani, Takahama, & Sobagaki, 1986). These models attempt to explain much more than color matching across contexts. In addition, these models attempt to derive symbolic representations of color appearance.

There is a contradiction, however, between the complexity of the color appearance models and simple regularities observed in cross-context color matching experiments. Beginning in the 1950's, cross-context matching experiments, using fairly simple stimuli have been consistent with a model in which the CIE XYZ tristimulus coordinates of matching lights are related by an affine transformation (e.g. Burnham, Evans, & Newhall, 1957; Hurvich and Jameson, 1972; Shevell, 1978). Our own work (Brainard, 1989; Brainard and Wandell, 1990; Brainard and Wandell, 1991) suggests that these regularities can be generalized to more complex laboratory viewing contexts. Since to make high-fidelity image reproductions requires knowledge only of when image regions will appear the same, we suggest that there is no need to solve the complete problem of predicting color names before we can design and implement successful color reproduction procedures.

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References

Brainard, D. H. (1989). *Understanding the illuminant's effect on color appearance.* Unpublished Doctoral Dissertation, Stanford University.

Brainard, D. H., & Wandell, B. A. (February 11-16, 1990). The effect of the illuminant on color appearance. *Proceedings of the SPIE/SPSE Symposium on Electronic Imaging Science and Technology.*

Brainard, D. H., & Wandell, B. A. (1991). A Bilinear model of the illuminant's effect on color appearance. In J. A. Movshon, & M. S. Landy (Eds.), *Computational Models of Visual Processing*. Cambridge, MA: MIT Press. (In press.)

Brown, W. R. J., & MacAdam, D. L. (1949). Visual sensitivities to combined chromaticity and luminance differences. *J. Opt. Soc. Am., 39*, 10, 808-834.

Burnham, R.W., Evans, R.M., & Newhall, S.M. (1957). Prediction of Color Appearance with Different Adaptation Illuminations. *J. Opt. Soc. Am., 47*, 1, 35-42.

CIE. (1978). *Recommendations on uniform color spaces, color-difference equations, psychometric color terms* Supplement No. 2 to CIE Publication No. 15. Paris: Bureau Central de la CIE.

Hunt, R.W.G., & Pointer, M.R. (1985). A colour-appearance transform for the CIE 1931 standard colorimetric observer. *Col. Res. Appl., 10*, 12-19.

Jameson, D., & Hurvich, L. M. (1972). Color adaptation: Sensitivity contrast, and afterimages. In L. M. Hurvich, & D. Jameson (Eds.), *Handbook of Sensory Physiology* (pp. 568-581). Berlin: Springer.

Lindbloom, B. J. (1989). Accurate color reproduction for computer graphics applications. *Computer Graphics, 23*, 117-126.

MacAdam, D. L. (1942). Visual sensitivities to color differences in daylight. *J. Opt. Soc. Am., 32*, 5, 247-274.

Nayatani, Y., & Sobagaki, H. (1986). Prediction of color appearance under various adapting conditions. *Col. Res. Appl., 11*, 62-71.

Robertson, A.R. (1977). The CIE 1976 color-difference formulae. *Col. Res. Appl., 2*, 1, 7-11.

Schreiber, W.F. (1986). A color prepress system using appearance variables. *J. Imaging Technology, 12*, 4.

Shevell, S. K. (1978). The dual role of chromatic backgrounds in color perception. *Vision Res., 18*, 1649-1661.

Wyszecki, G., & Fielder, G. H. (1971). New color-matching ellipses. *J. Opt. Soc. Am., 61*, 9, 1135-1151.