Is the Sharp Adaptation Transform more plausible than CMCCAT2000?

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Abstract

The modified Bradford chromatic adaptation transform (CMCCAT2000) is a von Kries type model of adaptation that best accounts for a variety of corresponding colour data sets. The transform works in three stages. First, XYZs are linearly mapped to a new 'RGB' space. The RGB sensitivities are somewhat like the cones but have their sensitivity concentrated in narrower regions of the visible spectrum. In the second stage of the transform, the Red, Green and Blue responses are multiplied by three scalars to model illuminant change. Finally, RGBs are transformed back to XYZs (in order that well established formulae for colour appearance might be used). The Sharp adaptation transform (SAT), derived from theoretical arguments, is exactly the same as CMCCAT2000 except that the sharp RGB sensor sensitivities have even narrower support. Research has shown that the SAT delivers, statistically, the same performance as CMCCAT2000.

In this paper we consider whether there is any reason why CMCCAT2000 or SAT might be preferable if adaptation is considered from an observers viewpoint. Our argument builds on the premise that an observer in making a corresponding colour match is matching surface reflectance. Starting with this premise the adaptation problem is clearly ill-posed: a pair of different surface reflectances might look the same under one light but different under another (this is the metamerism problem). However, we argue that an observer understands this metamerism and so seeks only to make a plausible reflectance match. Let us suppose a reflectance B viewed under a target light is chosen to match reflectance A viewed under a reference light. We say B is plausible if and only if it is possible that if B is also viewed under the reference light it is identical to A. Adopting this definition of plausibility, we found that the Sharp Adaptation Transform supports plausible adaptation but that CMCCAT2000 supports implausible adaptation.

1. Introduction

Colour measurements depend strongly on the colour of the illuminant: XYZs for the same surface measured under two lights are quite different. Yet, perceived surface colours are fairly stable across illumination. To understand how colours appear under different lighting conditions a variety of corresponding colour experiments have been carried out (e.g. see [1, 2, 3]). Typically an observer views a surface under a reference light and a variety of surfaces under a second target light. The aim of the experiment is to find a surface that when viewed under the target light looks as if it has the same colour as the surface viewed under the reference light. The observer in a corresponding colour experiment might realistically be performing one of two tasks. First, the surface colours viewed under the target light might be interpreted simply as colours in a palette. There is no need for the observer to associate the reflectances as having a relationship to the reflectance viewed under the first light. Alternately, the observer task might be interpreted as finding the same surface reflectance. There are two reasons which strongly support the second interpretation. In corresponding colour experiments, the same physical samples are used for reference stimuli and for test matches and this fact is known to the observers. Second, the idea of making physical matches has been found to be important in asymmetric matching experiments[4] (if the idea of a physical match is not made then observers have poor colour constancy: surface colours would be highly unstable across viewing conditions). Henceforth, we assume that observers are thinking about and matching surfaces. This assumption is at the heart of our arguments concerning plausible adaptation.

Chromatic adaptation transforms attempt to model how observers make corresponding colour matches. To see how one might proceed, we begin by measuring the XYZ of a surface viewed by an observer under a reference light. We now change the colour of the light and ask an observer to select a surface (from a set of possible matches) that most looks like the colour seen under the reference conditions. The XYZ for the matching surface is measured. This experiment is repeated for many different surfaces. The result is the set of corresponding colour measurements: the XYZs that induce similar colour precepts across an illumination change. We might now solve for a mapping which best maps reference XYZs to those observed under the second target light. This map can then be applied to all reference XYZs (even those not in the original experimental sets) to predict the corresponding colours under the target light.

The form of the mapping is important. It is not practical to carry out the above experiment for all pairs of possible lights. Rather it is desirable to design a mapping which can be parameterized by measurements of the reference of target and reference lights. If (X_r, Y_r, Z_r) is the measurement of a surface under a reference light and (X_{rw}, Y_{rw}, Z_{rw}) and (X_{tw}, Y_{tw}, Z_{tw}) the XYZs of perfect white diffusers seen under the reference and target lights, then von Kries adaptation predicts that the corresponding colour under the target colour is equal to:

$$\begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix} = \begin{bmatrix} X_{tw}/X_{rw} & 0 & 0 \\ 0 & Y_{tw}/Y_{rw} & 0 \\ 0 & 0 & Z_{tw}/Z_{rw} \end{bmatrix} \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} \tag{1}$$

The intuition behind (1) is that the effect of the illuminant can be removed (or adapted to) through the application of three simple scalars e.g to make the illuminant redder we need only increase the X values relative to the Y and Z values. Furthermore, the scalars themselves are the ratios of the XYZ measurements for a white patch viewed under the two lights: if white looks right across illuminants then so should the other surfaces (or so the reasoning goes).

Unfortunately, Equation (1) does not do a good job of predicting corresponding colour. Yet (1) is admirable for its simplicity: the transform relies on two simple measurements of white under the two lights. Researchers have sought ways to improve on the accuracy afforded by (1) without losing the intrinsic simplicity. The CMCCAT2000[5] adaptation transform is identical to (1) except that measurements are transformed to an RGB space prior to the application of the adaptation diagonal matrix. The transform used is derived from an optimization of corresponding colour data. Mathematically, we can write CMCCAT2000 as:

$$\underline{x}^t = [\mathcal{T}^c]^{-1}\mathcal{D}^{tr,c}\mathcal{T}^c\underline{x}^r \tag{2}$$

where $\underline{x}^r$ and $\underline{x}^t$ are the XYZs of the reference and target measurements written in vector form (throughout this paper underscoring denotes vector quantities). The 3×3 matrix $\mathcal{T}^c$ maps XYZs to CMCCAT2000 RGB space. The diagonal matrix $\mathcal{D}^{tr,c}$ is the ratio of the RGB white points of the reference and target lights (if $\underline{R}^{rw} = \mathcal{T}^c\underline{X}^{rw}$ and $\underline{R}^{tw} = \mathcal{T}^c\underline{X}^{tw}$ then $\mathcal{D}^{tr,c}_{ii} = R^{tw}_i/R^{rw}_i$ $(i = 1, 2, 3)$).

While the CMCCAT2000 transform does indeed best fit corresponding colour data, it does not, in a statistical sense, do so uniquely. Indeed, the Sharp adaptation[6, 7] transform (or SAT) has recently been shown to, statistically, perform equally well. The sharp transform is defined as:

$$\underline{x}^t = [\mathcal{T}^s]^{-1}\mathcal{D}^{tr,s}\mathcal{T}^s\underline{x}^r \tag{3}$$

All that has changed is we now use the linear transform $\mathcal{T}^s$ to take XYZs to RGBs. To visualize the difference between the CMCCAT2000 and Sharp transforms we can plot corresponding sensitivity profiles (since applying a linear transform to XYZs is the same as applying it to the XYZ matching functions). The XYZ, CMCCAT2000 and Sharp sensors are shown in Figure 1.

It is clear that CMCCAT2000 and Sharp are fairly similar except that the Red sensitivity of the sharp sensor is significantly narrower than that for CMCCAT2000. Interestingly, sharp sensors were (initially) designed independent of knowledge of corresponding colours. Rather, adaptation was examined from an engineering perspective. Given *physical measurements*, in what colour space does von Kries adaptation best account for an illumination change? It has been shown[8] that if there existed a linear combination of XYZs that resulted in truly narrow band sensitivities (sensors responsive to a single wavelength of light) then von Kries adaptation would be perfect. The sharp transform, in some sense, is the best approximation to this circumstance. As such the sharp transform also serves as an explanation of the shape of the CMCCAT2000 sensors which are also quite sharp. Though, it should be pointed out that sharp sensors are also derivable starting from the statistics of XYZs[6, 9].

Of course it is unsatisfactory to find that two different transforms perform equally well. We would prefer to make a recommendation of a single transform to use. In this paper we look to our own visual system to see if there might be be reasons for choosing one transform over the other. We consider adaptation from an observers viewpoint. More specifically, in making a corresponding colour match we propose that an observer is attempting to find the same reflectance under the second light as they have seen under the first. Of course a little thought convinces us that the observer cannot succeed in this task problem. Two surfaces that look the same under one light may look different under another: metamerism is a real phenomenon. Confronted with two different colours the observer will, perforce, select two distinct surface reflectances as match-

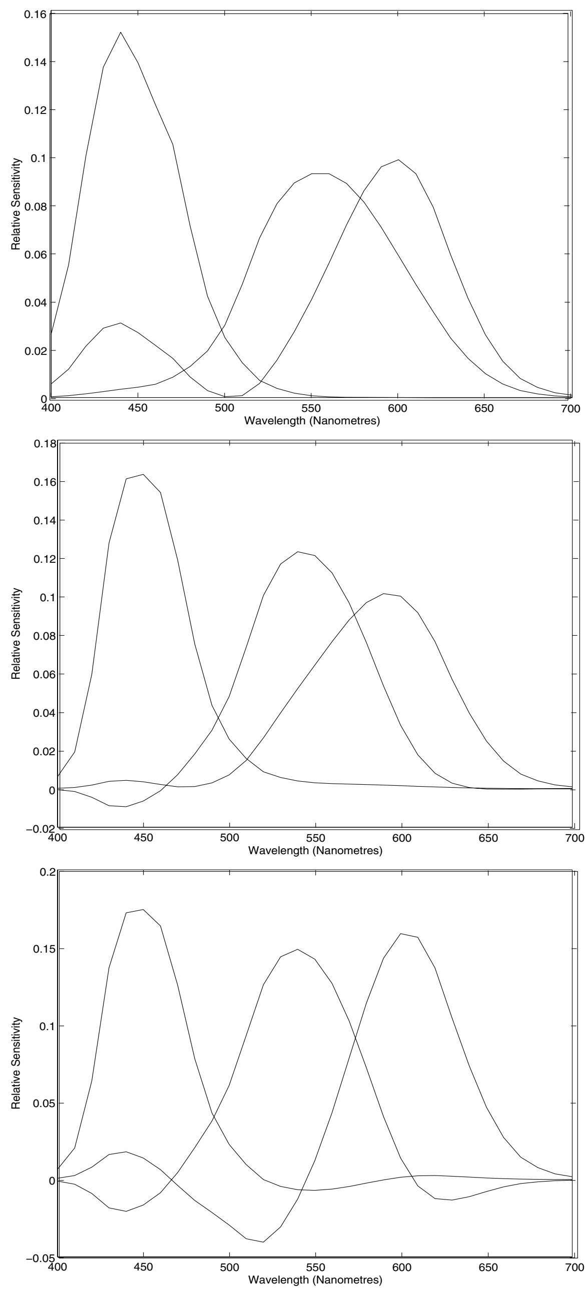

Figure 1: *XYZ, CMCCAT2000 and Sharp Sensitivities*

es. However, though it is not possible for an observer to choose the same reflectance we argue the observer has enough information to make a plausible reflectance match.

Finlayson and Morovic[10] have shown how it is, in principle, possible to solve for the set of surface reflectances that induce a particular XYZ for a surface viewed under reference lighting conditions. The actual reflectance will be a member of this set. While this *metamer set* integrates to a single XYZ under the reference light it integrates to a set of distinct XYZs under a second target light. In fact under the target light the metamer set projects to a small bounded convex *plausible* region of XYZ space. In a corresponding colour experiment we are proposing that an observer attempts to find a physical reflectance that is the same as that observed under the reference light. While metamerism makes it impossible for an observer to choose the correct reflectance it should still be possible to choose a plausible reflectance. All that the observer has to do is to ensure is that the matching surface has an XYZ that is plausible with respect to the reference light. If this condition is met it is, from the observers viewpoint, plausible that the reflectance that is chosen under the target light integrates to the same reference light XYZ. In contrast if a match is chosen that has an XYZ outside the plausible set then the reflectance chosen cannot match the reference XYZ under any circumstances. The match would be implausible from a reflectance matching perspective.

We evaluated the plausibility of SAT and CMCCAT2000 for a large set of natural reflectances with reference lights D40 and D100 and a target light of D65. For this data set we found that the sharp transform always delivered a plausible answer and in this sense is a *plausible vehicle* for adaptation. In contrast CMCCAT2000 often delivered implausible answers. Plausibility is a powerful argument that supports SAT but not CMCCAT2000.

In section 2 of this paper we review the ideas of metamerism and metamer sets. This leads to the development of plausible adaptation in section 3. Experiments are reported in section 4.

2. Metamer Sets

Equation (4) is at the heart of all colorimetry:

$$\underline{x} = \int_{\omega} \underline{X}(\lambda)E(\lambda)S(\lambda)d\lambda \qquad (4)$$

where $\underline{X}(\lambda)$ are the 3 colour matching functions, $E(\lambda)$ is the spectral power distribution incident at the surface reflectance function $S(\lambda)$. The visible spectrum ω runs from 400 though 700 Nanometres.

It is immediate from(4) that the equation is not invertible. Given knowledge about $\underline{x}$, $\underline{X}(\lambda)$ and $E(\lambda)$, it is not in general possible to solve for $S(\lambda)$ since many reflectances integrate to give the same tristimulus measurement. However, Finlayson and Morovic have shown that it is possible to solve for the set of reflectances, *the metamer set*, that satisfy (4).

Finlayson and Morovic have shown that the reflectances satisfying (4) live in a $(n-2)$-dimensional convex bounded region of reflectance space (where n is typically 6, 7 or 8[11, 12, 13]). This space is called the metamer set and is denoted $\mathcal{M}(\underline{x}, E(\lambda))$. Clearly if we integrate the plausible set with respect to the same illuminant we get the same XYZ tristimulus:

$$\underline{x} = \int_\omega \underline{X}(\lambda)E(\lambda)S(\lambda)d\lambda = \int_\omega \underline{X}(\lambda)E(\lambda)\mathcal{M}(\underline{X}, E(\lambda))d\lambda \tag{5}$$

But, if we integrate with respect to a second illuminant we get a set of plausible tristimuli $\mathcal{P}(\underline{x}, E(\lambda), E'(\lambda))$:

$$\int_\omega \underline{x}(\lambda)E'(\lambda)\mathcal{M}(\underline{X}, E(\lambda))d\lambda = \mathcal{P}(\underline{X}, E(\lambda), E'(\lambda)) \tag{6}$$

$\mathcal{P}(\underline{x}, E(\lambda), E'(\lambda))$ is a bounded convex region of XYZ space. Unless $E(\lambda)$ is very similar to $E'(\lambda)$, it has been found that $\mathcal{P}(\underline{x}, E(\lambda), E'(\lambda))$ occupies a significant region of colour space (up to 10 Delta E units wide).

3. Plausible Adaptation

Chromatic adaptation transforms attempt to predict corresponding colours across illumination. The XYZ $\underline{x}^r$ for a surface reflectance $S(\lambda)$ viewed under a reference light $E^r(\lambda)$ equals:

$$\underline{x}^r = \int_\omega \underline{X}(\lambda)E^r(\lambda)S(\lambda)d\lambda \tag{7}$$

Chromatic adaptation transforms attempt to predict corresponding colours across illumination. What tristimulus $\underline{x}^t$ will induce the same colour as $\underline{x}^r$ under target lighting conditions? Since our everyday experience shows us that surfaces look similar under different lights. We might assume that $\underline{x}^t$ would equal the integral:

$$\underline{x}^t = \int_\omega \underline{X}(\lambda)E^t(\lambda)S(\lambda)d\lambda \tag{8}$$

Equation (8) simply intuits (what we perceive to be more or less true) that the same surfaces look to have the same colour when seen under different lights.

It follows that we might use (8) as a criterion for solving for an adaptation transform. Let the ith surface tristumuls under reference and target lights be denote $\underline{x}_i^r$ and $\underline{x}_i^t$ respectively. The sharp adaptation transform (SAT) (defined in (3)) minimizes:

$$\sum_{i=1}^{N} ||[\mathcal{T}^s]^{-1}\mathcal{D}^{rt,s}\mathcal{T}^s\underline{x}_i^r - \underline{x}_i^t||^2 \tag{9}$$

that is the SAT enforces, in a least-squares way, Equation (8) subject to the constraint that the ransform is of the form of (2) an (3). Here, the diagonal matrix $\mathcal{D}^{tr}$ is the ratio of the white points of the reference and target lights (if $\underline{R}^{rw} = \mathcal{T}^s\underline{x}^{rw}$ and $\underline{R}^{tw} = \mathcal{T}^s\underline{x}^{tw}$ then $\mathcal{D}_{ii}^{tr,s} = R_i^{tw}/R_i^{rw}$ $(i = 1,2,3)$). We use the notation $||,||$ to denote vector magnitude. The computational methods for finding the best $\mathcal{T}^s$ for a large set of surfaces and many pairs of lights are set forth in[6].

The CMCCAT2000 transform was similarly derived though rather than invoking surface constancy as an intuition, matching experiments were carried out across illuminants. Observers would find the surface $S'(\lambda)$ that appeared to have the same colour under $E^t(\lambda)$ as $S(\lambda)$ had under $E^r(\lambda)$. Given these corresponding surfaces, corresponding XYZ tristimuli were readily measured. Denoting the ith of N corresponding tristimuli $\underline{x}_i^{t,c}$: the CMCCAT2000 transform minimizes:

$$\sum_{i=1}^{N} ||\mathit{CIELab}([\mathcal{T}^c]^{-1}\mathcal{D}^{rt,c}\mathcal{T}^c\underline{x}_i^r) - \mathit{CIELab}(\underline{x}_i^{t,c})||^2 \tag{10}$$

where the diagonal matrix is now the ratio of white RGBs with respect to the CMCCAT2000 transform. The function *CIELab* maps the tristimulus to CIE Lab colour space. The derived RGB sensitivities for the SAT and CMCCAT2000 sensors are shown in Figure 1. While they are clearly similar there is clearly a significant difference in the red sensitivity. This might make us more ready to choose the CMCAT2000 transform over the SAT: since, the colorimetric performance is optimal and the SAT sensors are clealy somewhat different.

However, caution must be applied here. Even the best fit derived by Luo and Lee[5] still leaves significant error. Indeed, it was found that, in terms of their ability to predict corresponding colour data that SAT and CMCCAT2000 delivered statistically similar performance[7]. That this is so leads to the following question: *' if we cannot discriminate between the sharp and CMCCAT2000 transform using the corresponding colour data how can we choose which adaptation transform to use?'*.

To find a way forward let us reconsider the metamer set idea introduced in the last section. There we showed how many plausible reflectances integrate to form the same tristimulus $\underline{x}^r$ under a reference light $E^r(\lambda)$ but integrate to form many different tristimuli under a second target illuminant $E^t(\lambda)$. The set of plausible tristimuli for the target light was denoted $\mathcal{P}(\underline{x}^r, E^r(\lambda), E^t(\lambda))$. That the plausible set is non empty, informs us that we cannot hope to see the same surface colour under different lights (metamerism is a real phenomenon). We propose therefore that the best that might be reasonably achieved is to find a tristimulus under the target light that is plausible. Formally, that the tristimuli $\underline{x}^t$ recorded under the test light $E^t(\lambda)$ that induces the same colour as $\underline{x}^r$ recorded relative to the reference light $E^r(\lambda)$ should satisfy:

Adaptation Transform	Reference Lights D40	D100
CMCCAT2000	3.67%	6.42%
Sharp	74%	45%

Table 1: % Plausability for SAT and CMCCAT2000 for D45 and D100 reference lights (D65 target)

Adaptation Transform	Reference Lights			
	D40		D100	
	Mean	Max	Mean	Max
CMCCAT2000	2.0	6.4	1.0	3.6
Sharp	0.04	2	0.06	0.4

Table 2: Mean CIE Lab error (distance to Plausible set)

$$\underline{x}^t \in \mathcal{P}(\underline{x}^r, E^r(\lambda), E^t(\lambda)) \tag{11}$$

This idea of plausibility can also be used test chromatic adaptation transforms. We say that the CMCCAT2000 transform delivers plausible adaptation if:

$$[\mathcal{T}^c]^{-1}\mathcal{D}^{rt}\mathcal{T}^c\underline{x}_i^r \in \mathcal{P}(\underline{x}^r, E^r(\lambda), E^t(\lambda)) \tag{12}$$

The sharp adaptation transform is plausible if:

$$[\mathcal{T}^s]^{-1}\mathcal{D}^{rt}\mathcal{T}^s\underline{x}_i^r \in \mathcal{P}(\underline{x}^r, E^r(\lambda), E^t(\lambda)) \tag{13}$$

The index i denotes the ith reflectance viewed under reference conditions.

4. Experiments

In our experiments we used the 219 natural reflectance spectra measured by Koivisto[14, 15]. Characteristic vector analysis[11] was carried out to find the best 7 dimensional linear model approximating the reflectance spectra (7 basis functions fitted the data with vanishingly small error). Each of the 219 reflectances is represented by a 7-component coefficient vector (weighting the contributions of the 7 basis functions). These 7-dimensional vectors taken together are used to form the plausible reflectance sets defined in (6). Each plausible set is a 5 dimensional (7-2) convex region of reflectance space.

For reference illuminants we used CIE D40 (reddish daylight) and CIE D100 (Bluish daylight)[16]. The target for adaptation was CIE D65 (an off white daylight)[16]. For a given pair of reference and target lights (either D40 and D65 or D100 and D65) we calculated (using (4)) the XYZ tristimuli for a perfect white diffuser. These white patch responses were used to calculate the CMCCAT2000 and SAT transforms (2) and (3). For each of the 219 natural reflectances surface reflectance we calculated the corresponding tristimulus under the reference light: $\underline{x}^r$. Then, using equations (12) and (13) we evaluated the plausibility of the CMCCAT2000 and SAT transforms. The % of surfaces that are mapped plausibly according to the two adaptation transforms is given in Table 1.

The Sharp transform seems somewhat plausible in that about 60% of of matches are themselves plausible. In comparison CMCCAT2000 works significantly less well: it almost never makes matches that are plausible. Of course Equations (12) and (13) are very stringent tests of plausibility. A mapped reference tristimulus might be almost within the plausible set but regarded as implausible. So, in a second experiment we computed the closest, in terms of CIE Lab ΔE, point in the plausible set to the adapted reference tristimulus (the ΔE is zero if it is in the set). The ΔE statistics for the two transforms and two reference lights are given in Table 2.

The error for SAT is vanishingly small. For both reference light conditions the mean error is close to zero and the overall maximum is less than 2 ΔE. In contrast, CMCCAT2000 maps reference tristimuli well outside the plausible set. The over all mean is larger than 1 ΔE and the maximum error is as high as 6.4 ΔE (a colour difference that is quite large).

The plausibility of the sharp adaptation transform coupled with the fact that they near optimally fit psychophysical corresponding colour data, provides an intriguing reason for choosing SAT over CMCCAT2000. However, we also note that there are other reasons in favour of adopting a sharp transform. Sharp sensors like those shown in Figure 1, have been found in numerous psychophysical studies (e.g. [17, 18, 19]) and so appear to have fairly wide psychophysical applicability. they are also close to standard monitor color spaces[20] and have numerous positive theoretical properties[21]. In contrast, to the authors' knowledge, the Bradford-type[1] RGB sensitivities used in the CMCCAT2000 transform have not been reported in other psychophysical or theoretical studies.

5. Conclusions

The CMCCAT2000 and Sharp Adaptation Transforms both work equally well in predicting corresponding colour data[7]. Moreover, performance is significantly better than most other adaptation transforms. Of course, it is a little unsatisfying that both transforms should work equally well. We would rather propose a single transform. However, to discriminate between the two, we probably will need to look at secondary factors other than corresponding colours.

In this paper we looked for such a secondary factor in considering adaptation from an observers viewpoint. We proposed that in matching corresponding colours, observers seek reflectances under a target light that look the same as a given reflectance viewed under a reference light. We set forth arguments that show (and this is a well known experimental result) that observers cannot solve this problem. However, in principle they can solve an easier problem. There is enough information available to an observer to make what we call a plausible reflectance match. We then evaluated the CMCCAT2000 and Sharp Adaptation Transforms according to this plausibility assumption. The SAT transform was found to b plausible and the CMCCAT2000 transform implausible.

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