

# Colour vision deficiency transforms using ICC profiles

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## Abstract

*We show how ICC profiles can be used to handle a variety of transforms intended to either simulate the appearance of a colour image to an observer with a colour vision deficiency (CVD), or adjust the image to improve the discriminability of colours to the CVD observer. In ICC v4, the different profile classes transform between a data encoding and the ICC Profile Connection Space (with the exception of the DeviceLink profile, which is a transform between two data encodings). Some simulation and Daltonization algorithms can be concatenated into a single matrix, which can be encoded as a v4 LUT-based profile or a matrix/curve profile. Alternatively a more complex transform can be encoded in the colour look-up table in a LUT-based profile. The new iccMAX architecture provides some additional possibilities, such as parameterized transforms for individual observers, encoding of functional transforms in the MPE and Calc elements, and the use of custom colorimetric observer and profile connection space. By using the ability to connect spectral data, iccMAX profiles also enable computation of the spectral response of the CVD observer to a given spectral reflectance, light source or emission.*

## Introduction

Colour vision deficiency (CVD) is a problem affecting a significant proportion of individuals. A considerable amount of work has been done to improve understanding of the problems faced by the CVD observer, and to modify the presentation of information to such observers to compensate at least partially for their lack of discrimination between certain colours.

In this work we aim to show how ICC profiles [1] can be used to handle a variety of transforms intended to either simulate the appearance of a colour image to a CVD observer, or adjust the image to improve the discriminability of colours to the CVD observer.

Colour vision deficiencies are classed into those where one of the L, M, S cones are missing (Protanopia, Deuteranopia and Tritanopia respectively) or modified from the normal observer (Protanomalous, Deuteranomalous and Tritanomalous respectively). Those with anomalous colour vision may have different degrees of modification and hence a range of different abilities to discriminate between (most commonly) red and green.

## Objectives

Modelling such observers may have a number of different objectives. First, it may be desired to produce an approximation of the appearance of a colour image to a CVD observer, so that person of normal vision can obtain a visualization of the limited palette available to the CVD observer and (for example) make appropriate adjustments to the design of information graphics. Secondly, colour images can be adjusted through a process known as Daltonization [2] to enhance the discriminability of colours to the CVD observer. There could also be potential use cases for inverting these transforms, so that the CVD-simulated or Daltonized image can be returned (to the extent possible) to its appearance to a normal observer. Thirdly, it may be desirable to parameterize a simulation

or Daltonization transform to reflect the degree of deficiency experienced by the anomalous observer. Finally, it may be desired to apply the matching functions of the CVD observer to spectral data in order to estimate the spectral response of the observer.

Both simulation and Daltonization algorithms typically take the form of a conversion from XYZ to LMS, followed by a linear conversion to a modified LMS space that corresponds to the type and degree of colour deficiency, and finally a transform back to XYZ from modified LMS. In a Daltonization algorithm, a further operation is performed on the modified LMS data to shift those spectra that are difficult for the CVD observer to discriminate into the visible range, based on the magnitude of the difference between the original and CVD-simulated image.

## Using ICC profiles

In ICC v4 [1], the different profile classes transform between a data encoding and the ICC PCS (with the exception of the DeviceLink profile, which is a transform between two data encodings). The PCS is always D50 colorimetry, while the data encoding may be device coordinates, colour space coordinates or PCS coordinates. The data encoding colour spaces enumerated in the v4 specification include colorimetry-based spaces (XYZ, CIELAB, CIELUV YCbCr, and CIEYxy, and device encodings such as RGB, CMYK and n-colour. HSV and HLS are also enumerated, although it is not defined whether these are derived from colorimetry or device data. LMS is not currently included, although if it were desired to transform between PCS and LMS coordinates it is possible to assign the channels of, say, a profile with an RGB data colour space to LMS if it is understood by the users of the profile how to interpret the data.

ICC has recently published an interim specification for a new colour management architecture, iccMAX [3], in which the connection space can be colorimetric, spectral or material. A colorimetric PCS can be any desired colorimetry (i.e. alternative observers and illuminants are possible), and the data encodings include those in ICC v4 together with spectral (reflectance or emission) and material channels.

The different ICC profile classes support a range of possible CVD transforms, depending on the data encodings it is desired to use as source or destination to the transform. In practical workflows, where there may be limited support for Colorspace, Link and Abstract profiles, the most useful type of profile would be one that converts from a standard RGB encoding such as sRGB to the PCS, and back. Both matrix/curve and look-up table based profiles could be used.

ICC profiles that are based on multi-dimensional look-up tables support multiple rendering intents, making it possible for example to define the conventional colorimetry in the Colorimetric intent, and the CVD observer transform in the Perceptual intent.

ICC v4 profiles pre-define a transform, and do not directly support run-time parameterization. However, by use of a programmable CMM [4] it is possible to define and apply custom transform matrices based on the individual observer's degree of anomalous colour deficiency, or to adjust pixels based on the

difference between the original and that predicted by a simulation algorithm.

A programmable CMM is a solution where a custom application for CVD users is being developed. The alternative is to generate a profile with greater functionality that can be used with a standard CMM, which is made possible in ICC's next-generation colour management architecture, iccMAX [5, 6]. iccMAX incorporates a number of features that can support CVD transforms. Multi-processing elements (MPE) enable an arbitrary sequence of transform elements to be encoded, for example allowing each of the different matrices to be separately encoded and thus more readily edited for individual observers.

Spectral viewing conditions include illuminant and colorimetric observer, thus making it possible to include the colour matching functions of the individual observer, if known. Elsewhere in the profile it is possible to encode the linear transform from custom colour matching function to a 'colorimetric' observer and a custom PCS. The iccMAX format includes a custom-to-standard PCS transform so that the CVD observer PCS can be transformed to PCS XYZ. The custom observer in an iccMAX profile can be convolved with spectral input data to generate the spectral response of the CVD observer.

CVD transform methods can be standardised in an iccMAX Interoperability Conformance Specification, essentially a sub-set of iccMAX tags and types defined for a particular use case.

The iccMAX technology also makes a number of other implementations possible, which are not explored here. For example, the CVD observer spectral sensitivities can be considered as sensor excitations and encoded using a Material Connection Space [3], with further connections to colorimetric visualization, cone fundamentals and other transforms.

## Example implementations

To demonstrate the principles described above, a number of profiles have been generated and are available for evaluation and use. They can be downloaded from <http://www.color.org/resources/cvd.xalter>. The process of generating the profiles is simplified by the use of the IccXml tool, which converts between the binary profile format and a human-readable xml version. [7] Both binary profiles and xml files are available to download, and the corresponding filenames are given below for each profile.

### Simulation

A method for simulating deuteranopia and protanopia was described by Brettel, Viénot and Mollon [8], and a practical implementation described in a subsequent paper by Viénot et al [9]. This paper assumes that the source image data is encoded in sRGB, which is converted to XYZ and then to LMS. From LMS the data is linearly transformed to simulate either deuteranopic or protanopic viewing using a 3x3 matrix, and the inverse transform from LMS to sRGB is then applied so that the output is encoded in the same space as the source image data. The conversion matrices at each step are provided, and a sample of the RGB space and the corresponding RGB values for deuteranopic or protanopic simulation are tabulated.

There are several possibilities for encoding and applying this transform in ICC profiles.

After linearization of RGB values, the 5 matrices that convert from the RGB data encoding to XYZ, LMS, LMS modified for dichromats, D65 XYZ and finally D50 PCS XYZ can be pre-multiplied into a single matrix that defines the complete transform from linearized sRGB to simulated or Daltonized PCS XYZ.

In order to connect via the ICC PCS, the output of the profile should normally be PCS XYZ or PCS LAB, and the inverse transform to sRGB or any other colour encoding can be provided at run-time. The exception is where a DeviceLink profile is generated, which converts directly from one data encoding to another without going via the PCS.

### V4 Matrix/TRC profiles

An ICC v2 or v4 matrix/TRC contains three 1-D curves which are applied to the source data encoding, followed by a 3x3 matrix which converts from the linearised RGB output of the curves into the XYZ Profile Connection Space. The linearization curves in Viénot et al are encoded as a simple exponent, and the 5 matrices converting RGB' -> XYZ -> LMS -> LMS' -> XYZ are pre-multiplied as a single 3x3 matrix. A chromatic adaptation transform is then applied, converting the D65 XYZ resulting from the matrix to the D50 of the ICC PCS, and this matrix stored as the 'rXYZ', 'gXYZ' and 'bXYZ' tags. A 'chad' tag representing the chromatic adaptation conversion of the D65 illuminant to the D50 illuminant is also stored in the profile.

*Profiles: CVDdeutan.icc, CVDprotan.icc*  
*Xml: CVDdeutan.xml, CVDprotan.xml.*

### V4 Lut-based profiles

Both ICC v2 and v4 specifications define a multi-dimensional look-up table that can be used in any profile class. The Viénot et al paper tabulates a colourmap comprising 256 colours, of which 216 follow the rules for input table formation in the ICC profile specification and can be used to form a 6x6x6 LUT. This LUT converts from one RGB data encoding to another, and so therefore can be encoded directly as the CLUT of an AToB0 tag in a DeviceLink class profile, setting the matrix and curves to identity.

*Profiles: CVDlink-deutan.icc, CVDlink-protan.icc*  
*Xml: CVDlink-deutan.xml, CVDlink-protan.xml*

Using the same colourmap, the output RGB values were converted from sRGB to D65 XYZ, chromatically adapted to D50 XYZ, and finally converted to D50 CIELAB and encoded as PCS LAB values in the AToB0 tag of an Input class profile.

*Profiles: CVDcolormap-deutan.icc, CVDcolormap-protan.icc*  
*Xml: CVDcolormap-deutan.xml, CVDcolormap-protan.xml*

The matrix/TRC profile described above converts in one direction from RGB to PCS; inversion is handled by the CMM which applies the inverse matrix and inverse curve to XYZ data to obtain RGB. Matrix/TRC profiles are only permitted in Colorspace, Input and Display class profiles, and to generate an Output profile it is necessary to build a full set of multi-dimensional LUTs for the Perceptual, Colorimetric and Saturation rendering intents, in both forward and inverse directions. The Viénot et al transform was encoded as a LutAToBType by the following steps: first, an input table was constructed in RGB with the required number of nodes, the Viénot et al transform steps were applied to convert this to PCS XYZ as above, and this data was converted to CIELAB and encoded as an AToBx LUT. In the Input class profile generated, the deuteranopia or protanopia simulation transform was encoded as an AToB0 Perceptual rendering intent, while the AToB1 Colorimetric tag encodes the transform for normal viewing, so that the simulation transform is selected by means of the rendering intent.

*Profiles: CVDlut-deutan.icc, CVDlut-protan.icc*  
*Xml: CVDlut-deutan.xml, CVDlut-protan.xml*

### ***iccMAX profile encoding the Viénot et al simulation transform***

The Matrix/TRC profile described above concatenates the different steps in converting from linearised sRGB to deuteranopic and protanopic simulation PCS XYZ into one matrix, since in a v4 profile the available transforms only support the encoding of a single matrix. In the iccMAX specification [2] a Multi-Processing Element (MPE) transform is defined, which permits curves, LUTs and matrix elements to be combined in any number and processing sequence. This enables creation of a profile which encodes each of the transform elements described by Viénot et al, the advantage being that the xml file can now be edited to modify any of the transform elements. An example profile was created to represent a deuteranomalous simulation, in which the LMS  $\rightarrow$  LMS' transform was adjusted in an arbitrary fashion to approximate a state between normal and deuteranopic vision.

*Profiles: CVDdeuteranope-iccMAX.icc, CVDdeuteranomally-iccMAX.icc;*

*Xml: CVDdeuteranope-iccMAX.xml, CVDdeuteranomally-iccMAX.xml*

### ***iccMAX profile encoding a notch filter***

Red-green discrimination is said to be enhanced by a notch filter that has one or more stop bands, especially at wavelengths where the cone spectral sensitivities overlap. This approach has been implemented as an optical filter in glasses for CVD users [10]. (It should be noted that a simulation of this effect found the effects negligible [11]) Alternative methods of implementing a notch filter exist, and one approach is to modify the spectral power distribution of the illuminant used in computing colorimetric quantities from spectral reflectance.

The iccMAX specification defines spectral connections through the use of spectral viewing conditions, in which both observer and illuminant used in the conversion to colorimetry can be defined. The iccMAX NamedColor class of profile supports conversion of spectral reflectance data for specified colours to a spectral or colorimetric profile connection space. A notch filter profile was generated by setting the D50 SPD to zero at 455-485nm and 565-595nm in a NamedColor profile, based on an example profile in the iccMAX Reference Implementation [7]. The profile has a SpectralPCS signature of 'rs0024', denoting reflectance spectra with 36 channels, CIE 1931 Standard Colorimetric Observer, and the spectral reflectances of five colours. Unmodified, the profile can be used to convert solid colours and tints of the named colours 'Black', 'Gray', 'Red', 'Green' and 'Blue' to colorimetry by connecting to a suitable profile. With the stop bands of the notch filter applied to the illuminant SPD in the profile, the resulting colorimetry is adjusted with the goal of enhancing the difference between red and green to a CVD observer. Such enhancement can be tested by normal observers by applying one of the simulation profiles described above.

It should be noted that conversion to RGB primaries will inevitably lose much of the effect of the notch filter, and better results should be obtained by generating spectral rather than colorimetric output.

*Profile: CVDnotch-RG-iccMAX.icc,*

*Xml: CVDnotch-RG-iccMAX.xml*

### ***iccMAX profile encoding a custom observer***

Dichromat cone spectral sensitivities measured by Smith and Pokorny [12] (and converted from the published figures to data by CVRL [13]) were encoded in place of the CIE 1931 Standard

Colorimetric Observer in the sample profile used in the previous example. When applied to reflectance data, LMS cone fundamentals for deuteranopes and protanopes are computed.

The dichromat cone sensitivities in Smith and Pokorny were based on 5 protanopes and 4 deuteranopes. Where measurements or estimates of cone sensitivities for an individual observer exist, they can be inserted into the xml file as a custom observer, so that the profile computes LMS values for that observer.

*Profile: CVDdeutan-custom-iccMAX.icc*

*Xml: CVDdeutan-custom-iccMAX.xml*

### ***ICC v4 profile converting between ICC PCS XYZ and LMS***

It should be noted that there is no PCS colour space defined for LMS in either v4 or iccMAX, so to connect the profile above either a Custom-to-Standard PCS transform is required, or must be connected to a destination profile that treats the source data as LMS. A Colorspace profile was generated that uses the transform described in Viénot et al to convert between LMS and XYZ. This is a simple Matrix/TRC profile in which the TRC is identity and the output is chromatically adapted to D50 PCS XYZ. The profile can also be used to provide the inverse transform, from PCS XYZ to D65 LMS.

*Profile: LMS.icc*

*Xml: LMS.xml*

### ***V4 and iccMAX profiles encoding simulation and Daltonization transforms by Kotera***

A Daltonization algorithm based on lost spectra was described by Kotera [14]. This involves the use of Matrix R to decompose an sRGB image into a fundamental colour image and a metameric black. The fundamental spectral image  $C^{*DICimg}$  for dichromats is computed by a linear transform, which can be pre-multiplied into a single matrix as above, or encoded as a series of MPE elements. The lost spectra  $\Delta C^{*DICimg}$  is found by subtracting  $C^{*DICimg}$  from the fundamental spectral image for normal  $C^{*LMSimg}$ .

For simulation purposes,  $C^{*DICimg}$  is converted to LMS and then opponent-colour IPT for the CVD observer, and the P or T component nulled depending on whether deuteranope, protanope or tritanope simulation is being computed. Finally RGB coordinates for the simulated colours for dichromatic vision are computed by converting IPT back to LMS, XYZ and finally sRGB. As with the Viénot algorithm, a Colorspace, Display or Input profile for standard PCS colorimetry would convert to PCS XYZ, and so the final conversion to RGB is omitted and the XYZ data is chromatically adapted to the D50 PCS.

A Daltonized image is computed by first shifting the lost spectra  $\Delta C^{*DICimg}$  into the wavelength region visible to dichromats to find the wavelength-shifted  $\Delta C^{*SHTimg}$ . This is a conditional operation depending on the relationship of the colour being transformed to the maximum and minimum wavelengths and the spectral shift. Finally the shifted lost spectra  $\Delta C^{*SHTimg}$  are added to the fundamental image  $C^{*LMSimg}$ .

This algorithm could be encoded in LUT form in a LutAtoBType, by applying the algorithm to compute output colours for a sample of RGB inputs, although it cannot be encoded as a functional transform since it involves arithmetic operators and conditionals not supported in the curve, matrix and CLUT elements. However, the iccMAX MPE Calc element does provide a wide range of math and logic operators, making it possible to encode the complete algorithm in an iccMAX profile.

## Workflow

The CVD profiles generated in this project are intended to be used as follows:

The v4 simulation profiles can be used as the source data encoding by assigning to an sRGB image and then previewing or converting to another colour space. The resulting image should illustrate the discriminability of colours in the image to a CVD observer.

The v4 Matrix/TRC profile can also be used for the inverse transform, i.e. to convert from a simulation image to an image for a normal observer. In this case, the profile is used as the destination profile when converting from a CVD simulation image, and the resulting data should approximate the original, non-simulation image. Since this inverse transform starts from a reduced-dimension image, the accuracy is expected to be low.

The v4 LUT-based DeviceLink profile can be applied to an sRGB image to convert it to a simulated representation of the image to a CVD user, also in sRGB.

The v4 profiles can be used with any CMM that supports the particular profile class – for example all are supported by Adobe Color Engine (ACE) in Photoshop and other Adobe applications. The v4 LMS profile can be used to convert LMS to PCS XYZ or the inverse, although the data encoding channels of the image must be nominally defined as RGB since the LMS colour space is not one of the enumerated encodings in the ICC specification [1].

The iccMAX notch filter profile is applied to named color data using the iccMAX CMM. The illuminant spectral power distribution with stop bands in this profile can also be added to the spectral viewing conditions tag in other types of iccMAX profile with a The iccMAX Reference Implementation includes a command-line tool called `iccApplyNamedCMM.exe` that can apply a selected profile or sequence of profiles to text-encoded data, and this can be used to facilitate the use of the iccMAX CVD profiles in the absence of support from other imaging applications.

Finally, the custom observer profile is applied to reflectance data to generate LMS values, again using the Reference Implementation tools in the absence of other support.

## Evaluation

The profiles generated were evaluated as follows.

The v4 simulation profiles were tested by assigning them to test images and previewing the results. They gave visually identical results to other simulation tools such as Photoshop's Protanopia and Deuteranopia proof set-up options.

The iccMAX notch filter profile was evaluated by converting text-encoded spectral reflectance data using the profile, and then converting to sRGB using the ICC v4 preference profile. The command line string to accomplish this was:

```
iccApplyNamedCMM NamedColorTest.txt 2 0 CVDnotch-RG-iccMAX.icc 3 sRGB v4_ICC_preference.icc 1
```

Since the notch filter profile was generated by changing the illuminant SPD in the file `NamedColor.xml` in the iccMAX Reference Implementation, it could be compared to the output of `NamedColor.icc` (in the Reference Implementation), as shown in Figure 1 below.



Figure 1. Reflectance data converted to sRGB using D50 illuminant SPD (`NamedColor.icc`) and notch-filtered illuminant (`CVDnotch-RG-iccMAX.icc`)

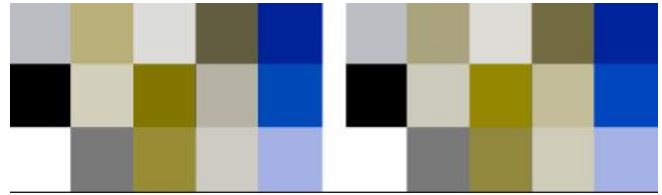


Figure 2. Simulation of standard and notch-filtered images in Figure 3, using `CVDdeutan.icc`

## Conclusions

The ICC profile provides a means of encoding a wide range of colour transforms. For those working on transforms for CVD users, the profile provides a simple method of implementing a simulation or Daltonization workflow. Transforms can either be pre-computed and encoded in a v4 Matrix/TRC or LUT-based profile, or they can be exposed as different transform elements using an iccMAX profile, making them readily editable through the xml representation. The iccMAX profile specification has a number of features of interest to those working on colour vision deficiency, including spectral connection spaces, custom observers and illuminants, and a Multi-Processing Element that includes support for conditional and math operators through the Calc element.

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