

Figure 9.2 Prediction of some example corresponding colors data using the von Kries model. Open triangles represent visual data and filled triangles represent model predictions

The von Kries transformation was used to predict the visual data of Breneman (1987) that were described in Chapter 8. The results are illustrated in a $u'v'$ chromaticity diagram in Figure 9.2. The open symbols represent Breneman's corresponding colors data and the filled symbols represent the predictions using a von Kries model. Perfect model predictions would result in the filled triangles completely coinciding with the open triangles. In this calculation, the chromaticities under daylight adaptation (open circles in Figure 9.2) were used to predict the corresponding chromaticities under incandescent adaptation (triangles in Figure 9.2). It is clear in Figure 9.2 that the von Kries hypothesis was indeed a good one and that the modern interpretation as a chromatic adaptation transformation predicts the data surprisingly well.

Helson, Judd, and Warren (1952) presented an early study in which corresponding colors were derived by memory matching and the von Kries hypothesis was tested and performed quite well. Examples of recent experimental data and analyses that address the utility and limitations of the von Kries hypothesis can be found in the work of Brainard and Wandell (1992) and Chichilnisky and Wandell (1995). There are some discrepancies between these, and other, visual data and the predictions of the von Kries model. Such discrepancies have led investigators down many paths that are described in the remaining sections of this chapter and throughout this

function nonlinearity was suggested in the classic brightness study by Stevens and Stevens (1963). Another interesting and important feature of the nonlinear model is that noise terms are added to the cone responses. This helps to model threshold behavior. Equations 9.12–9.14 are generalized expressions of the nonlinear model.

$$L_a = a_L \left(\frac{L + L_n}{L_0 + L_n} \right)^{\beta_L} \quad (9.12)$$

$$M_a = a_M \left(\frac{M + M_n}{M_0 + M_n} \right)^{\beta_M} \quad (9.13)$$

$$S_a = a_S \left(\frac{S + S_n}{S_0 + S_n} \right)^{\beta_S} \quad (9.14)$$

L_a , M_a , and S_a are the cone signals after adaptation; L , M , and S are the cone excitations; L_n , M_n , and S_n are the noise terms; L_0 , M_0 , and S_0 are the cone excitations for the adapting field; β_L , β_M , and β_S are the exponents and are monotonically increasing functions of the respective cone excitations for the adapting field; and a_L , a_M , and a_S are coefficients determined by the principle that exact color constancy holds for a nonselective sample of the same luminance factor as the adapting background.

The formulations for the exponents can be found in Nayatani *et al.* (1982). Takahama *et al.* (1984) extended the model to predict corresponding colors for backgrounds of various luminance factors. A version of the model (Nayatani *et al.*, 1987) was accepted for field trial by the CIE. This meant that the CIE, through its technical committee activities, wanted to collect additional data to test the model, possibly improve it, and determine whether it or some other model should be recommended for general use. The results of the field trials were inconclusive, so the CIE did not make a recommendation on this model. Refinements of the model were made during the course of field trials and these have been summarized in a CIE technical report (CIE 1994), which provides full details of the current formulation of the model.

The nonlinear model was used to predict Breneman's (1987) corresponding colors. The results, analogous to those presented in Figure 9.2 for the von Kries model, are illustrated in Figure 9.3. The predictions are quite good, but not as good as those of the simple von Kries model (for these particular data). One reason for this is that Breneman's data were collected under viewing conditions for which discounting-the-illuminant could not occur and thus chromatic adaptation was less complete. This is illustrated by the predictions of the Nayatani model, which are all shifted toward the yellow side of the visual data. This indicates that the incandescent adapting field in Breneman's experiment retained some yellowish appearance. Recent

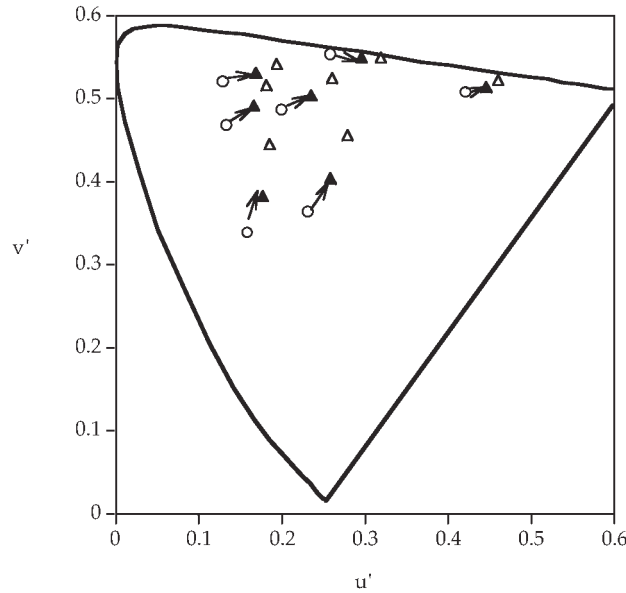


Figure 9.4 Prediction of some example corresponding-colors data using the Guth model. Open triangles represent visual data and filled triangles represent model predictions

$$k_L = ((\sigma + L_{r0})/(\sigma + L_{r0})) - (L_{r0}/(\sigma + L_{r0})) \quad (9.22)$$

$$k_L = (\sigma + L_{r0} - L_{r0})/(\sigma + L_{r0}) \quad (9.23)$$

$$k_L = \sigma/(\sigma + L_{r0}) \quad (9.24)$$

Figure 9.4 shows the Guth model prediction of Breneman's (1987) corresponding-colors data. The calculations were carried out using the nominal, published form of the Guth model. It is clear that there is a systematic deviation between the observed and predicted results. This discrepancy can be traced to the σ parameter. The Breneman data are fairly well predicted using a simple von Kries model. Thus if the σ parameter were made smaller, the prediction of the Guth model would improve. This highlights a feature (or a drawback) of the Guth model. As a framework for a vision model, it is capable of making impressive predictions of available data. However, the model often requires a small amount of adjustment in its parameters for any given viewing condition or experiment. This is acceptable when trying to predict various observed phenomena, but is not practical in many applications such as cross-media color reproduction where the viewing conditions are often not known until it is time to calculate a predicted image and there is no chance for iterations. Thus to apply the Guth adaptation model (and the full ATD model described in Chapter 14) to such situations, some interpretation of how to implement the model is necessary.

$$\begin{bmatrix} L'_2 \\ M'_2 \\ S'_2 \end{bmatrix} = \mathbf{C}_2^{-1} \begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} \quad (9.35)$$

$$\begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} = \mathbf{A}_2^{-1} \begin{bmatrix} L'_2 \\ M'_2 \\ S'_2 \end{bmatrix} \quad (9.36)$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \mathbf{M}^{-1} \begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} \quad (9.37)$$

The entire model can be expressed as the single matrix Equation 9.38.

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \mathbf{M}^{-1} \mathbf{A}_2^{-1} \mathbf{C}_2^{-1} \mathbf{C}_1 \mathbf{A}_1 \mathbf{M} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \quad (9.38)$$

Subsequent experiments (e.g., Pirrotta and Fairchild 1995) showed that the \mathbf{C} matrix introduced an unwanted luminance dependency that resulted in an overall shift in lightness with luminance level. This shift did not impact the quality of image reproductions since the whole image shifted. However, it did introduce significant systematic error in predictions for simple object colors. Thus the model was revised (Fairchild 1994b) by eliminating the \mathbf{C} matrix. This improved the predictions for simple colors, while having no impact on the results for images. It did remove the model's capability to predict the Hunt effect. However, in imaging applications, this turns out to be unimportant since any predictions of the Hunt effect would be counteracted by the process of gamut mapping. These changes, along with some further simplifications in the equations (different normalizations) were compiled and used as the basis for the latest version of the RLAB (Fairchild 1996) color appearance model presented in Chapter 13.

Figure 9.5 shows predictions of the Breneman (1987) corresponding-colors data using the Fairchild chromatic adaptation transformation. The predictions are identical for either version (original or simplified) of the model described above. The predictions are as good as, or better than, each of the models presented thus far. Quantitative analyses of all of Breneman's (1987) data confirms this result (Fairchild 1991a,b).

9.6 HERDING CATS

The CIE (1998) established the CIECAM97s color appearance model as described in Chapter 15. That model used a modified form of a chromatic

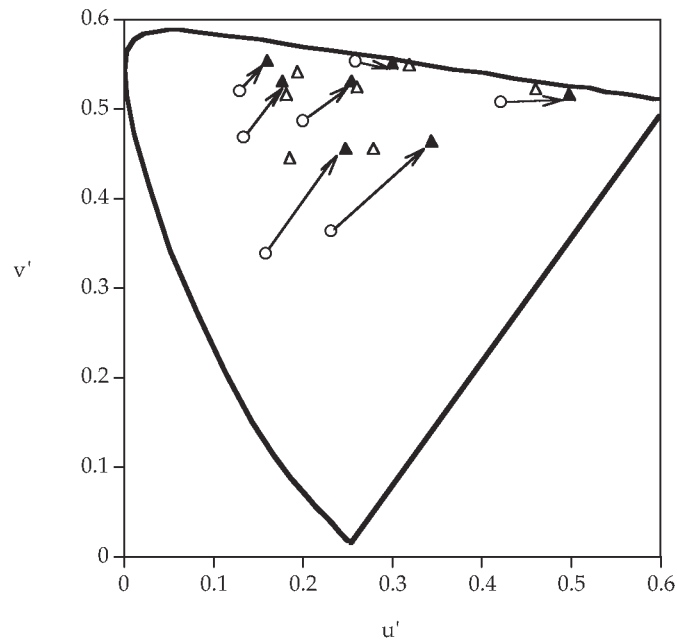


Figure 10.7 Prediction of some example corresponding colors data using the CIELAB model. Open triangles represent visual data and filled triangles represent model predictions

responsivities, the correct hue shift is predicted (Liu *et al.* 1995). Moroney (2003) explores the poor blue constancy of CIELAB in detail and expands on the above explanation.

The Breneman (1987) corresponding colors data that were used to compare chromatic adaptation models in Chapter 9 were also evaluated using the chromatic adaptation transform of the CIELAB equations. The predicted and observed results are illustrated using $u'v'$ chromaticity coordinates in Figure 10.7. The errors in the predictions are significantly larger than those found with a normal von Kries transformation (see Figure 9.2). The results indicate particularly large errors in the hue predictions for blue stimuli for this change in adaptation from daylight to incandescent. This is consistent with the errors observed by Liu *et al.* (1995) for tanzanite.

10.4 WHY NOT USE JUST CIELAB?

Given that CIELAB is a well-established, *de facto* international standard, color space that has been widely used for two decades and that it is capable of color appearance predictions, why are any other color appearance models necessary? As can be seen in Chapter 15, CIELAB performs quite well as a color appearance model in some applications. So why not just quit there and work with CIELAB?

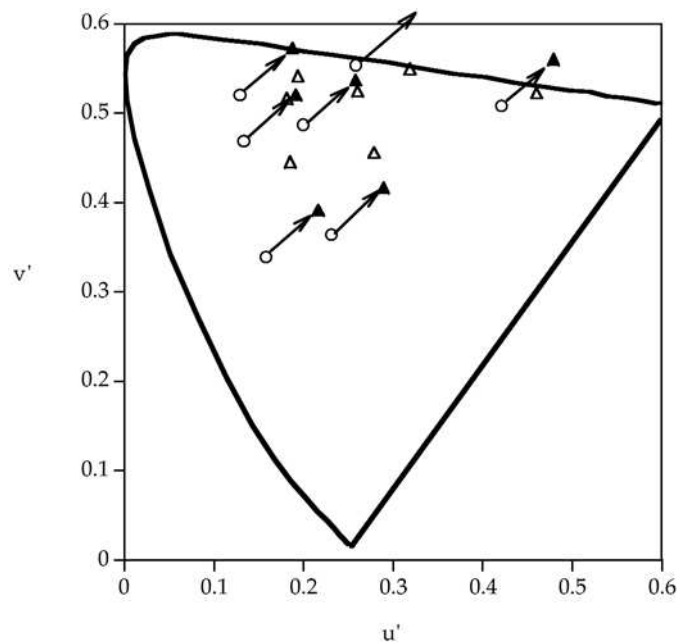


Figure 10.8 Prediction of some example corresponding colors data using the CIELUV model. Open triangles represent visual data and filled triangles represent model predictions

dicted tristimulus values less than zero, which cannot happen with the CIELAB transformation.) Even if this does not occur, the transform is likely to shift predicted colors outside the gamut of colors producible by any given device. In addition to this problem, the CIELUV adaptation transform is extremely inaccurate with respect to predicting visual data. This is illustrated nicely in Figure 10.8, which shows the CIELUV predictions of the Breneman (1987) corresponding colors data. Figure 10.8 illustrates how some colors are shifted outside the gamut of realizable colors (outside the spectrum locus on the $u'v'$ chromaticity diagram) and the inaccuracy of all the predictions.

The difficulties with the CIELUV adaptation transform are reason enough to eliminate it from serious consideration as an appearance model. However, additional evidence is provided by its poor performance for predicting color differences. The current CIE recommendation for color difference specification, CIE94 (CIE 1995b), is based on the CIELAB color space. So are the more recent CIE DE2000 (CIE 2001) color difference equations. While the DE2000 equations are more recent, their added complexity over the CIE94 specification is probably unwarranted in most applications. Alman *et al.* (1989) provide experimental evidence for the poor performance of CIELUV as a color difference equation. Additional comparisons between CIELUV and CIELAB have been made by Robertson (1990).

von Kries, and Hunt models. Mori *et al.* (1991) concluded that the Nayatani model made the best predictions. However, examination of their plots suggests that Hunt's model provides similar performance to it and the von Kries transform perhaps works better than both of them. They illustrated that the Nayatani *et al.* model could predict the Hunt effect data well, but they did not compare the results with predictions of the Hunt model. Similar analyses were performed for the Stevens effect and Helson–Judd effect data. The results showed a fairly small Stevens effect that was over-predicted by the Nayatani *et al.* model. The Helson–Judd effect, while observed in this experiment, was also over-predicted by the Nayatani *et al.* model. Further, quantitative analyses of these data have been carried out through CIE TC1-34 and are described later in the chapter.

Breneman (1987) collected a fairly extensive set of corresponding colors data for changes in chromatic adaptation and luminance level. These data were used to evaluate various chromatic adaptation transforms and color appearance models by Fairchild (1991a,b). The models were compared in terms of RMS deviations between observed and predicted results in the CIE 1976 $u'v'$ chromaticity diagram. The chromatic adaptation data were best predicted by the Hunt and RLAB models followed by the Nayatani and von Kries models. The CIELAB and CIELUV models performed the worst for these data. Breneman's data showed a small Hunt effect that was over-predicted by the Hunt and Nayatani *et al.* models and not predicted at all by the other models. The RMS deviations produced by of both sets of models are similar in magnitude, suggesting that making no prediction is as accurate as an over-prediction for these particular data.

Luo *et al.* (1991b) converted some of their magnitude scaling data (described in Section 17.4) to sets of corresponding colors for various changes in viewing conditions. They generated three sets of corresponding colors data for changes in chromatic adaptation from CIE illuminant D65 to D50, D65 to A, and D65 to white fluorescent, and then evaluated six different chromatic adaptation transforms using mean and RMS color differences in the CIELAB space. The results showed that the Bradford model, the basis of LLAB and CIECAM97s, performed best. The Hunt, Nayatani *et al.*, and CIELAB models performed similarly and almost as well. These were followed by the simple von Kries transformation and a transformation proposed by Bartleson. Additional results can be found in Kuo *et al.* (1995).

Braun and Fairchild (1997) performed an experiment in which observers were asked to adjust CRT-displayed images to match printed images viewed under a different white point. Matching images were obtained for five observers using two different images for white point changes from 3000 K to 6500 K and 9300 K to 6500 K. The data were analyzed by segmenting the images into meaningful object regions to avoid overly weighting large image areas. The corresponding colors were analyzed in terms of average and RMS CIELAB color differences. The results showed that RLAB, LLAB, and CIELAB best predicted the observed corresponding colors. The Hunt and Nayatani *et al.* models did not perform as well.