Chromatic adaptation in colour management

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Abstract. Chromatic adaptation transforms are used to predict corresponding colours viewed under a different adapting illuminant. In colour management it is often necessary to apply such a transform in order to achieve a corresponding-colour match on a reproduction medium. A linear version of the Bradford CAT has been standardized for this purpose, due to its advantages of computational simplicity and invertibility. Despite being in use in colour management since 2001 the performance of this linear Bradford transform has had limited evaluation. In this paper it is tested for the first time on a comprehensive corresponding-colour data set, and it is shown that the performance is not significantly different from the original Bradford transform, and is a little better than the more recent CAT16 transform. Other issues related to the use of chromatic adaptation in colour management workflows are also discussed.

Keywords: Chromatic adaptation, colour management, ICC.

1 Introduction

Colour management is the set of procedures that are used to achieve a colour reproduction goal on an output system or encoding, given a data source from a different system or encoding – or, as described by the International Color Consortium (ICC), to "make colour seamless between device and documents" [1].

In colour management, rather than create a transform to connect every pair of data encodings, the resulting potential combinatorial explosion is avoided by connecting each encoding to a reference intermediate colour space based on the appearance of the colour under specified observing conditions. In the widely used ICC v2 [2] and v4 [3] specifications for colour profiles (collectively known as ICC.1), this is known as the Profile Connection Space (PCS). The PCS is defined as CIE colorimetry based on a D50 illuminant and the CIE 1931 Standard Colorimetric Observer, and can be considered primarily as an exchange space rather than a source or destination colour space.

Since the source and destination encoding are usually different, the match made between source and destination is not exact colorimetry but corresponding colour [4]. The set of procedures required to give acceptable results will include adjustments for the actual viewing conditions and the colour gamuts of the source and destination encoding. Of interest in the present paper is the procedures adopted when source and destination encodings have different white points for either or both of the media and adopted white point. Having a fixed PCS requires that the connection to or from the

PCS includes chromatic adaptation into the fixed observing conditions of the PCS. Experience has also shown that acceptable matches require that the media white of the source be matched to the media white of the destination by default, while the somewhat rarer case that D50 colorimetry is matched regardless of any differences in the media white points (resulting in either dark or clipped white points in the reproduction) is also supported. In ICC colour management, this is the case for the Media-Relative Colorimetric and ICC-Absolute Colorimetric rendering intents respectively. (The Perceptual intents are also based on media-relative colorimetry but some additional procedures are required to map PCS colours into a reference gamut.)

In order to consistently achieve a good corresponding-colour match when source and destination illuminants are different, a number of requirements are imposed on the chromatic adaptation transform in use in colour management. First, it should give a good prediction of the corresponding colour as seen by an observer with normal colour vision. Second, it should give the same results when transforming in two stages via the PCS as when transforming directly from source to destination illuminant. Finally, it should be readily invertible so that a round trip transform from source to PCS and back to source results in the same values within the usual limits of precision. The purpose of this paper is to evaluate the current solutions in the light of these criteria.

2 Chromatic adaptation

A chromatic adaptation transform predicts corresponding colours by transforming XYZ colorimetry into cone space, performing the adaptation by applying ratios of cone excitations for the source and destination illuminant, and converting back to XYZ. Many of the elements in this process are linear matrix operations which can be concatenated. Below we outline the particular forms of chromatic adaptation transform considered in this paper.

2.1 The linear Bradford CAT

The ICC v4 specification [3] recommends a particular CAT, which is based on the Bradford CAT [5] but where the non-linear exponent has been eliminated. A linear CAT has a number of major advantages: for a given combination of source and destination illuminant it can be applied directly to XYZ PCS data as a 3x3 matrix, making it computationally efficient. The matrix is also analytically invertible, which permits data to be converted in both forward and inverse transforms without accumulating errors. These are both important considerations in colour management.

The linear Bradford transform is described in Annex E of the v4 ICC specification, with a recommendation to use it in almost all cases, using alternatives “only to address specific known issues, recognizing that the resulting profile will most likely produce different results than profiles from other sources.” [3] Where alternative CATs are used, there may be a loss of interoperability with profiles that use the linear Bradford transform.

The linear Bradford transform was introduced in a proposal approved by ballot of ICC members [6] in 2000. The proposal was included in the v4 ICC profile specification from 2001 onwards. In this workflow, all colorimetry is chromatically adapted to the D50 PCS, and the 3x3 matrix used to perform the adaptation is stored in the profile as a ‘chad’ tag. Five cases can be then considered in a colour managed workflow:

1. No transform. The colorimetry in a profile is already D50, in which case the ‘chad’ matrix is identity and no conversion is required.
2. A non-D50 illuminant in source or destination. A corresponding-colour match to or from the ICC PCS is required and is provided by the CAT. By inverting the ‘chad’ matrix in the profile, the tristimulus values of the non-D50 white point and the untransformed data can be obtained if required.
3. A non-D50 illuminant in both source and destination. The source and destination colorimetry are the same, but different from D50. In this case the inverse CAT (PCS to destination) transform is the inverse of the forward CAT (source to PCS), and the step of converting to intermediate PCS colorimetry has no effect on the final output.
4. Different non-D50 illuminants in source and destination. Both source and destination colorimetry are different from each other and from the ICC PCS. This case is similar to the two-step method of converting via a daylight reference illuminant recommended by Li et al [8]. The linear conversion to and from an intermediate illuminant cancel each other out when the degree of adaptation set to 1, so that the two-step method implied in an ICC workflow gives identical results to converting directly from source to destination using the linear Bradford transform.
5. Undefined. The colorimetry in a profile is not D50 and no ‘chad’ tag is present. In this case the meaning of the data in the PCS is unknown. This situation is permitted in v2 profiles, but in a v4 profile would render the profile invalid. The removal of this ambiguity is a primary reason for recommending the v4 profile format.

The linear Bradford transform was reviewed by Finlayson and Süsstrunk [7], who evaluated it on a limited data set, but some questions remain unanswered:

- How well does linear Bradford perform in predicting corresponding colours across a broader range of test data?
- Should linear Bradford be replaced by a more recent transform such as CAT16?
- How significant is the difference between the predictions of linear Bradford and those of other CATs?

Some other issues relating to the appropriate use of chromatic adaptation in a colour management workflow are also discussed in this paper.

2.2 CAT16

The CAT16 transform was proposed by Li et al [8], partly to avoid the widely-acknowledged computational problems with the CAT02 transform used in CIECAM02. CAT16 was derived by replacing, the matrices M_{02} and M_{HPE} by a single matrix M_{16}, derived by optimization on a combined corresponding-colour data set, as shown in eqns 1-3.

$$M_{16} = \begin{matrix} 0.401288 & 0.650173 & -0.051461 \\ -0.250268 & 1.204414 & 0.045854 \\ -0.002079 & 0.048952 & 0.953127 \end{matrix} \quad (1)$$

The CAT16 transform is then represented by:

$$\Phi_{r,t} = M_{16}^{-1}\Lambda_{r,t}M_{16} \quad (2)$$

where $\Lambda_{r,t}$ is the diagonal adaptation matrix, and when the luminance of the test and reference illuminants match is given by:

$$\Lambda_{r,t} = \begin{pmatrix} D\frac{R_{wr}}{R_w} + 1 - D & 0 & 0 \\ 0 & D\frac{G_{wr}}{G_w} + 1 - D & 0 \\ 0 & 0 & D\frac{B_{wr}}{B_w} + 1 - D \end{pmatrix} \quad (3)$$

where $[R_w, G_w, B_w]$ and $[R_{wr}, G_{wr}, B_{wr}]$ are the results of applying M_{16} to the XYZ values of the test (source) and reference (destination) illuminant respectively, and D is the degree of adaptation. D is computed as in CAT02 and CIECAM02, and when adaptation is not complete (D<1) the transform is not transitive and it is recommended that a two-step transform is applied – first to a reference, daylight illuminant, and secondly to a final destination illuminant using the inverse of eqn 2 [8].

The simplified structure of CAT16 (when compared with other CATs such as Bradford or CAT02) has the effect that for a given test and reference illuminant $\Phi_{r,t}$ is a 3x3 matrix and its implementation within an ICC profile would have the same form as linear Bradford. Conversion from source to destination via the ICC PCS is a two-step transform with D50 as the reference illuminant, thus satisfying the above recommendation.

CAT16 has been shown to perform well in predicting corresponding-colour data [8], and a summary of its performance in comparison with the Bradford transform is included in Table 1 below.

2.3 Degree of adaptation

The degree of observer adaptation to an adapting illuminant has been widely studied, e.g. [9, 10]. Full adaptation only takes place when the adapting illuminant is close to daylight and/or the Plankian locus for the black body radiator [11], and in a real viewing environment is likely that there are multiple potential sources of adaptation. Many colour appearance models and CAT transforms include a factor for the degree of adaptation to the test illuminant. It has also been found that for printed surface colours there is a degree of adaptation to the colorimetry of the substrate [12-15].

Matching colours using an assumption of partial adaptation can give good results [13-14], but are outside the scope of this paper. One difficulty in implementing a partial adaptation is that an estimated partially-adapted white point may be outside the gamut of the reproduction medium.

In the linear Bradford transform there is no parameter for the degree of adaptation and hence full adaptation to the destination illuminant is assumed. In the ICC v4 it is in effect assumed that the observer is fully adapted to the display white for emissive colours, and to the perfect diffuse reflector for surface colours.

2.4 Media-relative colorimetry

Scaling to media-relative colorimetry has been used for many years in ICC colour management with considerable success, since it meets the most common user requirement of matching media white points. In ICC-Absolute colorimetry, the PCS white point is a perfect diffuse reflector viewed under a D50 illuminant, with CIELAB values of [100,0,0]. In media-relative colorimetry, the PCS white point is also [100,0,0], but to match this the X, Y and Z components are scaled by eqn 4 [3].

$$\begin{aligned} X_r &= \frac{X_{D50}}{X_{MW}} X_a \\ Y_r &= \frac{Y_{D50}}{Y_{MW}} Y_a \\ Z_r &= \frac{Z_{D50}}{Z_{MW}} Z_a \end{aligned} \tag{4}$$

where X_r, Y_r, Z_r are the media-relative XYZ values, X_{D50}, Y_{D50} and Z_{D50} are the colorimetry of the D50 illuminant, X_{MW}, Y_{MW} and Z_{MW} are the measured XYZ values of the media white point (chromatically adapted to D50) and X_a, Y_a and Z_a are the measured XYZ values of the stimulus after chromatic adaptation to D50.

Because eqn 4 has the same form as what is known as a ‘wrong von Kries’ transform, it is sometimes assumed that media-relative scaling is a kind of chromatic adaptation. It is important to understand that media-relative scaling is applied solely to data that is already chromatically adapted to D50, and that the operation is simply a linear scaling to ensure that it is possible to connect source and destination white points. Because the ratio of X, Y and Z components may be altered by media-relative scaling, there can be a change in chromaticity which can become evident if the source and destination media white points are significantly different.

The XYZ values of the media white point, chromatically adapted to D50, are stored in the profile in the mediaWhitePointTag [3]. This allows the CMM to compute ICC-absolute colorimetric values from media-relative values when required by undoing the scaling in eqn 4.

In the ICC v2 specification the PCS is D50 but requirement to chromatically adapt all data to the PCS is less clearly expressed. If the data is not chromatically adapted, the media-relative scaling is then also performing a ‘wrong von Kries’ adaptation with potential for inconsistent results, especially when the media white point tag stored in the profile is not adapted to D50.

3 Evaluating chromatic adaptation transforms

Three criteria for chromatic adaptation transforms used in colour management workflows were outlined in section 1 above. As shown in section 2, the criteria of invertibility and of equivalence between a one-step transform and a transform via the PCS are satisfied by the use of a single 3x3 matrix to convert to and from the PCS. The remaining criterion, of good prediction of corresponding colour, is reviewed below.

Since a chromatic adaptation transform predicts the change in appearance of a given stimulus when the adapting illuminant changes, there is no corresponding measurement and the transform can only be evaluated by comparing its predictions with data obtained through psychophysical experiments. It is acknowledged that such visual data will always be intrinsically noisy, and so deriving a good CAT requires attention to the principles and objectives of a corresponding colour transform rather than solely fitting to minimize the errors in a data set.

Finlayson and Süsstrunk [7] compared the performance of linear Bradford in predicting the corresponding-colour data set of Lam and Rigg [5] used in deriving the Bradford transform, with that of the original Bradford transform and a ‘sharp’ version, derived by optimizing the transform matrix to minimize the RMS error in XYZ between the corresponding-colour sample pairs for D65 and Illuminant A. It was found that the original Bradford performed better than either the sharp transform or linear Bradford, but the differences were not statistically significant.

The Lam and Rigg data comprises 58 sample pairs. A more comprehensive data set, based on 21 corresponding-colour experimental data sets with a total of 584 sample pairs (and including the Lam and Rigg data), was accumulated by Li et al [8] to evaluate the new CAT16 transform. We used this data set to compare the performance of Bradford, linear Bradford and CAT16, and the results are shown in Table 1. Where a degree of adaptation factor, *D*, is present in the transform, it was set to 1, assuming complete adaptation. (This gave slightly better results for CAT16 than calculating *D* according to [8] with parameters for ‘average’ viewing condition.) The median error provides the best estimate of central tendency for data that is not normally distributed, and the maximum is included since in colour management workflows this can sometimes be of greater importance than the central tendency.

Table 1 Performance of Bradford, linear Bradford and CAT16 chromatic adaptation transforms in estimating corresponding-colour data on 584 sample pairs

	Bradford		Linear Bradford		CAT16	
	ΔE^*_{ab}	ΔE_{2000}	ΔE^*_{ab}	ΔE_{2000}	ΔE^*_{ab}	ΔE_{2000}
Median	5.52	3.42	5.55	3.49	6.04	3.78
Max	34.55	17.13	35.03	17.17	44.78	18.82

It can be seen from Table 3 that the linear Bradford transform performs only slightly less well than the original Bradford, which suggests there is no advantage in using the greater complexity of the original Bradford transform to predict corresponding colours in a colour management workflow. CAT16 performs a little worse than both linear Bradford and the original Bradford transform.

Of the different data sets included in the test, only one (Lutchi D65 to D50) is directly relevant to the use case of converting to or from the ICC PCS, and it is interesting to note that in this case linear Bradford actually performs best. However, this single data set is too small (44 sample pairs) to draw conclusions from.

To determine the statistical significance of the differences between the predictions of the different CATs, a two-tailed Student's t-test was performed on paired samples in X, Y and Z, between the predictions of the different CATs and between the CATs and the perceptual data accumulated by Li et al [8]. Table 2 shows the resulting p values indicating the probability that the data are significantly different, where $p<0.05$ indicates a significant difference at the 95% level.

Table 2 Results of the Student's t-test comparing the significance of differences between predictions of the CATs for 584 sample pairs in the corresponding-colour data set (CCD) [8]

	X	Y	Z
Bradford-Linear Bradford	0.29152	0.23225	0
Linear Bradford – CAT16	0	0	0
Bradford – CAT16	0	0	0
CCD-Bradford	0.00022	0.62246	0
CCD-Linear Bradford	0.00027	0.61030	0
CCD-CAT16	0	0.00002	0

The results show that the corresponding colours predicted by all the CATs differ significantly from each other and from the perceptual data, with the following exceptions: Bradford and Linear Bradford only differ in the prediction of Z, and both Bradford transforms predict Y values that do not differ significantly from the perceptual data.

4 Material equivalence

In this section we review the role of material equivalence transforms in colour management and summarise previous results comparing such transforms with chromatic adaptation transforms.

In a corresponding-colour transform, a source stimulus viewed under one adapting condition is transformed to a different stimulus which visually matches the original source stimulus when the observer is adapted to a different viewing condition. In colour management, a chromatic adaptation transform is always required when the colorimetry of source or destination is not D50.

However, in certain cases the source colour is a reflectance whose colorimetry has simply been computed using a different illuminant from the PCS illuminant, and there is no source viewing condition to consider. In this case the intended viewing condition is represented by the destination illuminant, not by the illuminant actually used to calculate the colorimetry, and the correct procedure would be compute the colorimetry from the reflectance using the destination illuminant (if using an ICC profile the destination illuminant will be D50). In the absence of the 'correct' colorimetry or the spectral reflectance from which to compute it, it is appropriate to make the best estimate which is equivalent to the original reflectance computed using the D50 illuminant. Material equivalence has been discussed in a number of papers including [16-18].

Derhak proposed an intermediate color equivalency representation, Waypoint that is an estimate of the material color is used. Waypoint Wpt coordinates are obtained using normalization matrices (*T*), where matrix T_1 transforms tristimulus values (C_{src}) under the source observer function and source illuminant to its equivalent Wpt representation and similarly, matrix T_2 is a Wpt normalization matrix to the destination conditions.

Similarly to a CAT, the Wpt based MAT is then used to transform C_{src} to destination tristimulus values (C_{dest}) and is then given by:

$$\mathrm{C}_{dest} = T_2^{-1} T C_{src} \tag{4}$$

Derhak et al [18] compared the performance of four different transforms in predicting the colorimetry under one illuminant given the colorimetry under a different illuminant. D65, D50, F11 and A were used as the reference and test illuminants, with all pairs of these as reference and test evaluated. The results showed that the Waypoint material adjustment transform (Wpt MAT), originally trained on Munsell reflectances [15], gave the best overall performance in predicting the colorimetry of both the Munsell data and the in-situ natural reflectances provided in ISO 17321, while for certain illuminant pairs linear Bradford gave a slightly better performance in predicting the colorimetry of the ISO 17321 data. The overall results of Derhak et al [18] for linear Bradford, Waypoint MAT and CAT16 are summarized in Table 3.

Table 3. Performance of linear Bradford, Waypoint MAT and CAT16 in predicting material equivalence for combinations of D65, D50, F11 and A as reference and test illuminants

Data set	Transform	Mean error
Munsell reflectances	CAT16	3.86
	Linear Bradford	3.02
	Wpt MAT	1.58
ISO 17321 in-situ reflectances	CAT16	5.78
	Linear Bradford	5.25
	Wpt MAT	5.00

It is interesting to note that linear Bradford has a similar performance to Waypoint MAT in predicting a test data set different from the training set. Although a material adjustment transform is not intended to produce the same results as a chromatic adaptation transform, the results in Derhak et al suggest that linear Bradford could reasonably be used for both purposes.

A MAT transform would fall into the category of a 'reason to use a different CAT' [3] and its output could validly be encoded in a v4 profile in place of linear Bradford for situations where a material equivalent representation is desired. Alternatively, a MAT transform can be encoded in an ICC.2 (iccMAX) profile [19] and used to convert source data to either the D50 PCS or to a custom PCS as required. We suggest that a MAT could be determined that was optimal for a wider set of training data, and also that a custom MAT could be computed that was optimal for a particular class of colour data (such as specific printing conditions or display types).

5 iccMAX

ICC has adopted a next-generation colour management architecture, known as iccMAX, which has been standardized as ICC.2 [19] and ISO 20677 [20]. A goal of iccMAX is to permit "greater flexibility for defining colour transforms and profile connection spaces" by allowing "PCS transform results to be relative to arbitrary illuminants and observers" [19], while also continuing to achieve unambiguous transform results. This is achieved by removing the requirement to use D50 for all PCS data; instead, the spectralViewingConditionsTag can used to encode the colorimetric observer and the illuminant which constitute the PCS of the profile. A customToStandardPCS transform ('c2sp') (and its inverse, standardToCustomPCS or 's2cp') is required to be present when the PCS of the profile is not D50, in order to support cases where the PCS of the profile does not match the PCS of the profile to be connected to.

iccMAX also supports spectral source and destination data and a spectral PCS. Thus it is possible, for example, to have a spectral source data encoding (reflectance, transmittance or bi-directional reflectance) and transform it to a colorimetric PCS using any colorimetric observer and/illuminant [18]. The greater flexibility of transform encodings in iccMAX make it possible to implement a chromatic adaptation transform or even a full colour appearance model within the profile if required. The choice of spectralViewingConditionsTag can also be deferred to run-time, so that the user can select the colorimetric PCS required for a particular workflow without having a proliferation of profiles.

Thus in ICC.2 it is possible to achieve the same results as in a profile created according to the v4 specification, but additionally non-D50 illuminants, spectral data, custom observers, alternative CATs, MATs and colour appearance models can all be supported. To ensure that transforms using profiles built according to the new architecture are unambiguous, ICC recommends that Interoperability Conformance Specifications are defined for ICC.2 workflows [19].

6 Conclusions

Current solutions for chromatic adaptation in colour management have been evaluated using a comprehensive corresponding-colour data set. The linear Bradford transform used in ICC colour management performs reasonably well, and also has a number of advantages that make it suitable for use in ICC v4 colour management: notably its computational simplicity, its analytic invertibility and its ability to transform colours into and out of the ICC PCS with no loss in accuracy.

Two main cases have been identified in the present paper where an alternative to linear Bradford may be preferred. The first is where a state-of-the art CAT with best performance on corresponding colour data sets is required. Although CAT16 avoids the computational problems of CAT02, it does not perform better than linear Bradford, and there is no compelling reason to use it in preference. The second case is where a material equivalence transform is needed in order to predict the colorimetry under a different illuminant, rather than corresponding colour appearance. In this case Waypoint MAT may give a better performance, although it is possible that it could be optimized further for particular types of reflectance or emission. However, linear Bradford can continue to be used with confidence for most colour management applications, and it is not proposed here that it should be superseded for ICC v4.

For cross-media colour reproduction workflows with more advanced requirements that go beyond the D50 colorimetric PCS, the ICC.2 architecture provides a range of potential solution. These include the use of different CATs as well as MATs and colour appearance transforms.

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