The ZLAB Color Appearance Model for Practical Image Reproduction Applications

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ABSTRACT

At its May, 1997 meeting in Kyoto, CIE TC1-34 considered 4 proposed color appearance models for adoption as the CIECAM97s model. The ZLAB model was one of those considered. Although it was rejected by TC1-34 because of its simplicity, there are many situations (such as typical cross-media image reproduction) for which a more complex model might not be necessary, or even useful. Thus, the ZLAB model is being published as a simpler alternative to CIECAM97s that retains many of its positive features.

1. INTRODUCTION

This paper details a proposal for a simple color appearance model that was submitted for consideration, but not adopted, by CIE TC1-34 at the Kyoto meeting. It is based on the work of Luo and Hunt, who submitted two proposed models to the committee (one of which, in slightly modified form, has since become CIECAM97s), and the conceptual formulation of the RLAB model.

This model (now designated the ZLAB color appearance model) is a significant simplification of the CIECAM97s model. This was accomplished by removing the luminance dependency, thereby producing a significantly simpler model that is capable of predicting lightness, chroma, and hue. The cost of this simplification is an inability to predict brightness and colorfulness.

It is believed that the ZLAB model can meet the needs of many practical image reproduction applications (*i.e.*, desktop and home imaging using International Color Consortium profiles) by providing accurate predictors of the relative appearance attributes of lightness, chroma, and hue and an accurate chromatic adaptation transform for intermediate luminance levels. It is also consistent with the results obtained by CIE TC1-27 that suggest more complicated models are not warranted for cross-media image reproduction applications.

This model will perform as well as the CIECAM97s model for corresponding-colors predictions and nearly as well for the appearance-attribute data collected for intermediate luminance levels and medium gray backgrounds. For situations in which the appearance attributes of brightness and colorfulness are required, CIECAM97s or CIECAM97c would be required. It is important to remember that the ZLAB model's lack of brightness and colorfulness predictors, restriction to intermediate luminance levels, and possible inaccuracies for very light and very dark colors are overridden by gamut-mapping issues and poor viewing-condition control and specification in most digital imaging applications.

It is suggested that the ZLAB model be considered for use in situations in which knowledge and control of the viewing conditions do not warrant the added capabilities of the CIECAM97s or CIECAM97c models, but greater performance than that obtained using the CIELAB color space is required. This paper provides an overview of the derivation, formulation, and performance of the ZLAB model.

2. PEDIGREE

Four color appearance models were considered by CIE TC1-34. These were tentatively named models 97A, 97B, 97Z, and 97R. Model 97A represented a significant simplification of the Hunt 1994 color appearance model combined with features from a wide variety of other models (*e.g.*, incomplete adaptation from RLAB, the Bradford adaptation transform from LLAB, *etc.*) Model 97B was a simplification of model 97A that utilized a modified form of the CIELAB color space and closely paralleled the formulation of the LLAB model. Models 97A and 97B were submitted to the committee by R.W.G. Hunt and M.R. Luo. Ultimately the committee came to the compromise of establishing Model 97A as the CIECAM97s model. The structure of this model is described elsewhere in these proceedings.[1] It was felt by some committee members that even model 97B was far too complex for practical applications. Thus M.D. Fairchild further simplified model 97B to form model 97Z and submitted that formulation to the committee for consideration. Model 97R was a reformulation of model 97B derived by K. Richter.

Model 97Z was not adopted by the committee since it was felt by some to be too simple and not easily extensible to a comprehensive form of the model. After rejection by TC1-34, model 97Z has been renamed ZLAB as described in this paper. It is important to acknowledge the fact that the ZLAB model was derived from the work of TC1-34, especially that of Hunt and Luo, and is not a completely independent creation. More complete explanations of the history of these models and those that preceded them can be found in reference [2].

3. SIMPLIFICATIONS OF CIECAM97s

ZLAB represents a simplification of the CIECAM97s model in four significant areas: (1) the compressive nonlinearity used, (2) limitation to only medium gray backgrounds, (3) use of a modified CIELAB color space, and (4) elimination of the absolute appearance attributes of brightness and colorfulness.

The s-shaped function (sometimes referred to as a hyperbolic function) used as the compressive nonlinearity in the CIECAM97s model was adopted from the Hunt 1994 color appearance model since it was felt that the threshold behavior and limiting maximum were necessary to predict color appearance over a very wide range of luminance levels. However, for intermediate luminance levels, this nonlinearity is identical in function to a simple square root. Thus, ZLAB utilizes a square-root nonlinearity to be similar to CIECAM97s for intermediate luminance levels. The square root nonlinearity is the origin of the $1/2\sigma$ exponent in the ZLAB equations (where σ is used to account for changes in surround relative luminance).

CIECAM97s is also designed to handle backgrounds of various luminance factor. Since the background in image reproduction applications is, at best, ill-defined, such capabilities are never utilized in these applications. (If they are, the predictions are often, if not usually, inaccurate.) Thus ZLAB is limited to medium gray backgrounds and cannot be used to predict changes of appearance with background. It is most similar to CIECAM97s when the background relative luminance is 0.20. For such a background, z=1.45 in the CIECAM97s model. This is the origin of the 1.45 in the exponent of the ZLAB lightness equation.

ZLAB uses a modified form of the CIELAB color space rather than the modified form of the Hunt 1994 color space used in the CIECAM97s model. This is essentially a direct result of the simplifications described above and is self-evident in the ZLAB equations.

The absolute appearance attributes of brightness and colorfulness were dropped from CIECAM97s in the formulation of ZLAB. This results in substantial simplification of the model. In most practical image reproduction applications, lightness, chroma, and hue are the appearance attributes of interest rather than brightness, colorfulness, and hue. Thus the lack of brightness and colorfulness predictors in ZLAB will seldom be a limiting factor. This minor limitation is overwhelmingly counterbalanced by the simplification of the formulation and implementation of the ZLAB model. The relative appearance attribute of saturation is included in the ZLAB model (it is sometimes found useful in gamut mapping algorithms).

4. ZLAB EQUATIONS

4.1 Input Data

The input data to the model are the luminance of the adapting field, L_A (taken to be 0.2 times the luminance of a reference white), the tristimulus values of the sample in the source conditions, XYZ, the tristimulus values of the source white in the source conditions, $X_wY_wZ_w$.

4.2 Chromatic Adaptation

As with CIECAM97s the Bradford chromatic adaptation transform is used to go from the source viewing conditions to corresponding colors under the reference (equal-energy illuminant) viewing conditions. First, all three sets of tristimulus values are normalized and transformed to sharpened cone responses using the Bradford transformation as given in Eqs. 1 and 2.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M} \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix} \quad (1)$$

$$\mathbf{M} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \quad (2)$$

The chromatic-adaptation transform is a modified von Kries transformation (performed on a type of chromaticity coordinates) with an exponential nonlinearity added to the short-wavelength sensitive channel as given in Eqs. 3 through 6. In addition, the variable D is used to specify the degree of adaptation. D is set to 1.0 for complete adaptation or discounting the illuminant. D is set to 0.0 for no adaptation. D is set to intermediate values for various degrees of incomplete chromatic adaptation. The D variable could be left as an empirical parameter, or calculated using Eq. 7, as in CIECAM97s, with F=1.0 for average surrounds and F=0.9 for dim or dark surrounds. If Eq. 7 is used, it is the only place absolute luminance is required in the ZLAB model.

$$R_c = \left[D\left(1.0/R_w\right) + 1 - D\right]R \quad (3)$$

$$G_c = \left[D\left(1.0/G_w\right) + 1 - D\right]G \quad (4)$$

$$B_c = \left[D\left(1.0/B_w^p\right) + 1 - D\right]|B|^p \quad (5)$$

$$p = \left(B_w / 1.0\right)^{0.0834} \qquad (6)$$

$$D = F - F/\left[1 + 2\left(L_A^{1/4}\right) + \left(L_A^2\right)/300\right] \qquad (7)$$

If B happens to be negative, then B_c is also set to be negative. R_c, G_c, and B_c represent the corresponding colors of the test stimulus under the reference condition (*i.e.*, illuminant E). The final step in the adaptation transform is to convert from the sharpened cone responses back to CIE XYZ tristimulus values for the reference condition as illustrated in Eq. 8.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \mathbf{M}^{-1} \begin{bmatrix} R_c Y \\ G_c Y \\ B_c Y \end{bmatrix} \qquad (8)$$

4.3. Appearance Correlates

Opponent responses are calculated using modified CIELAB-type equations with the power-function nonlinearity defined by the surround relative luminances. These were derived from a simplification of the CIECAM97s model by recalling that the hyperbolic nonlinear function in CIECAM97s can be approximated by a square-root function for intermediate luminances. Thus the opponent responses reduce to the forms given in Eqs. 9 and 10.

$$A = 500\left[\left(X_c/100\right)^{\frac{1}{2\sigma}} - \left(Y_c/100\right)^{\frac{1}{2\sigma}}\right] \qquad (9)$$

$$B = 200\left[\left(Y_c/100\right)^{\frac{1}{2\sigma}} - \left(Z_c/100\right)^{\frac{1}{2\sigma}}\right] \qquad (10)$$

The exponents are directly related to those used in CIECAM97s as illustrated in the following table. The values of $1/\sigma$ (called c) in CIECAM97s are modified to $1/2\sigma$ in ZLAB in order to incorporate the square-root approximation to the hyperbolic nonlinearity of CIECAM97s.

	Surround *Average*	 *Dim*	 *Dark*
$1/\sigma$	0.69	0.59	0.525
$1/2\sigma$	0.345	0.295	0.2625

Hue angle is calculated in the typical manner as illustrated in Eq. 11.

$$h^z = \tan^{-1}\left(\frac{B}{A}\right) \qquad (11)$$

Hue composition is also determined in the usual way via linear interpolation between the defined angles for the unique hues. These are h^z_r=25°, h^z_y=93°, h^z_g=165°, and h^z_b=254°.

ZLAB is only specified for a background of medium (20%) luminance factor. Thus the z parameter from the CIECAM97s model takes on a constant value of 1.45 and lightness, L^z, is expressed as shown in Eq. 12.

$$L^z = 100\left(Y_c/100\right)^{\frac{1.45}{2\sigma}} \qquad (12)$$

Chroma, C^z, is given by Eq. 13 as originally defined in the LLAB model to predict magnitude estimation data well. Saturation, s^z, is simply the ratio of chroma to lightness as illustrated in Eq. 14.

$$C^z = 25\log_e\left[1 + 0.05\left(A^2 + B^2\right)^{1/2}\right] \qquad (13)$$

$$s^z = C^z / L^z \qquad (14)$$

If rectangular coordinates are required for color space representations, they can easily be obtained from C^z and h^z using Eqs. 15 and 16.

$$a^z = C^z \cos(h^z) \qquad (15)$$

$$b^z = C^z \sin(h^z) \qquad (16)$$

5. PERFORMANCE

By design, the performance of ZLAB is very similar to that of CIECAM97s. Since the same chromatic adaptation transform is utilized, the two models make identical predictions of corresponding colors across changes in chromatic adaptation as long as the background and surround do not change. Predictions for changes in surround will be very similar, but not mathematically identical. ZLAB also performs well for scaling data since its derivation is based on a long lineage of models that incorporated fits to available scaling data. In image reproduction applications, it is expected (based on analysis of the model structure) that ZLAB would perform nearly as well as the best models in previous experiments (*i.e.*, it should perform similarly to the Hunt and LLAB models and nearly as well as RLAB).

Hunt presented the results of a variety of model tests to CIE TC1-34. These included tests of the accuracy of corresponding colors predictions for a set of seven different experiments and an analysis of the accuracy of appearance scale predictions from the collected set of LUTCHI data.

The accuracy of corresponding colors predictions can be analyzed using an average color difference metric (between the observed and predicted results). Hunt chose the CMC(1:1) color difference metric. For the seven data sets analyzed, CIECAM97s had a mean error of 4.2 CMC(1:1) units, ZLAB also produced an error of 4.2 CMC(1:1) units, and the estimated observer variability was on the order of 4 CMC(1:1) units. The equality of the predictions of the two models is precisely as expected since they utilize the same chromatic adaptation transform. For some perspective, consider that a simple von Kries transform results in average error of 5.6 CMC(1:1) units and the CIELAB transform results in an average error of 5.7 CMC(1:1) units.

For the LUTCHI data, Hunt analyzed the coefficients of variation (CV, essentially the percent standard deviation) between the predicted and observed results for scaling of lightness, colorfulness, and hue on a gray background. For lightness, colorfulness, and hue respectively:

- CIECAM97s produced values of 11.8, 17.6, 7.0;
- ZLAB produced values of 11.4, 21.1, 7.3; and
- observer variability was 13, 18, 8.

Both models perform better than observer variability for lightness and hue. CIECAM97s performs better than ZLAB for the prediction of colorfulness, but this is not surprising since CIECAM97s includes a predictor of colorfulness, and a scaled version of ZLAB chroma must be used for comparison. For intermediate luminance levels, it is expected that the difference between the two models will be reduced, if not eliminated.

An extensive series of experiments (see [2]) has been completed to test various models for cross-media image reproduction. Unfortunately these experiments were completed to test existing models and the results cannot be used to test the performance of models formulated after the experiments were completed. In general, the RLAB model has been shown to produce the best results. While the structure of RLAB and ZLAB do differ markedly in some aspects, their predictions are similar for a variety of typical imaging situations and it is expected that ZLAB would perform nearly as well (if not equally well) as RLAB in these situations.

6. LIMITATIONS

The ZLAB model has several limitations when compared to the CIECAM97s model. These include:

- no prediction of background changes;
- no brightness or colorfulness;
- limitation to intermediate luminance levels;
- not easily extensible to predict everything; and
- not CIE adopted.

While these limitations are very real, they result in tradeoffs that produce a much simpler model and the limitations are generally not of practical significance. As mentioned earlier, their is no straightforward and practical method for incorporating changes in background into image reproduction procedures. Brightness and colorfulness either cannot, or should not, be reproduced in most situations. (Additionally, the data necessary for accurate brightness and colorfulness predictions are generally not available. Reasonable assumptions about the reproduction situation will not adversely impact lightness and chroma reproduction.)

Limitation to intermediate luminance levels essentially means that the ZLAB model is limited to normal photopic vision. It cannot be applied to low luminance levels near the threshold of color vision or high luminance levels at which photoreceptor saturation becomes important. Image reproductions generally will not, and should not, be viewed under such extreme luminance levels.

The fact that the ZLAB model can not be easily extended to include wide luminance ranges, rod input, brightness, colorfulness, *etc.* is one of the main reasons it was not adopted by TC1-34. This shortcoming will likely not be of significance in practical applications.

The fact that ZLAB is not a CIE adopted model is only a limitation when communication using an internationally recognized “standard” is required. However, it should be noted that corresponding colors predictions for changes in chromatic adaptation made using the ZLAB model will be equal to those made using CIECAM97s.

7. ADVANTAGES

The ZLAB model has several advantages over CIECAM97s that warrant its consideration for some practical applications. These include:

- good performance;
- simplicity;
- inversion procedure;

•not a compromise; and

•probable sufficiency.

The performance of ZLAB as a color appearance model is as good as CIECAM97s for chromatic adaptation changes and nearly as good for scaling data. It will perform as well as CIECAM97s in nearly all practical image reproduction applications. Since the ZLAB model uses the same Bradford chromatic adaptation transformation as CIECAM97s, ZLAB can be considered “CIECAM97s compatible” for changes in chromatic adaptation.

The simplicity of the ZLAB model is self evident. There is no reason to utilize a more complex model unless its predictions are significantly superior. The following table provides a few measures of the simplicity of the model.

Model	*Number of Equaitons.*	*Lines of Excel Code*	*Lines of IDL Code*
CIECAM97s	26	66	105
ZLAB	13	35	42
Percent Fewer	50%	53%	40%

As illustrated in the table, ZLAB requires 50% of the equations to express, 53% of the lines to implement in a Microsoft Excel® spreadsheet, and 40% of the lines to implement in IDL® code when compared with the CIECAM97s model. These economies translate directly into savings in time to implement and execute the model.

The ZLAB model can be inverted (a necessity for image reproduction) in a very straightforward manner. The CIECAM97s model is invertible, but the technique is neither simple nor self evident and requires a slight approximation at one stage. This again, will result in significant savings when implementing and executing the ZLAB model.

Of the available choices, CIECAM97s was the only model that the entire membership of TC1-34 could agree upon to adopt. While this is an outstanding accomplishment in its own right, the various members of the committee each had different reasons for believing that the model was acceptable. All of the committee members were not focused on image reproduction applications. Thus, the CIECAM97s is, necessarily, a committee compromise. ZLAB, on the other hand, was formulated specifically with image reproduction applications in mind since the imaging industry was the only one putting pressure on TC1-34 to adopt a model.

The final advantage of the ZLAB model is that, despite its simplicity, it is probably completely sufficient for most applications. Particularly those revolving around the implementation of color management systems using ICC profiles. To date, there is no experimental evidence to suggest otherwise. Of course, this point cannot be completely proven either.

8. RECOMMENDATIONS

Color appearance models will remain a topic of active research and advancement for some time to come. In the interim, several practical recommendations can be made as outlined below in a hierarchy of increasing application complexity.

(1) If possible, the best solution is to make the viewing conditions for original and reproduction identical and thus avoid the use of color appearance models altogether. In such situations CIE XYZ tristimulus values are sufficient.

(2) If changes in white point, or color difference metrics, are required, then the CIELAB color space can be used as a reasonable approximation to a color appearance model.

(3) If CIELAB is inadequate, then simple color appearance models such as RLAB or ZLAB should be considered. These will be particularly helpful when predictions of incomplete chromatic adaptation or changes in image contrast with changes in surround relative luminance are required.

(4) If, in addition, predictors of the absolute appearance attributes of brightness and colorfulness are required, then the CIECAM97s model should be used. One application in which this could be the case might be the description of image quality or color gamut volume for projection displays.

(5) Finally, if effects such as the contribution of rods to color appearance or the variation of appearance across huge changes in adapting luminance must be predicted, then a comprehensive color appearance model such as the forthcoming CIECAM97c or the Hunt 1994 model should be used.

9. FUTURE DIRECTIONS

The prediction of color appearance phenomena with models that treat color stimuli in a point-wise manner with limited parameters for the surround and background is probably reaching fundamental limits. It appears that real advances might be made by combining research in human vision, image quality modeling, and color appearance modeling to produce a model that incorporates spatial, as well as chromatic, signal processing. The promise of such models is that by incorporating the complexity of human visual adaptation into the spatial aspects of the model, predictors of the necessary color appearance attributes might fall out of the model with very simple expressions. It is hoped that research along these lines will produce the next significant advancement in color appearance modeling.

REFERENCES

[1] R.W.G. Hunt and M.R. Luo, *The Structure of the CIECAM97 Colour Appearance Model (CIECAM97s)*, **CIE Expert Symposium '97, Colour Standards for Imaging Technology,** Scottsdale, (1997).

[2] M.D. Fairchild, **Color Appearance Models**, Addison Wesley, Reading, Mass. (1998).

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