ICC Color Management and CIECAM02

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Abstract

The International Color Consortium (ICC) has developed and refined a comprehensive and rigorous system for managing color. The CIE technical committee 8-01 has proposed a color appearance model for imaging applications. This paper describes issues that have to be considered when the CIECAM02 color appearance model is used within the framework of the ICC color management system. They concern decisions about the purpose of using CIECAM02, the selection of appropriate viewing condition parameters, and methods how to deal with the fact that a subset of ICC PCS Lab encoding values are transformed into invalid CIECAM02 values. The proposed solution is to perform a pre-clipping to the boundary of a 3D gamut, which is based on an extended spectral locus and contains most real color world colors, before using CIECAM02. This paper might be a useful reference for researchers and developers, who want to utilize CIECAM02 for generating ICC profiles.

1. Introduction

Color Management can be implemented in various ways, but the ICC has developed an open system architecture, in which ICC profiles are used to translate source color data, which could have been created on a variety of devices and encoded in a number of color spaces, into a reference color space, and from there into a destination color encoding or device's native color space. The core elements are ICC profiles describing how the colors of a particular encoding or device color space should be interpreted in terms of their appearance, the Profile Connection Space (PCS) and Color Management Modules (CMMs), which apply ICC profiles. Within that framework different color reproduction goals are supported and color rendering can either be incorporated in the individual profile perceptual or saturation rendering intents (smart profile) or applied by the CMM (smart CMM) using the colorimetric data from the profiles and potentially content specific information.

The CIECAM02 model provides equations to convert CIE XYZ tristimulus values to and from perceptual attribute correlates based on the specific viewing conditions. The model was optimized by fitting to available data sets of real world colors. It includes a chromatic adaptation transform, non-linear response compression, some luminance level adaptation, and perceptual attribute correlates for three surrounds. The chromatic adaptation transform uses the CAT02 matrix; a more sharpened RGB space that was fitted to many imaging-applicable data sets. The next step converts the data to the Hunt-Pointer-Estevez RGB space before a hyperbolic non-linearity is applied. Afterwards, an initial set of opponent coordinates are computed before calculating perceptual attribute correlates. The model also describes the inverse equations for computing XYZ values given perceptual attribute correlates and viewing condition parameters. CIECAM02 has been defined for individual stimuli (i.e. color patches) presented in a particular environment. It does not address all aspects of appearance in images.

The ICC architecture supports a set of different profile types, but this paper will focus on the generation of output profiles when making use of CIECAM02. An output profile provides a color management system with the information necessary to convert color data between native device data and colorimetric PCS values. The CMM can use any of the four different rendering intents (ICC-absolute colorimetric, media relative colorimetric, perceptual, saturation), where each one represents a different type of color re-rendering suitable for different reproduction goals. This is accomplished by each rendering intent converting to and from the colorimetry of an image in the PCS. The colorimetric intent converts to and from the colorimetry of the actual reproduction, chromatically adapted to the D50 PCS white point. The perceptual intent converts to and from the colorimetry of an image that has been color re-rendered for the perceptual intent reference medium with the re-rendering optimized for natural, pictorial images. The saturation intent converts to and from the colorimetry of an image that has been color re-rendered, with the re-rendering optimized for images with graphical elements, such as solid colors and vector objects.

Color transforms going from device to PCS (XYZ or CIELab data) are stored in AToBx (x=0 for perceptual, x=1 for colorimetric, x=2 for saturation) tags and the data going from PCS to device is stored in BtoAx tags. In the case of a colorimetric rendering intent the AtoB1 tag contains the PCS values corresponding to a uniform sampled 3D grid in device space. The BtoA1 tag contains the device values corresponding to a uniform sampled 3D grid in the PCS. This concept implies that gamut mapping is included and encoded into one 3D LUT for the colorimetric rendering intent. In more detail, the device values for PCS values of the regular grid, which are inside the gamut of the device as represented in the PCS, are interpolated from the measured device values, but the device values for PCS values outside of the gamut have to be mapped at first to the gamut boundary before an interpolation is performed. The concept is visualized in *Figure1*, in which grid points marked with a star symbol are inside the device gamut, versus grid points marked with a black square have to at first be mapped to the gamut boundary, before the interpolation can be performed resulting in corresponding device values. The mapping is visualized as an example for two of the whole set of grid points.

The important issue is that all the points within the encoding range of the PCS (L* between 0 and 100 and a* and b* between -128 and 127) have to be treated in that way. Gamut mapping can be performed in different color spaces. The most straightforward approach would be to use either the XYZ or CIELab PCS color spaces. Gamut mapping in XYZ can cause problems because of the perceptual non-uniformity. Expected problems with gamut mapping in CIELab are hue shifts, especially in the blue area, and issues related to the deviations from perceptually isotropic behavior of CIELAB, especially at large chromas. CIECAM02 has been shown to have a superior perceptual uniformity as well as a better hue constancy, which makes it a candidate color space in which to perform gamut mapping.

The rest of this paper provides details on an implementation using CIECAM02 within the ICC framework to overcome the before mentioned issues. Encountered problems and open issues will be discussed. It should be noted that this discussion applies primarily to the use of CIECAM02 for gamut mapping, as is needed for colorimetric rendering intent transforms. It is important to remember that output profile perceptual and saturation intent transforms re-optimize colors from the PCS reference medium to the actual destination medium, and therefore contain full color re-rendering.

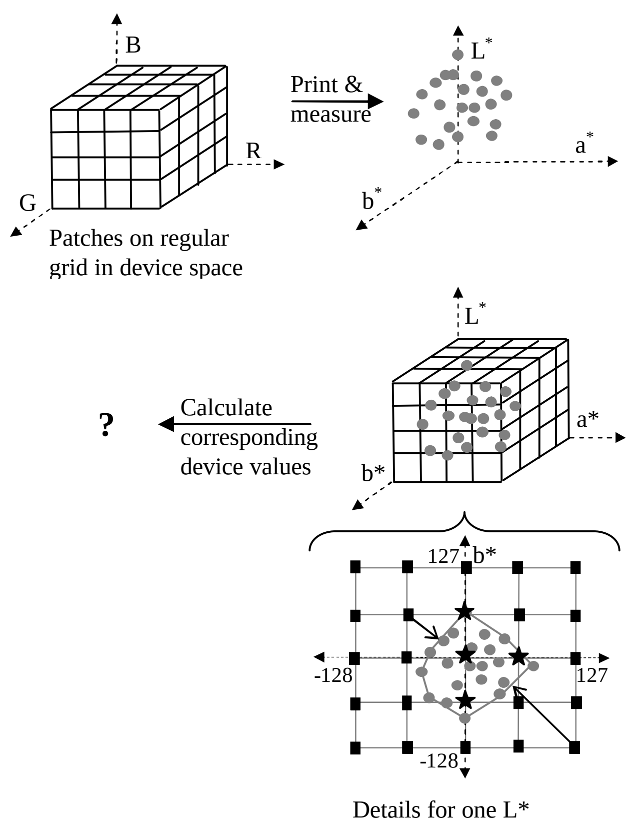


Figure 1: Visualization of the concept how to generate the BtoA1 tag of an ICC profile.

2. Example Implementation

The first step in using the CIECAM02 model is to acquire a solid understanding of the meaning of the different parameters that have to be filled in.

2.1 Meaning of CIECAM02 parameters

The CIECAM02 color appearance model requires the specification of a set of parameters describing the viewing condition for a specific application. Within the ICC framework the PCS can be used in two different ways: the colorimetric PCS simply describes the colorimetry of the actual original or output medium using the colorimetric rendering intents. The perceptual PCS describes the colorimetry as color re-rendered to the standard reference medium under its defined specific viewing condition. It is supposed to hold reference print output-referred image data, which is assumed to be color rendered for the well-defined perceptual reference medium when viewed using the reference viewing condition, which is defined in ISO 3664 as the P2 viewing condition for graphic arts and photography (e.g. the chromaticity of illumination is that of D50, and the illumination level is 500 lux).

With CIECAM02, the calculation of perceptual attributes are for a single color stimulus (patch) with a visual subtense of 2 degrees, surrounded by a background of 10 degrees, viewed within an adapting field (surround). Such calculations require specification of the following parameters:

- **Luminance of the adapting field (L_A):** Luminance of the visual field outside of the background, provided in cd/m^2. In some cases, L_A is estimated from the assumed adapted white point, which is in turn estimated by measuring the luminance reflected from a pressed halon patch with a photometer, or by measuring at first the illuminance (E in lux) and then calculating the luminance ($L=E/\pi$). Making a gray world assumption, the luminance of the adapting field can be approximated by $L_A=L/5$. Depending on the actual application the luminance of the adapting field might have a different relation to E or L. This is just a rule of thumb in the case that no other information is available.

- **CIECAM02 Adopted White Point (X_W, Y_W, Z_W):** This is the computational white point used within the CIECAM02 color appearance model and it may or may not correspond with the adapted white point (see ISO 22028-1 for definitions of the adapted white point and adopted white point). The CIECAM02 Adopted White Point tristimulus values are supposed to be relative to the adopted white point values (e.g. Yw is supposed to be the luminance factor). Also, the CIECAM02 Adopted White Point does not have to be a perfect reflecting diffuser. Going back to L_A, and using a gray world assumption, the absolute values

(Y_{AW} in cd/m2) for the CIECAM02 Adopted White point can be estimated by

$$Y_{AW} = 5 * L_A$$

The relative (X_w, Y_w, Z_w) values can be calculated from the given absolute adopted "reference" white (X_{RW}, Y_{RW}, Z_{RW}) values as follows, and are used as input for CIECAM02

$$X_W = X_{RW} * 100 / Y_{AW}$$

$$Y_W = Y_{RW} * 100 / Y_{AW}$$

$$Z_W = Z_{RW} * 100 / Y_{AW}$$

- **Luminance of the background area (Y_b):** The background is the region immediately surrounding the stimulus and for images it is usually the neighboring portion of the image. If no other information is available an expected mean value can be used, for example by applying a gray world assumption from the CIECAM02 Adopted White Point ($Y_b = 0.2*Y_W$). Some implementers choose a gray world assumption of 0.18 reflectance factor ($Y_b = 0.18*Y_w$).

- **Surround (S_R):** CIECAM02 distinguishes between 3 different types of surround (average, dim, dark), which subsequently define the input parameters c, N_c, F and finally the degree of adaptation. More details on that can be found in the CIE document.

- **Degree of Adaptation (D):** Depending on the application, D can either be directly set (D=1 complete adaptation, D=0 no adaptation) or it can be calculated based on the surround.

2.2 Motivations for using CIECAM02 within an ICC framework

Within an ICC framework a color appearance model can theoretically be used in two different ways:

1) CIECAM02 can be used to create perceptually uniform color spaces for gamut mapping and interpolation purposes

2) CIECAM02 can be used to produce corresponding colors in different viewing conditions, to deal with the color appearance aspects of color re-rendering

In the first case, the hue-constancy and the isotropic behavior of CIECAM02 are used to overcome problems encountered in CIELAB. For an ICC profile, building the PCS to device table for the perceptual rendering intent, the PCS values are first color re-rendered for the actual reproduction medium (typically using proprietary methods), then transformed into CIECAM02, mapped to the device gamut boundary and then transformed into device values. The viewing condition going into CIECAM02 is the same as the one going out of CIECAM02, and should be that of the actual reproduction. The relation between device values and measured colorimetry should be obtained by measurements in the actual viewing conditions. For the colorimetric rendering intents, the relation between measured colorimetry and PCS colorimetry should be encoded in the chromatic adaptation tag.

In the second case, the perceptual intent reference medium viewing condition is used to convert to the CIECAM02 Ja_cb_c values (the rectangular coordinates derived from the chroma correlate), and the reproduction viewing condition parameters are used to convert from Ja_cb_c values directly to corresponding colorimetry in the actual viewing conditions and subsequently to device values. Using CIECAM02 as a reproduction model will by definition attempt to reproduce appearance. In many cases, the most important and difficult to determine part of the perceptual rendering intent is the color re-rendering. Thus, even using CIECAM02 to deal with viewing condition differences doesn't avoid the need for high quality color re-rendering when the destination medium is very different from the source medium, and perceptual re-rendering is desired. Such color re-rendering has to be incorporated when determining perceptual intent transformations. For example, the PCS reference medium colorimetry can be converted to corresponding colorimetry appropriate for the actual output medium viewing conditions prior to performing the color re-rendering, or the color re-rendering can be performed first to create a desirable reproduction on the actual output medium (as transformed to the reference viewing conditions), which is then transformed to the actual output viewing conditions using CIECAM02.

For the implementation described in this paper we used the first approach, but with the additional simplification that the perceptual intent reference medium viewing condition parameters were used for all rendering intents. This avoids the need to use different viewing condition parameters for each actual viewing condition. Since CIECAM02 is only being used as a color space for gamut mapping, this simplification should work well for most actual viewing conditions.

2.3 Selection of CIECAM02 parameters

The CIECAM02 parameters most appropriate for the ICC v4 perceptual intent reference medium viewing conditions were determined in the following way:

1) Virtual prints on the perceptual intent reference medium are assumed to be seen under 500lux, which results in an approximation of the luminance of the adapting field (L_A) of 31.83 cd/m^2.

2) The chromaticities of the white point of the PCS are D50. Calculating the absolute values for the adopted white point leads to X_{RW}=153.45 Y_{RW} =159.15 and Z_{RW}=131.28, which results in the relative values X_W=96.42 Y_W=100 and Z_W=82.49 for the CIECAM02 Adopted White Point.

3) Using the above mentioned guidelines, Y_b=20.

4) For the ICC PCS complete adaptation is assumed, thus the degree of adaptation (D) is set to 1.

5) An average surround is assumed.

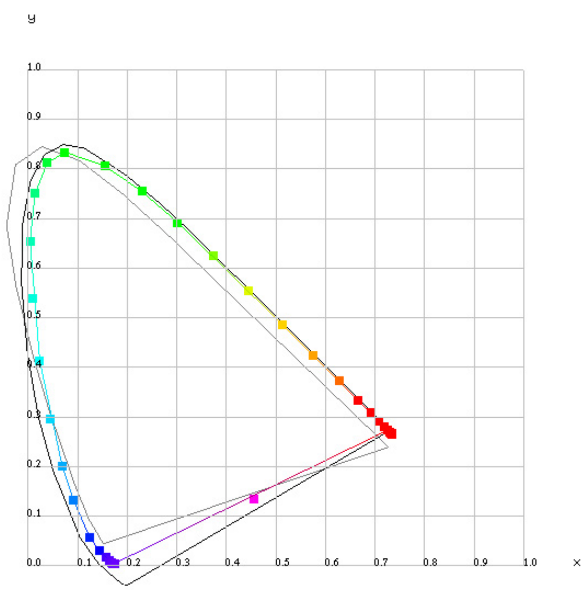
2.4 Valid CIE Lab PCS values are transformed into invalid CIECAM02 values

The goal for this implementation, as mentioned before, is simply to apply the gamut mapping algorithms in CIECAM02 instead of CIELAB, with the objective to avoid the hue shifts occurring when hue-preserving gamut mapping algorithms are applied in CIELAB. At the first glance this just seems to imply an additional transformation from CIELAB into CIECAM02. From an implementation point of view, additional challenges arise and have to be dealt with.

The details are as follows: The color transformation going from the PCS into a device color space is defined for a range of 0 to 100 for L* and -128 to 127 for a* and b*. Thus, those values have to be transformed into XYZ and subsequently into CIECAM02 values. Once in CIECAM02, the values can be further processed. Some of the extreme Lab values will result in negative XYZ values. The ICC specification acknowledges that and recommends that those values are clipped to zero on a component by component basis. Trying to convert those values into CIECAM02 values and then back into XYZ reveals that certain extreme values in the dark area are not invertable. *Figures 4a-d* visualize four different L* slices illustrating the areas within the a*, b* encoding range (-128 to 127) that are not invertable. The lack of invertability of some values creates an engineering problem that has to be dealt with. From a theoretical point of view, CIECAM02 is a color appearance model based on experiments performed with real stimuli, which were well inside the spectrum locus. Colors outside the spectrum locus were not considered in the design.

2.5 Procedure how to deal with Lab values resulting in invalid CIECAM02 values

Existing ICC & CIECAM02 implementations deal with the problem by pre-clipping on various gamuts and once they are within the valid range of CIECAM02 they use CIECAM02. Going along that trajectory and wanting to avoid an arbitrary selection of a pre-clipping gamut, the question is: What is the largest realistic gamut of colors, within which the CIECAM02 calculations hopefully still work? The goal is to take full advantage of the hue constancy and good isotropic behavior of CIECAM02 in as large area as is meaningful. Stimuli used for the definition of CIECAM02 are all well inside the spectrum locus, which is also the boundary for any real world stimuli. The only chromaticity coordinates outside the spectral locus that have to be considered are corresponding colors to real world stimuli viewed with different adaptation states. We considered chromatic adaptation only, using different illuminants. The illuminants that were considered in the current implementation are black body radiators from 2000K to 10000K. *Figure 2a* depicts the points of the spectrum locus, which were considered for the calculation (colored lines) as well as the corresponding colors of the original points using a black body radiator of 2000K (gray line) and 10000K (black line) as extreme examples. Chromaticity values with negative y values (tri-stimulus values with negative luminance) visible in the lower left corner of *Figure 2a* were excluded from subsequent calculations. All the other points were used to calculate a convex hull in 2D and a gamut in 3D. Specifically, the chromaticity values of the convex hull are transformed into rays in the 3D XYZ space and intersected with a plane of Y=100 (this choice is somewhat arbitrary, and could be changed for output devices capable of producing brighter-than-white colors). The 3D object is transformed into CIELAB and can be used as a pre-clipping gamut. The chromaticities of that gamut are visualized in *Figure 2b* (black line) and the 3D gamut is visualized in *Figures 3a* and *3b*. The chromaticities are also provided in *Table 1*.



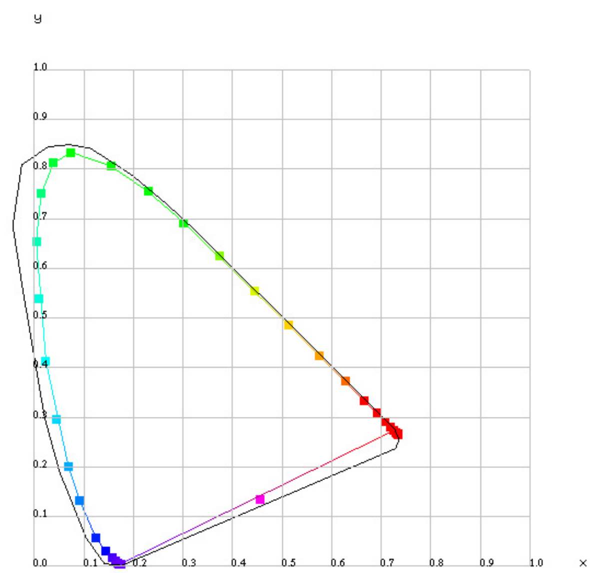
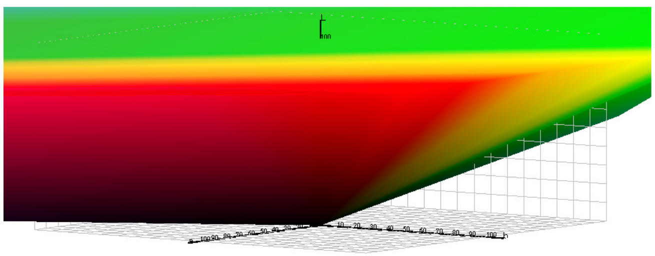


Figure2a (left): Spectral Locus (colored points), Corresponding Colors for spectral stimuli viewed assuming adaptation to a black body radiator of 2000K chromatically adapted to D50 (gray line) and Corresponding Colors for spectral stimuli viewed assuming adaptation to a black body radiator of 10000K chromatically adapted to D50 (black line).
Figure2b (right): Spectral Locus (colored points), chromaticities of gamut proposed to be used for pre-clipping (black line).



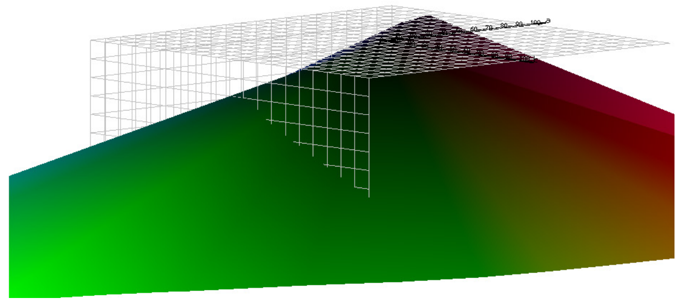


Figure 3a (left): Visualization of Pre-clipping Gamut in CIELAB (L vertical, L*=0 at bottom, L*=100 at top, a* to the left, b* to the right). The top of the gamut is flat with L* values equal to 100.*
Figure 3b (right): Visualization of Pre-clipping Gamut in CIELAB (L vertical, L*=0 at top, L*=100 at bottom, a* to the back, b* to the front).*

x	y
0.0508	0.1904
0.1044	0.0574
0.1412	0.0052
0.7288	0.2373
0.7359	0.2560
0.7359	0.262
0.7354	0.2649
0.7349	0.2665
0.7346	0.2674
0.7344	0.2681
0.7341	0.2689
0.7330	0.2701
0.7263	0.2768
0.71	0.2931
0.672	0.3311
0.5898	0.4136
0.4693	0.5343
0.4034	0.5999
0.3366	0.6651
0.2686	0.7282
0.1962	0.7883
0.1132	0.8418
0.1029	0.8436
0.071	0.8492
0.28	0.8449
-0.0256	0.8087
-0.0435	0.6854
-0.0244	0.5637
0.0206	0.2997

Table 1: Chromaticity values of the pre-clipping gamut

It is also important to note that, as illustrated in *Figure 4a-d*, there are PCS values inside the pre-clipping gamut that are not round-trippable through CIECAM02. We were not aware of this prior to performing this study (although we were aware that chromatic adaptation transforms can produce negative Y values). So far, we have not explored the best way to deal with these dark colors. Fortunately they are well outside the gamut of the perceptual intent reference medium, so they should have minimal impact on the use of ICC color management for print applications.

Having developed a pre-clipping gamut, the second issue is how to use it. Obviously, the pre-clipping can be performed in various color spaces and different mapping algorithms can be deployed for the pre-clipping and the gamut mapping performed in CIECAM02. In the current implementation we used CIELAB as the color space to perform the pre-clipping and a lightness and hue preserving clipping to the pre-clipping gamut. Once inside we used a minimum delta E clipping in CIECAM02 to go to the boundary of the device gamut. One point to be considered is that the colors that need to be pre-clipped are mostly in the dark area. This is clearly visible in *Figure 3a*, where the vertical axis corresponds to L* with white at the top and black at the bottom and vice versa in *Figure 3b*. (The regular grid is for visualization purposes at L*=0 and a*=-100 and b*=-100.) The choice of the mapping to the pre-clipping gamut has an effect for subsequent mapping of colors that are inside, but near to the boundary of the pre-clipping gamut. Colors that are well inside the gamut are not affected. The goal is to avoid any artifacts resulting from the combination of two gamut mapping processes. Again, when we use CIECAM02 to deal with the ICC LAB PCS values, there is no way to avoid some pre-clipping process.

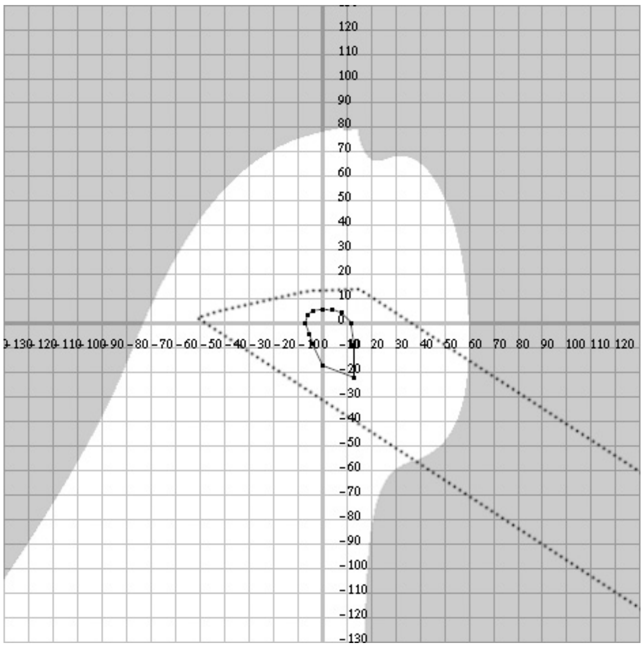


Figure 4a: Visualization of the L= 5 slice of the encoding range of the ICC PCs, indicating the area that is not invertable (gray), in combination with the adapted spectral color clipping boundary from figure _ (dotted line), and the ICC v4 perceptual reference medium gamut (connected small squares).*

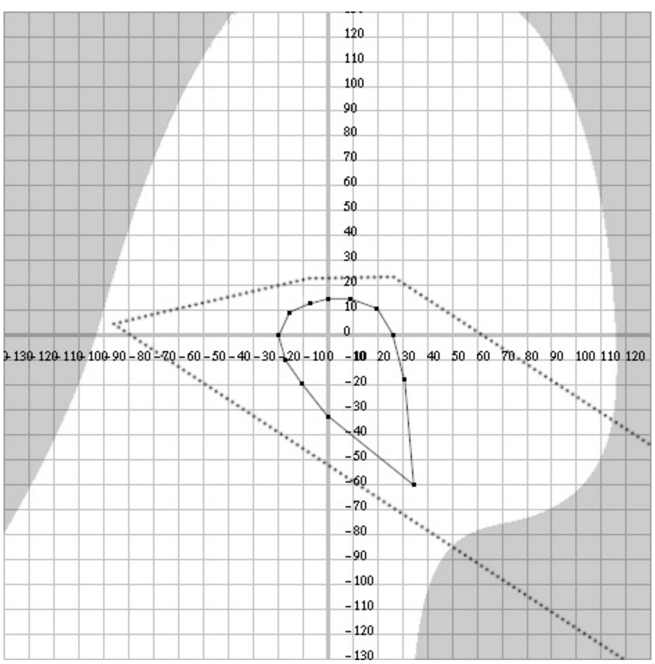


Figure 4b: Same as 2a except L= 10.*

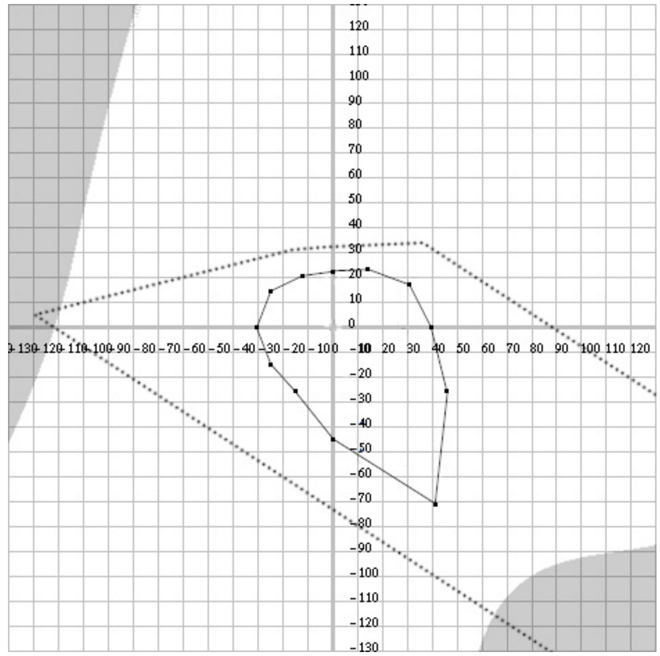


Figure 4c: Same as 2a except L= 15.*

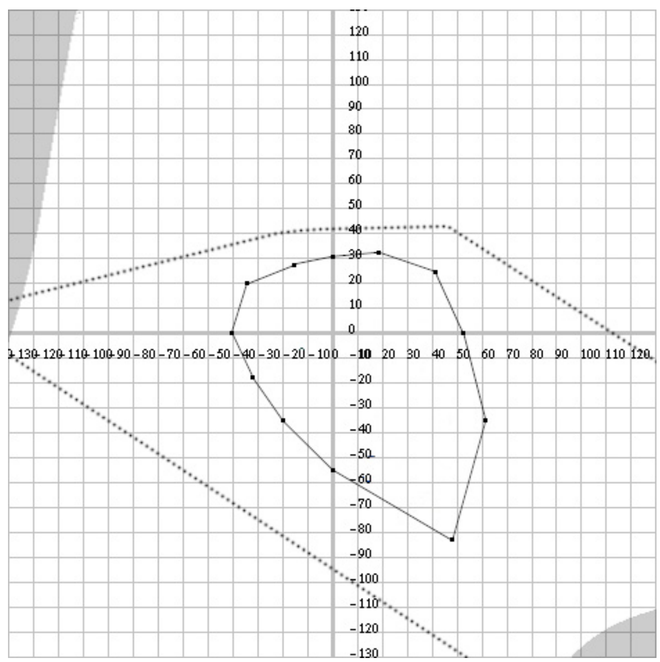


Figure 4d: Same as 2a except L= 20.*

3. Special ICC version 2 perceptual intent issue

There is also a problem unique to ICC version 2 perceptual intents that we encountered. With v2 perceptual intents, the device black point is scaled to zero L* or X,Y,Z in the PCS. The recommended scaling is XYZ scaling, as described in the ICC white paper on black point scaling. However, some profile creation software may apply L* scaling. This can cause erratic behavior near the black point if the scaled values are converted into appearance correlates. For example, a black point that is not exactly neutral will fall outside the spectrum locus if L* is scaled to zero, because colors that have no luminance also cannot have any chroma. Such values are likely to be pre-clipped, and even if not, make no sense from a color appearance standpoint. Ideally, it is best to perform XYZ black point scaling to create the v2 PCS values after all color re-rendering and gamut mapping has been completed using un-scaled values.

4. Generating the perceptual intent of an ICC v4 profile using the Reference Medium Gamut

Until now the focus of this paper has been on how to use CIECAM02 in the process of generating the colorimetric intents of ICC output profiles. However, as mentioned previously, there are some additional considerations when generating perceptual intents, especially for v4 profiles, that are related to the color re-rendering. Unlike the situation in ICCv2, where data from the whole encoding range of the PCS are mapped to the device gamut, ICCv4 has a clearly defined reference medium gamut, and a re-rendering going from the RMG to the device gamut is being performed. From a conceptual point of view data of the encoding range of the PCS is mapped to the boundary of the RMG and then re-rendered to the device gamut. In an implementation those steps can be combined, but care has to be taken to do this in a way that does not create artifacts. It is also necessary to be sure to coordinate the color re-rendering with any gamut mapping that happens either before or afterwards. These considerations are mentioned so they can be expressly included in the design and evaluation of perceptual rendering intent transforms.

5. Discussion

CIECAM02 does not invert for a range of colors, real and impossible, inside the encoding range of the ICC PCS. Therefore, any processing needs to consider careful handling of these colors. This implementation does two geometric mappings – one to the extended spectrum locus and another to the device gamut. It is important to ensure that artifacts do not result from these distinct mappings.

Another point worth considering is whether a color appearance model like CIECAM02 is the best possible choice if one wants to attack the problem of hue constancy and perceptual uniformity. Alternatives would be to perform the gamut mapping in a space like IPT.

Conclusions

Trying to use CIECAM02 within an ICC framework is not as simple as switching from XYZ to CIELAB. It requires careful thought about the goals that one hopes to achieve, careful selection of the CIECAM02 input parameters and management of the expectations. It is not the answer to all the problems and it also produces new problems that have to be dealt with in an appropriate way. Nevertheless, we have outlined an example of successfully using CIECAM02 within the ICC framework.

Acknowledgments

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