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Color appearance processing using iccMAX

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Abstract

ICC.2:2017 is a revision to the next-generation colour management specification iccMAX that introduces new support for colour appearance processing. iccMAX includes a built-in colour appearance model IccCAM, together with a rich programming environment, and support for spectral data, material channel connections, BRDF and processing elements that make it possible to functionally encode any appearance model. ICC.2:2017 introduces many new capabilities, including the ability to provide environment variables which allow parameters such as image statistics or viewing conditions to be passed to the transform at run-time. ICC.2:2017 supports a wide range of colour appearance computations within the colour management workflow.

Introduction

The ICC.1 profile specification [1], first published in 1996, established a well-defined architecture for communicating colour. ICC.1 was based on the concept of a reference intermediate colour space, and a profile which transformed all colour data encodings into or from this colour space, thus avoiding the combinatorial explosion of a many-to-many connection and enabling each colour device to be defined by a single profile.

This fixed Profile Connection Space (PCS), based on D50 colorimetry for a CIE 1931 2 degree standard observer, ensured interoperability of profiles regardless of who created them. The ICC.1 architecture employs a small set of transform elements – curve, matrix and multi-dimensional look-up table – that are applied in a predetermined sequence. The ICC.1 specification described the PCS for the Perceptual rendering intent as representing “the CIE colorimetry which will produce the desired color appearance if rendered on a reference imaging media and viewed in a reference viewing environment” [2]. This implies that as well as the device model the transform also embodies any gamut mapping, colour appearance and preference adjustments. In ICC.1 all these adjustments are combined into the values encoded in the AToB and BToA tags; using the curve, matrix and LUT transform elements there is no scope to encode the appearance transform separately, or to provide metadata on the transform or the conditions used, in a standard way.

The ICC.1 architecture also includes a default media-relative scaling of colorimetry. This can be over-ridden where needed, but a matching of source media white point to destination media white point is the most common expectation of colour management users. This media-relative scaling should not be confused with chromatic adaptation: although the form is similar to the Von Kries transform, both source and destination have a common illuminant (since all PCS colorimetry is required to be D50), and its function is primarily to ensure that source white is mapped to destination media white point. The adjustment made by media-relative scaling does in practice go some way to handling cross-media reproduction with different media white points where there **is** a degree of adaptation to the media white [3]. The media-relative PCS should be considered as a virtual colour space which allows two encodings to be connected, rather than a representation of actual colorimetry.

It can be seen from the above that ICC.1 is a well-defined but highly constrained architecture for colour transforms. Since 1996 many new requirements have emerged and the ICC.2 architecture [4], first published as an ICC specification in 2016, was designed to address them with a more flexible approach to connecting different colour spaces [5]. The ICC also publishes a Reference Implementation [6] which enables developers to make immediate use of ICC.2 constructs. The ICC.2 specification (also referred to as iccMAX) supports more flexible communication of:

i) Colorimetry. There is support for connection spaces other than D50, including specification of the illuminant and observer colour matching functions within the profile. Spectral data (reflectance or emission) is supported, both as input to a transform and as a PCS.

ii) Colour appearance. Colour appearance can readily be communicated by implementing a transform between different adapting conditions as a multiProcessElement within an iccMAX profile. For example, XYZ data for one adapting condition can be transformed via the desired appearance model into the adapting condition of the PCS of the profile. iccMAX incorporates a default IccCam model, which is a variant of CIECAM02.

iii) Other aspects of appearance. iccMAX includes directional appearance (through support for a number of BRDF models), and fluorescence (through support for input and processing of a full Donaldson matrix). Texture information can be communicated through height maps and normal maps associated with the BRDF model.

In addition to communicating appearance in terms of colour space values, iccMAX supports communication of metadata describing the adapting conditions as Spectral Viewing Conditions. The open format of the profile specification and the ability to convert between binary profiles and human-readable xml makes it possible for profile readers and users to extract the adapting viewing conditions from the profile and to modify them.

Finally, the ability to pass in an environment variable to parameterize the transform at the point when the profile is applied provides further flexibility. For example the environment variable can be used to input the adapting conditions at run-time, avoiding the need for an array of static profiles for each adapting condition.

The iccMAX profile format specifies a 32-bit floating point data type for all MPE transform elements, and both input and output data can also be encoded as 32-bit floats. The Reference Implementation source code can be compiled to perform computations at either 32-bit or 64-bit precision.

Application

In this paper we investigate some aspects of sensor adjustment transforms using iccMAX. A sensor adjustment transform (SAT) is used to transform colorimetry from one observing condition to a different observing condition based on various criteria [19]. Two types of sensor adjustment transform are considered in this paper:

chromatic adaptation transforms, and material adjustment transforms.

A chromatic adaptation transform (CAT) attempts to predict the corresponding colour for a given tristimulus value when the chromaticity of the adapting illumination changes. Chromatic adaptation has always been an important element of ICC.1 colour management, since in order to achieve interoperability all colorimetry with a different illuminant from the D50 PCS must be chromatically adapted to D50. ICC recommends a linearized version of the Bradford chromatic adaptation transform [1], which is implemented as a single 3x3 matrix. The matrix is stored in the ICC.1 profile and is used in the inverse direction when it is desired to transform from the PCS to the original colorimetry.

The CAT02 chromatic adaptation transform is an element of the CIECAM02 appearance model [8]. CIECAM02 performed well in predicting corresponding colour data sets, but a numerical instability in the transform has been reported and solutions proposed [9, 10, 11, 12, 13, 14, 15]. IccCam [4] replaces CAT02 by the HPE primaries and clipping to avoid negative RGB values. In the more recent CAT16, proposed as the chromatic adaptation transform in the CAM16 appearance model [15], the two stages of the CAT02 transform are replaced by a single matrix transform.

A common practice in implementing a CAT is to consider the inverse sense of the transform (where the test illuminant is the source and the reference illuminant is the destination) as the analytic inverse of the forward direction. Owing to the potentially different degree of adaptation in these two directions, and the tendency of the visual system to consider only near-daylight illuminants as neutral [18], it is suggested that where the test illuminant is chromatic the CAT model should not transform directly to it but using a two-step transform via a daylight illuminant or the equi-energy Illuminant E [15].

Chromatic adaptation transforms have generally been derived from corresponding-colour data sets and their performance evaluated in terms of their ability to predict such data [12]. Where the spectral reflectance for the colour exists, an alternative approach of forming a sensor adjustment transform to predicting the effect of a change of illuminant is of course to compute the tristimulus values for the test illuminant directly from the spectral data. This also suggests that a SAT can be derived from these XYZ values for reference and test illuminants computed from spectral reflectance, rather than via visual data sets. This approach is taken in e.g. [19, 20]. This type of transform assumes the reflectance of the object is unchanged and has been referred to as a Material Adjustment Transform (MAT) [19] or a Colorimetric Value Transform [20]. One distinguishing feature between a CAT and a MAT is that a material adjustment can provide a prediction of changes in observer in addition to changes in illuminant.

For connecting data encodings from different illuminants in a colour managed workflow, where both colorimetric and spectral data may be used, it is of interest to study the differences between the different SAT approaches in comparison to the tristimulus values under a different illuminant computed directly from spectral data. It has been shown that the degree of adaptation is reduced as the adapting illuminant becomes more chromatic and hence that CATs tend to over-predict the degree of adaptation and the resulting corresponding colours [16, 17].

Experimental

Several iccMAX profiles were used to transform colours from reflectance to colorimetry for the four adapting illuminants in Table 1. These colorimetric values were then transformed from the source (reference) illuminant to each of the other illuminants as destination or test illuminant, using the following SATs: CAT02 [8], CAT16 [15], linearized Bradford [1] and Wpt [19]. The degree of adaptation was set to 1.0 in all cases.

Table 1: Adapting illuminants

CIE illuminant	White point XYZ
D65	95.043, 100, 108.8801
D50	96.4197, 100, 82.5123
A	109.849, 100, 35.5825
F11	100.961, 100, 64.3506

The elements of the required adjustment transforms were computed in Matlab to determine the matrices used in the CustomToStandardPCS and StandardToCustomPCS tags. Using the existing iccMAX D65 colorimetric profile as a starting point, the xml was modified to encode these transforms, and profiles were subsequently created from the xml using the IccXml tool in the iccMAX Reference Implementation.

Two sets of reflectance data were selected. The first was the reflectance spectra of color chips from the Munsell Book of Color for Munsell Value 5 Chroma 6, measured at 1nm intervals [21] and subsequently corrected [22]. The second was the set of in-situ reflectance spectra from ISO 17231-1 [23]. The Wpt MAT was optimized for the corrected Munsell reflectances, so the ISO 17321 data set provides an independent test set.

The reflectance data were converted to XYZ for the reference illuminant using an iccMAX profile created to have a data colour space signature ‘nc0051’ representing 81 spectral channels, and a spectralViewingConditions tag populated by the CIE 1931 standard colorimetric observer over the range 380-780nm at 5nm intervals and the reference illuminant over the same range and interval. The command-line executable iccApplyNamedCmm [6] was called with the source data and profile as arguments. This was repeated for each of the reference illuminants in Table 1.

For each of the SATs tested, the transform was encoded in an iccMAX profile with an XYZ PCS and data colour space, in an A2B1 multiProcessElement-based tag, using the sequence of elements required by the transform. The XYZ data resulting from the previous step were converted to the test illuminant using iccApplyNamedCmm.

For each pair of reference and test illuminants, CAT02 and CAT16 transforms were performed both directly and via Illuminant E. The linearized Bradford transform assumes complete adaptation, so in CAT02 and CAT16 the degree of adaptation D was set to 1. The CAT02 and CAT16 transforms were also repeated with D = 0.93.

Results

The predicted XYZ values for each transform/illuminant combination were converted to CIELAB values, where the test illuminant was taken as the reference white in the conversion from XYZ to CIELAB. These values were compared with the XYZ values computed directly from Munsell and ISO 17321 in-situ reflectance spectra, similarly converted to CIELAB under the test illuminant. The test illuminant is expected to have CIELAB values of [100, 0, 0] after the above procedure. The differences between the different methods are shown in Table 2 and Figures 3-9, for degree of adaptation $D = 1$.

Table 2 (A-D): Mean CIELAB ΔE^*_{ab} differences between XYZ values predicted from the reference illuminant chromatically adapted to the test illuminant, and the XYZ values for the test illuminant computed directly from the spectral reflectances

A: Reference illuminant D65

	Forward model			Via Illuminant E		
Munsell	**D50**	**A**	**F11**	**D50**	**A**	**F11**
CAT02	1.13	4.72	2.81	1.13	4.72	2.81
CAT16	1.40	6.91	3.15	1.39	6.91	3.17
Linearized Bradford	0.95	3.86	3.21	-	-	-
Wpt	0.55	1.84	2.23	-	-	-
ISO 17321	**D50**	**A**	**F11**	**D50**	**A**	**F11**
CAT02	1.79	6.19	5.37	1.79	6.19	5.37
CAT16	1.91	7.65	6.06	1.90	7.65	6.07
Linearized Bradford	1.66	5.54	5.95	-	-	-
Wpt	1.72	5.29	4.52	-	-	-

B: Reference illuminant D50

	Forward model			Via Illuminant E		
Munsell	**D65**	**A**	**F11**	**D65**	**A**	**F11**
CAT02	1.09	3.56	2.91	1.09	3.56	2.91
CAT16	1.36	4.45	2.87	1.36	4.48	2.87
Linearized Bradford	0.92	2.94	3.14	-	-	-
Wpt	0.56	1.33	1.83	-	-	-
ISO 17321	**D65**	**A**	**F11**	**D65**	**A**	**F11**
CAT02	1.78	4.51	5.92	1.78	4.51	5.92
CAT16	1.92	4.81	6.19	1.92	4.85	6.19
Linearized Bradford	1.67	4.04	6.20	-	-	-
Wpt	1.83	3.89	5.00	-	-	-

C: Reference illuminant F11

	Forward model			Via Illuminant E		
Munsell	**D65**	**D50**	**A**	**D65**	**D50**	**A**
CAT02	2.94	3.00	4.79	2.94	3.00	4.79
CAT16	3.28	2.95	5.37	3.28	2.96	5.38
Linearized Bradford	3.45	3.27	3.89	-	-	-
Wpt	2.10	1.81	1.63	-	-	-
ISO 17321	**D65**	**D50**	**A**	**D65**	**D50**	**A**
CAT02	5.60	6.10	8.33	5.60	6.10	8.33
CAT16	6.27	6.33	8.50	6.27	6.34	8.50
Linearized Bradford	6.29	6.43	7.22	-	-	-
Wpt	4.51	5.11	7.44	-	-	-

D: Reference illuminant A

	Forward model			Via Illuminant E		
Munsell	**D65**	**D50**	**F11**	**D65**	**D50**	**F11**
CAT02	4.15	3.27	4.61	4.15	3.27	4.61
CAT16	5.30	4.16	5.16	5.30	4.17	5.14
Linearized Bradford	2.94	3.72	3.89	-	-	-
Wpt	1.43	2.01	1.61	-	-	-
ISO 17321	**D65**	**D50**	**F11**	**D65**	**D50**	**F11**
CAT02	6.39	4.68	8.54	6.39	4.68	8.54
CAT16	6.5	4.72	8.45	6.50	4.70	8.40
Linearized Bradford	5.99	4.37	7.67	-	-	-
Wpt	7.23	5.01	8.52	-	-	-

The distribution of the differences in CIELAB ΔE^*_{ab} is shown in the histogram in Figures 1 and 2 for the Munsell and ISO 17321 data respectively.

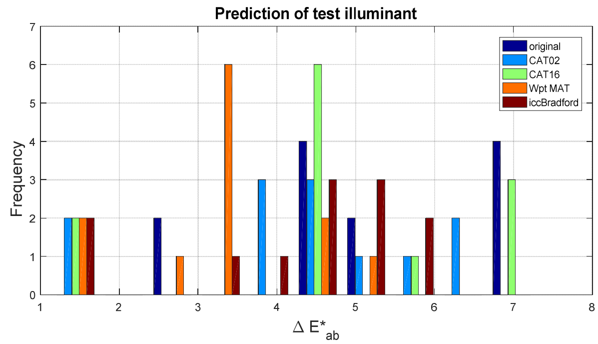

Figure 1. Distribution of mean differences between test illuminant calculated direct from spectra and predicted by SATs for all direct transform combinations in Table 1: Munsell and ISO 17321 in-situ reflectance data.

It can be seen from Table 2 that for the Munsell data set, Wpt-predicted XYZ values have smaller differences from the values computed for the test illuminant directly from the reflectances, compared with other transforms. However, when the ISO 17321-1 in-situ reflectances are considered Wpt has larger differences than the linearized Bradford transform.

It can also be seen from Table 1 and the examples in Figure 3 and 4 that for both CAT02 and CAT16, the differences between the predictions of the single-step transform and the transform via Illuminant E are negligible, as indicated in [15].

When the degree of adaptation was set to 0.93, the differences between the two workflows was similarly negligible, while the magnitude of difference was slightly larger when the reference illuminant was D50 and smaller when the reference illuminant was A.

In Figures 2-8 'original' represents the CIELAB a*, b* values of the colour computed from the reflectance under the reference illuminant; the CAT02 and CAT16 values are those predicted by the single-step transform from reference to test illuminant, and CAT02$_{23}$ and CAT02$_{24}$ values are transformed using the two-step workflow described in equations 23 and 24 in [15]. These can be compared with the values shown as 'from reflectance', which represent a*, b* values computed from reflectance under the test illuminant.

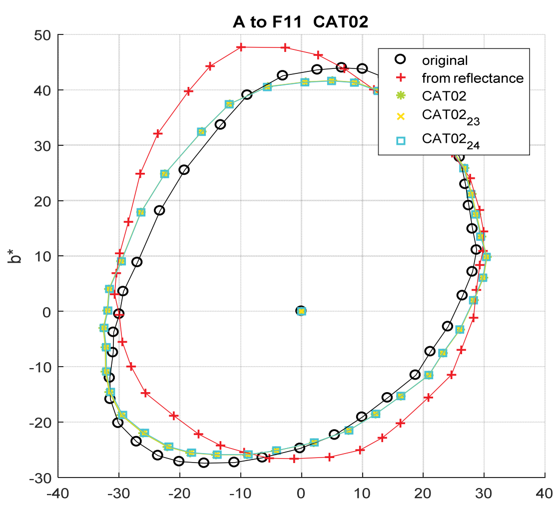

Figure 2. Differences in prediction of CAT02 using three workflows described in [15].

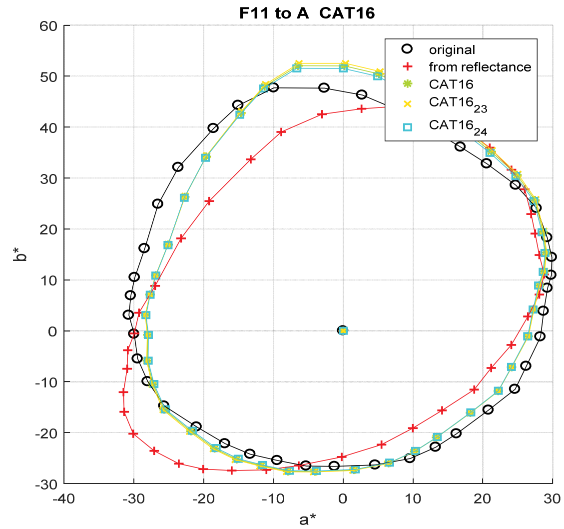

Figure 3. Differences in prediction of CAT16 using three workflows described in [15]

Examples of the differences between the predictions of the different SATs for the Munsell colours can be seen in Figures 4-8. As shown in Table 2, in most cases the Wpt transform tends to give the closest prediction of the Munsell colours computed from reflectance under the test illuminant.

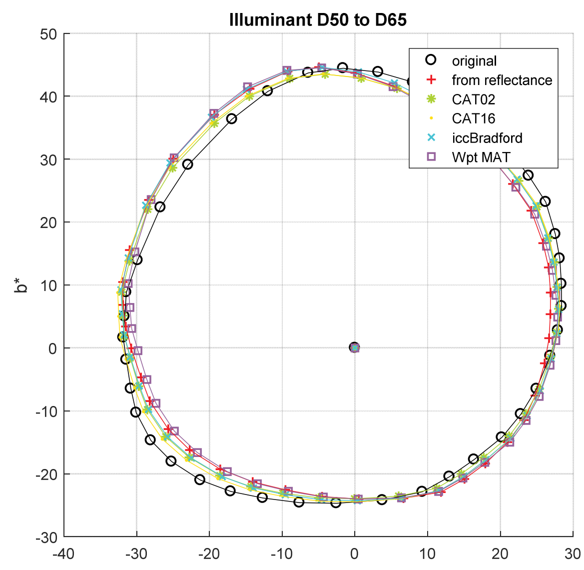

Figure 4. Munsell reflectances for D50 reference illuminant transformed to D65 by the 4 SATs

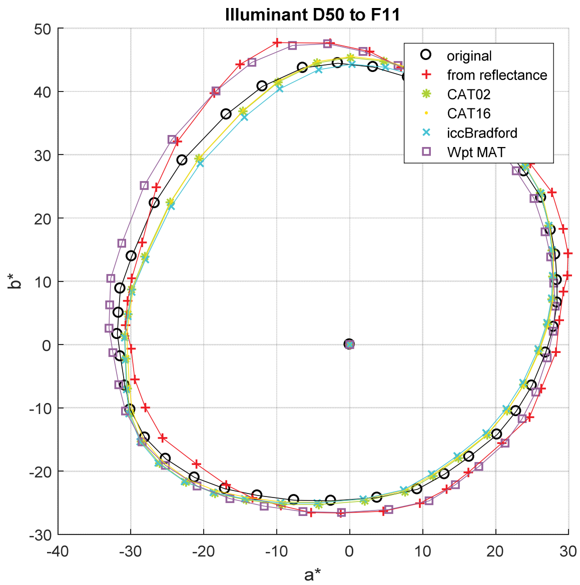

Figure 5. Munsell reflectances for D50 reference illuminant transformed to F11 by the 4 SATs

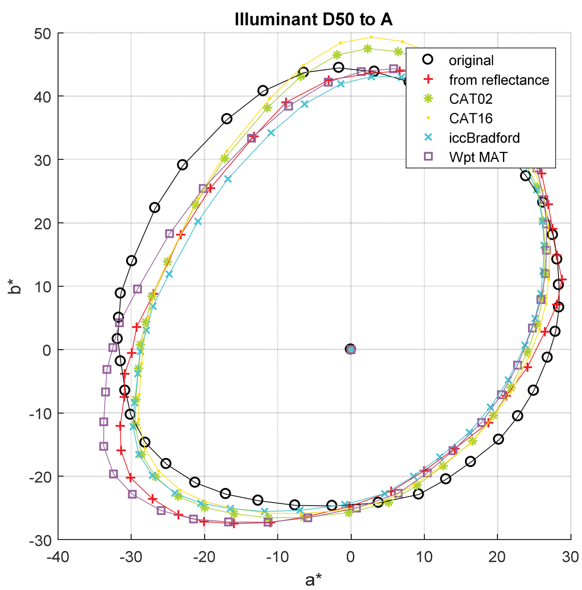

Figure 6. Munsell reflectances for D50 reference illuminant transformed to Illuminant A by the 4 SATs

As noted above, a CAT has a different derivation from a MAT and it is not necessarily expected that they should give equivalent results.

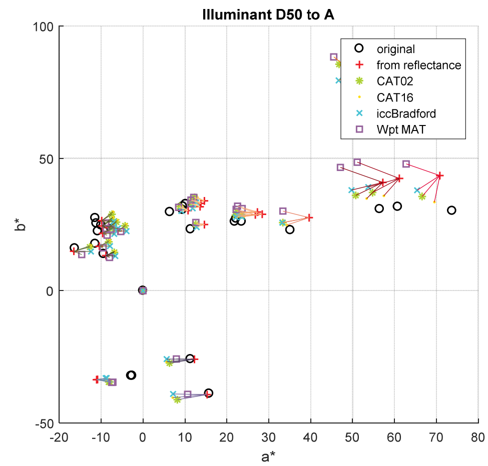

Figure 7. ISO 17321 in-situ reflectances for D65 reference illuminant predicted by the different SATs for D50, A and F11.

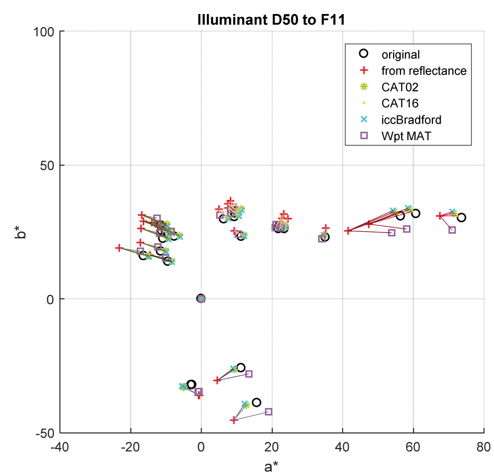

Figure 8. ISO 17321 in-situ reflectances for D65 reference illuminant predicted by the different SATs for D50, A and F11.

Conclusions

Four different transforms were used to predict the effect of a change in illuminant on two sets of reflectances, comprising the 1269 Munsell matt reflectances and the 24 ISO 17321-1 in-situ reflectances. Overall for the Munsell data the Wpt MAT gave the smallest differences between the tristimulus values predicted by the transform and those computed directly from the reflectance for the test illuminant, which is to be expected given that Wpt was optimized for the Munsell reflectances. CAT02 and CAT16 gave very similar predictions. For the ISO 17321-1 in-situ reflectance data the results vary with the reference and test illuminant and no single SAT performs best at predicting the colorimetry computed directly from reflectance, although the linearized Bradford transform adopted in ICC.1 performs reasonably well.

iccMAX provided a convenient framework for implementing the different transforms. Each transform was encoded as a v5 ICC profile using the IccFromXml tool in the iccMAX Reference Implementation. Conversion from reflectance to tristimulus values for the source illuminant was performed using PCC profiles provided in the Reference Implementation, with the header modified in accordance with the wavelength range and interval used, and the conversion from source XYZ to destination XYZ for the different SATs was performed by DToB multiProcessingElements in profiles generated with IccXml. All CMM computations were performed at single precision using 32-bit floats.

The iccMAX framework also supports a wide range of other appearance processing elements. Using the Calc element it is possible to encode any appearance model. Although appearance coordinates are not available as a colour space data encoding in iccMAX, the PCS can be based on appearance coordinates making it possible to connect colour space data via transforms to and from appearance, and an Abstract class profile can be used to connect PCS to modified PCS coordinates. The Calc element also enables transform elements to be defined or selected at run-time.

Although the iccMAX framework provides a technical and computational framework for colour appearance processing, further work is needed to support the wider use of colour appearance models in colour management. Such activities include:

- Create and disseminate best practice recommendations for implementing appearance transforms in colour management applications.
- Develop publicly-available tools such as templates, source code, example profiles, and test data.
- Document the implementation of practical applications in iccMAX, including:

a) One or more colour appearance models

b) A seamless workflow to communicate colour appearance using ICC profiles

c) A workflow that supports parameterization of viewing conditions as environment variables

d) Interoperability Conformance Specifications for the above.

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