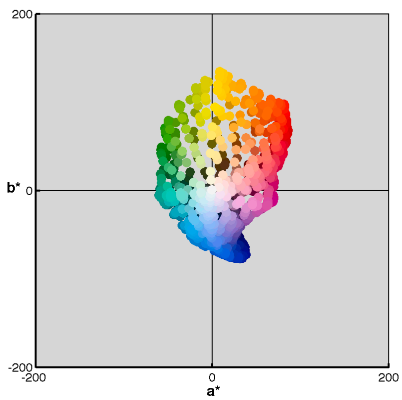
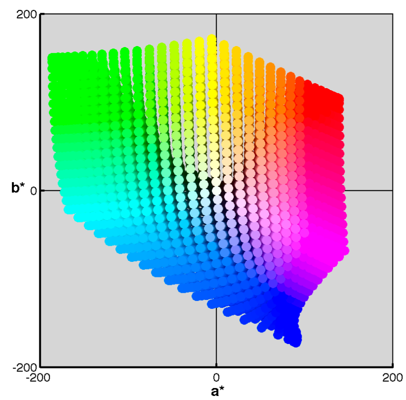
Technical Report

Camera Encoding Evaluation
for
Image Archiving of Cultural Heritage

Roy S. Berns





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Studio for Scientific Imaging and Archiving of Cultural Heritage
PoCS MCSL

Executive Summary

A computational analysis was performed to evaluate color errors caused by color-gamut rendering (encoding) when imaging cultural heritage. The encoding systems evaluated were sRGB, AdobeRGB(1998), eciRGBv2, ProPhotoRGB, ProStarRGB, and Lab. The sample sets included a glossy artist paint color target, eight fluorescent artist paints, a sampling of glossy high-chroma artist paints, computationally extended artist paints, the Pointer gamut, and a computationally extended Pointer gamut. Only the ProPhotoRGB, ProStarRGB, and Lab could encode these datasets without remapping. None of the encoding systems could encode fluorescent materials without error. At 16-bit encoding, gamma values between 1.8 and 2.4 resulted in negligible colorimetric errors while 8-bit encoding produced errors of 0.3CIEDE2000. For the artist paint target, sRGB, AdobeRGB(1998), and eciRGBv2 produced encoding errors between 0.3 and 7.3CIEDE2000 due to out-of-gamut colors. ProPhotoRGB, ProStarRGB, and Lab with 16-bit encoding resulted in negligible color error. Any of these systems are appropriate for cultural-heritage imaging as long as the artwork does not contain fluorescent colorants.

Introduction

Artwork, such a paintings, can have a large range of colors depending on choice of colorants, working method, and the application of a picture varnish. The term "color gamut" is often used to define any range of colors, in particular when the colors are defined by colorimetry. (Any system that produces color can be defined by its color gamut.) A digital camera is a measurement device where, ideally, its signals can be converted to colorimetry with high precision and accuracy enabling the quantification of the artwork's or coloration system's color gamut. That is, the measurement device does not, in itself, have a color gamut; it measures a coloration system's or painting's color gamut. Rather than encode images as floating-point CIE XYZ or CIE L*a*b* data, images are encoded in integer RGB where RGB can be transformed to XYZ with a known set of mathematical operations. ICC RGB profiles define such transformations and are often a combination of a linear matrix transformation and a nonlinear function or look-up table. Examples include sRGB, AdobeRGB(1998), ProPhotoRGB, ProStarRGB, and eciRGBv2. The RGB digital data can be stored as either 8- or 16-bit per channel per pixel.

The choices of primary chromaticities, white point, non-linear function ("gamma"), and bit depth affect color encoding accuracy, what I have called "color gamut rendering."[1] The purpose of this technical report is to evaluate common color gamut rendering encoding schemes used when imaging cultural heritage.

Current Practices

There are two guidelines in common use. The first is the Metamorfoze Preservation Imaging Guidelines,[2] which is "intended for the digitalization of two-dimensional materials

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[1] Berns, R.S, Let's call it "color gamut rendering," *Color Research and Application*, 32, 334-335 (2007).

[2] Dormolen, H. v., *Metamorfoze Preservation Imaging Guidelines: Image Quality, Version 1.0, January 2012* National Library of the Netherlands, The Hague, 2012.

such as manuscripts, archives, books, newspapers and magazines. They may also be applied for digitalizing photographs, paintings and technical drawings." The guideline specifies eciRGBv2 and either 8- or 16-bit depth depending on tonal range. The eciRGBv2 encoding scheme uses National Television System Committee (NTSC) primaries defined in 1953, a D50 white point, and CIE L* instead of an exponent (i.e., gamma).[3] (Version 1 had a 1.8 gamma.) ECI, the European Color Initiative, selected the NTSC primary set because it is already standardized and it is intermediate in rendering gamut between sRGB and ProPhotoRGB, important for 8-bit encoding. Its main purpose was for a pre-press workflow.

The second is the FADGI Technical Guidelines for Digitizing Cultural Heritage Material, which includes "manuscripts, books, graphic illustrations, artwork, maps, plans, photographs, aerial photographs, and objects and artifacts.[4] FADGI recommends AdobeRGB(1998) at 8-bit. This encoding space has a primary set that is based on the television primaries Rec. ITU-R BT.709 (also used in sRGB). Because of a typographic error, the green primary of AdobeRGB extended the encoding gamut compared with these television primaries. The non-linear function is a gamma of approximately 2.2. It has a D65 white point. Recommending AdobeRGB(1998) was based on evaluating cultural heritage with limited color gamuts such as manuscripts, photographs, and graphic illustrations. Artwork, such a paintings, was assumed to produce a similar color gamut compared with those tested.

Neither Metamorfoze nor FADGI evaluated their encoding guidelines for paintings. The main value of these documents is descriptions of objective measures of testing color and spatial image quality of images captured for archiving.

Many existing databases and consumer-level digital cameras encode in sRGB, developed to represent the color gamut of a typical 1990's computer-controlled CRT display driven by a Windows OS. It uses the Rec. ITU-R BT.709 standardized television primary set (also used in AdobeRGB), a gamma of approximately 2.2, and a D65 white point.[5] Encoding with sRGB enabled direct "plug and play" to displays and printers without additional transformations, such as the ICC profile connection space of XYZ or CIELAB.

There are two large-gamut encoding schemes that are in use today for artwork imaging: ProPhotoRGB and ProStarRGB. Kodak developed ProPhotoRGB; it was named ROMM RGB, originally.[6] Its primaries were selected to encompass most non-fluorescent reflecting materials' colorimetry and to minimize hue errors when used for video processing. It has a D50 white point and a 1.8 gamma. This particular gamma eliminated additional non-linear transformations when using an Apple OS computer-controlled

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[3] ISO/TS 22028-4, *Photography and graphic technology — Extended colour encodings for digital image storage, manipulation and interchange — Part 4: European Colour Initiative RGB colour image encoding [eciRGB (2008)]*, 2012.

[4] Group, F. A. D. I. F.-S. I. W., *Technical Guidelines for Digitizing Cultural Heritage Materials: Creation of Raster Image Master Files* U.S. National Archives and Records Administration, Washington, p. 46, 2010.

[5] Both AdobeRGB(1998) and sRGB have D65 white points. The Bradford chromatic adaptation transform was used to achieve D50 white points. That is, the ICC transformation matrices were used for each encoding space.

[6] Spaulding, K.E, Woolfe, G., Giorgianni, E.J., Optimized extended gamut color encoding for scene-referred and output-referred image states, *Journal of Imaging Science and Technology,* 45 418-426 (2001).

display with a nominal gamma of 1.8.[7] Scott Geffert (Metropolitan Museum of Art and ImagingEtc) and Karl Koch (BasICColor) developed ProStarRGB in 2010.[8] Geffert sought to replace ProPhotoRGB's 1.8 gamma with the L* encoding used in eciRGBv2. (eciRGBv1 was also developed by Koch.) Geffert called this ProStarRGB to clarify that it uses the ProPhotoRGB's primary set and white point and eciRGBv2's L* non-linear function. The reasoning was that for 8-bit encoding, the L* function would produce less banding artifacts than gamma functions in shadows. When used for museum imaging, encoding is always 16 bit.

In the Studio for Scientific Imaging and Archiving of Cultural Heritage (Studio), we currently use ProPhotoRGB and 16-bit encoding. We are using this encoding because of its large rendering gamut, white point of D50, and it is a RGB space. We would not use this for 8-bit encoding.

There are four aspects to choosing an encoding space for artwork archiving within current ICC-based color management: primary set, white point, gamma function, and bit depth.

Colorant Datasets

Six datasets were developed for this evaluation. The first was a set of Golden matte acrylic-dispersion artist paints: rutile titanium dioxide white (PW 6), cobalt blue (PB 28), ultramarine blue (PB 29), phthalocyanine blue (PB 15:4 green shade), phthalocyanine green (PG 7), pyrrole orange (PO 73), arylide yellow (PY 74), pyrrole red (PR 254), dioxazine purple (PV 23), and quinacridone magenta (PR 122) Computational mixtures, based on Kubelka-Munk theory,[9] were made using three chromatic paints and white where the three paints were adjacent in a hue circle. The samples were varnished computationally to a high gloss using the Saunderson correction for refractive index discontinuity.[10] The optical data from actual painted samples measured with an integrating sphere spectrophotometer with specular included were derived using Saunderson values of k_1 = 0.03, k_2 = 0.65, and k_{ins} = 0. When internal reflectance was converted to measured reflectance, k_{ins} was defined at 1.0, simulating a high gloss varnish. There were 1,792 spectra. Colorimetry was calculated for D50 and the 1931 standard observer.

The second dataset used the CIELAB coordinates of the paint dataset. A line segment was defined from L* = 50, C^*_{ab} = 0 to each coordinate defined by L* and C^*_{ab}. The line length was extended by 10%. This is a common type of color-gamut expansion. The reasoning was that this extended-paint gamut would represent more chromatic paints not included in the first dataset. Any colors with negative tristimulus values or luminance factor greater than 1.0 were excluded, resulting in 1,723 coordinates.

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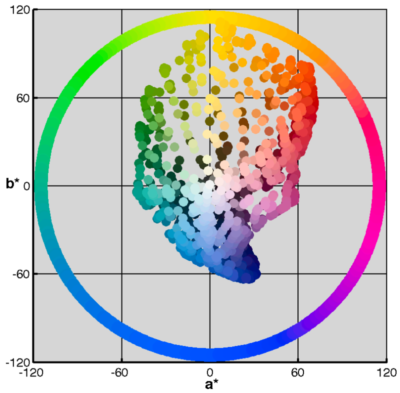
[7] There are various opinions about the reasons for the video card LUTs in an Apple Macintosh having a gamma of 1/1.8 and not 2.2. In my opinion, boosting contrast (2.2/1.8) improved tone reproduction between prints and displayed images because of ambient flare and poor black-level set up.

[8] Personal communications with Carl Koch and Scott Geffert May 2014.

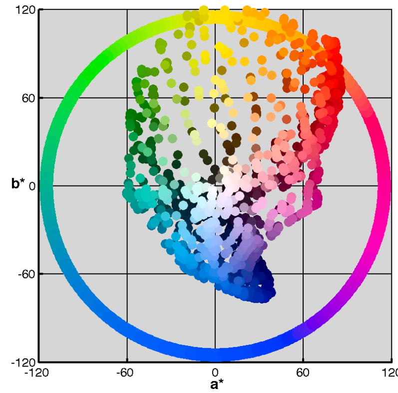
[9] Berns, R. S. and Mohammadi, M., Evaluating single- and two-constant Kubelka-Munk turbid media theory for instrumental-based inpainting, *Studies in Conservation* 52 (4), 299-314, 2007.

[10] F. Moghareh Abed, F.H, Berns, R.S., Masaoka K., Geometry-independent target-based camera colorimetric characterization, *Journal of Imaging Science and Technology*, 57 1050503-1,050503-15 (2013)

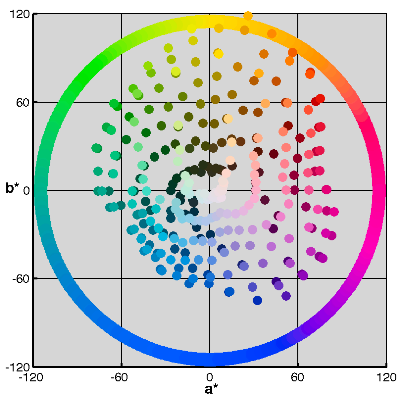
The third database was the well-known Pointer gamut, based on a number of color systems available during the late 1970's.[11] There are 296 CIELAB colorimetric coordinates for Illuminant C and the 1931 standard observer. The CIELAB values were transformed to XYZ and CIECAT02 was used to calculate corresponding colors for D50. The Pointer gamut was one of the datasets used by Kodak when developing ProPhotoRGB.



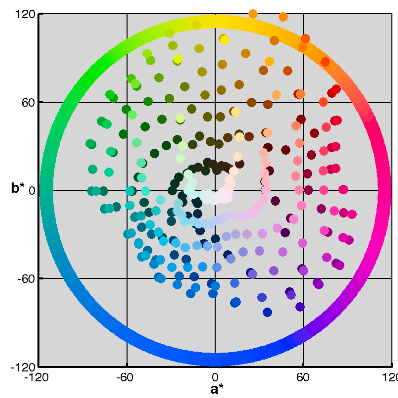
Paint gamut



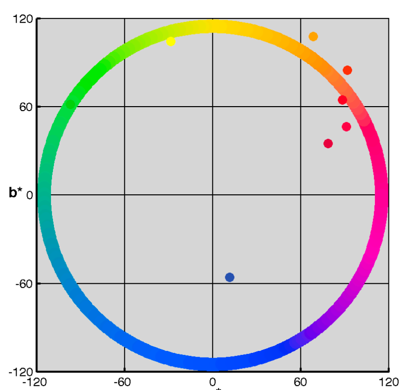
Extended Paint gamut



Pointer gamut



Extended Pointer gamut



Fluorescent paints

Figure 1. Color gamuts of each listed dataset. Image encoding ProPhotoRGB.

[11] Pointer, M.R., The gamut of real surface colours, *Color Research and Application* 5, 145–155 (1980).

The fourth database extended the Pointer gamut in the identical manner to extending the paint gamut, resulting in 295 coordinates. The reasoning was that this increase in color gamut would better represent current coloration systems.[12]

The fifth database was the set of eight fluorescent paints manufactured by Golden Artist Colors: chartreuse, orange-yellow, orange, red, pink, magenta, blue, and green. Drawdowns were prepared at 10mil thickness, followed by measurements with the Gretag-Macbeth XTH spectrophotometer, having a pulsed Xenon simulating D65. Colorimetry was calculated for D65 and the 1931 standard observer. CIECAT02 was used to calculate corresponding colors for D50. These five datasets are plotted in Figure 1.

The fifth dataset was the Artist Paint Target (APT)[13] that consists of 23 matte artist acrylic dispersion paints and Acktar Metal Velvet (sample F4), shown in Figure 2. The samples were measured using an Xrite i1 spectrophotometer and plotted in Figure 3 in CIELAB. Although this target has a large color gamut for matte samples, it is possible to further increase chroma by applying a glossy picture varnish. The Saunderson equation was again used to "varnish" matte samples, the results plotted in Figure 3. The varnished data formed this dataset.

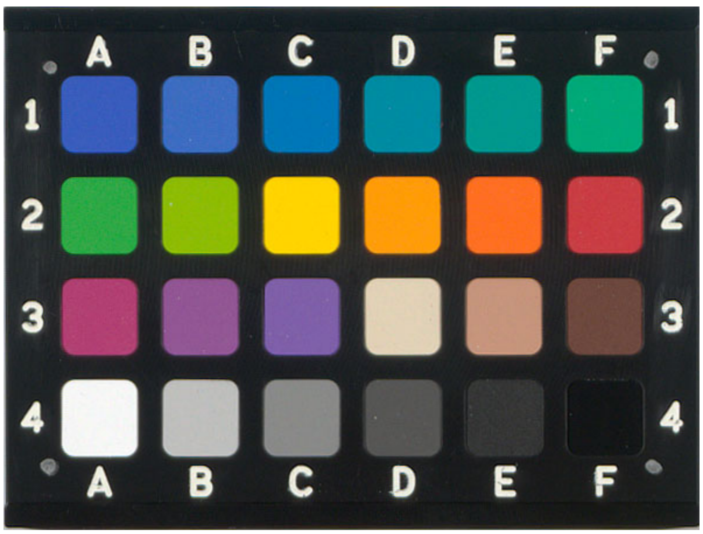


Figure 2. sRGB image of the Artist Paint Target. Image Science Associates manufactured the sample holder.

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[12] See the following for further discussions about color gamuts: Changjun Li, C, Luo, M.R., Pointer, M.R., Green, P., Comparison of real colour gamuts using a new reflectance database, Color Research and Application, on-line (2013).

[13] Berns, R.S, *Artist Paint Target: A Tool for Verifying Camera Performance*, PoCS/MCSL technical report, 2013.

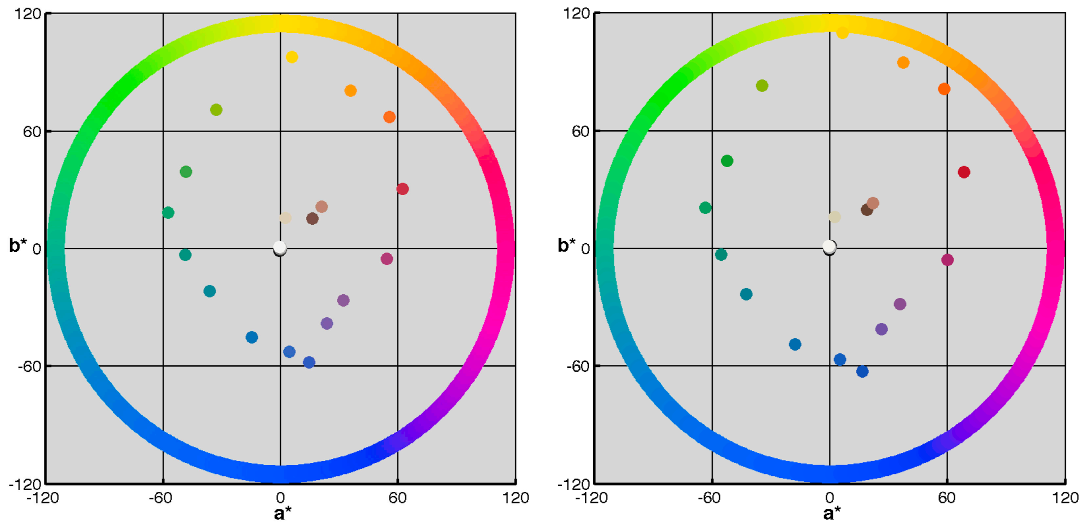
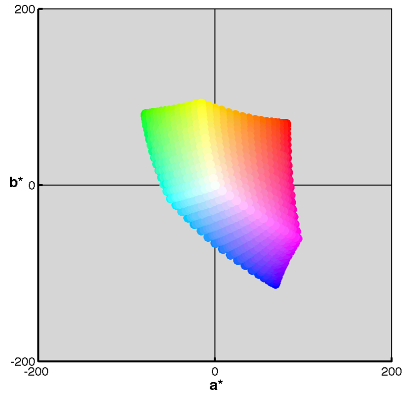


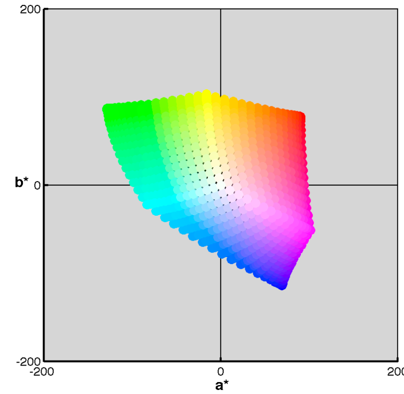
Figure 3. Matte (left) and simulated-glossy (right) Artist Paint Target plotted in CIELAB.

Primary Set Evaluation

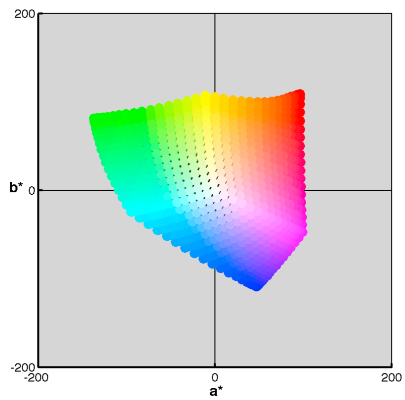
Each encoding space has a tristimulus transformation matrix based on the RGB primary chromaticities and white point XYZ values. Linear RGB floating point data were sampled as a grid, transformed to XYZ using the matrix, converted to LAB, then plotted. The results are shown in Figure 4. The sRGB encoding encompassed the smallest volume while ProPhotoRGB and ProStarRGB encompassed the largest volume, the expected result. Any color outside of a given encoding gamut must be remapped. The extended paint and Pointer gamuts are also shown. Based on a simple visual comparison, it seems that only the sRGB primaries will have encoding errors.



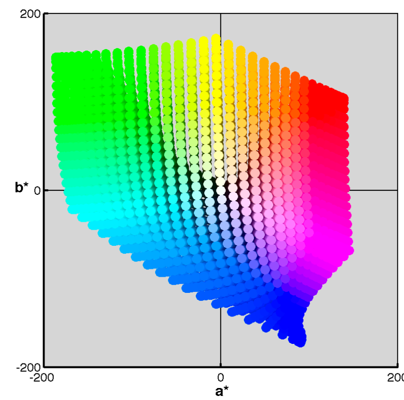
sRGB (Bradford CAT to D50)



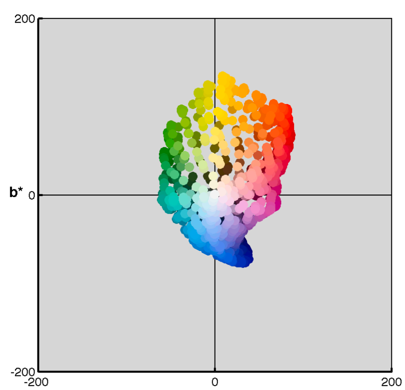
AdobeRGB(1998) (Bradford CAT to D50)



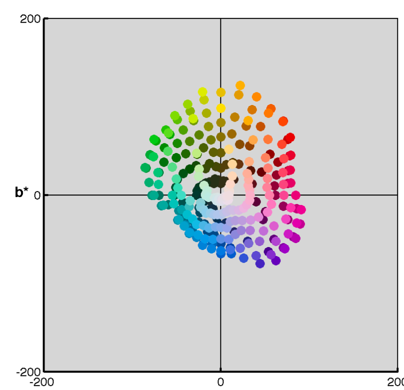
eciRGBv2



ProPhotoRGB or ProStarRGB



Extended Paint gamut



Extended Pointer gamut

Figure 4. Color gamuts of each listed encoding space and the extended paint and extended Pointer gamuts. (The images are encoded in ProPhotoRGB.)

Each database's XYZ data were transformed to RGB using the appropriate transformation matrix. RGBs value less than 0 or greater than 1 indicated an out of gamut color. The percentage of out of gamut colors for each dataset and each encoding scheme is listed in Table I. Colors beyond a* and b* ±128 and L* greater than 100 for the Lab encoding indicated an out of gamut color. The computational results indicate that projecting a color gamut onto the a*b* diagram as shown in Figure 4 is inadequate to evaluate a primary set. For the paint and Pointer gamuts, only ProPhotoRGB, ProStarRGB, and Lab had a sufficient encoding gamut. The poor performance of eciRGBv2 does not support its recommendation by the Metamorfoze Guidelines for paintings. The even poorer results for AdobeRGB(1998) does not support its recommendation by FADGI. ProPhotoRGB and ProStarRGB were unable to encode 21 colors from the two extended datasets. However, these 21 samples were either near white or black with unrealistic chroma values that could not be produced using real colorants (e.g., L* = 90.5, a* = 7.7, b* = 129). Nine of these colors could not be encoded for Lab. The fluorescent colors followed the same trend as the extended paint gamut. Because the chartreuse sample had an L* of 104, it could not be encoded in any of the schemes. ProPhotoRGB, ProStarRGB, and eciRGBv2 were not capable of encoding the chartreuse, orange-yellow, and orange samples. AdobeRGB(1998) could not encode magenta and red in addition to those colors already listed. sRGB could not encode any of the fluorescent colors without error.

Table I. Percentage of out of gamut colors for each listed encoding scheme.

	sRGB	Adobe RGB	eciRGBv2	ProPhoto or ProStar RGB	Lab
Paint gamut	32.2%	16.6%	6.8%	0.0%	0.0%
Extended paint	60.0%	43.8%	39.2%	1.2%	0.5%
Pointer gamut	48.6%	30.7%	22.0%	0.0%	0.0%
Extended Pointer	64.7%	41.4%	36.6%	0.3%	0.3%
Fluorescent paints	100.0%	75.0%	37.5%	37.5%	12.5%
Average	61.1%	41.5%	28.4%	7.8%	2.7%

Evaluating Non-Linear Function: "Gamma"

The glossy Artist Paint Target was used for this analysis. The XYZ data were transformed to RGB using the ProPhotoRGB matrix to insure none of the colors required remapping. The linear RGB data had a $1/\gamma$ applied, then multiplied by 2^16, and finally rounded to integer values. The process was inverted and CIELAB coordinates calculated.

Any encoding scheme leads to quantization errors when converting floating point to integer. A simple approach to evaluate quantization error is to add or subtract a digital count to the baseline digital signal and compare the colorimetric effect. For this analysis, 1 digital count was added to the R and B integer values and 1 digital count was subtracted from the G integer values. To simulate 8-bit encoding, 256 digits were either added or subtracted. The data before and after the addition and subtraction were compared using CIEDE2000.

Three gamma values were tested: 1.0 (linear), 1.8, and 2.4, the latter representing L*.[14] The color differences are plotted in Figure 5, ordered by chroma. The average errors

[14] Note that CIE L* is similar to a 2.4 gamma. See RLAB color space, described in Fairchild, M. D., *Color Appearance Models*, 3rd ed. John Wiley & Sons, Ltd, 2013.

were 0.02, 0.01, and 0.01 CIEDE2000 for the three values, respectively. Linear encoding, which is rarely used, resulted in a 0.17 CIEDE2000 for the black velvet sample. With 16-bit encoding, the differences between 1.8 gamma and 2.4 were negligible.

Some common opinions about optimal gamma values are based on 8-bit encoding. The calculations were repeated, except 256 counts were compared rather than 1 count. The results are plotted in Figure 6, about a 2,000% increase in error compared with 16-bit encoding! These results are consistent with an earlier analysis by the author.[15] These errors are a result of both the 8-bit encoding and the choice of primary set. A large encoding-gamut set such as ProPhotoRGB requires more than 8-bit encoding because reflecting materials do not encompass a large volume within the encoding gamut of ProPhotoRGB.

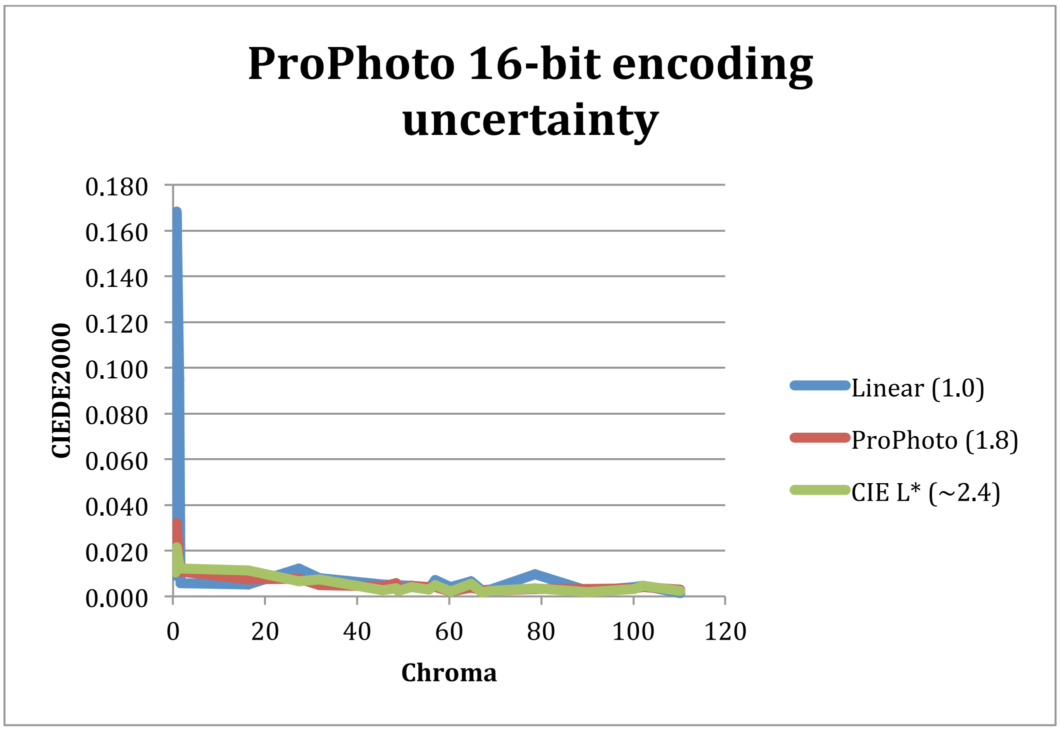


Figure 5. The effect of quantization caused by choice of gamma for 16-bit encoding.

[15] Berns, R. S., The science of digitizing paintings for color-accurate image archives: A review, *Journal of Imaging Science and Technology* 45, 373-383, 2001.

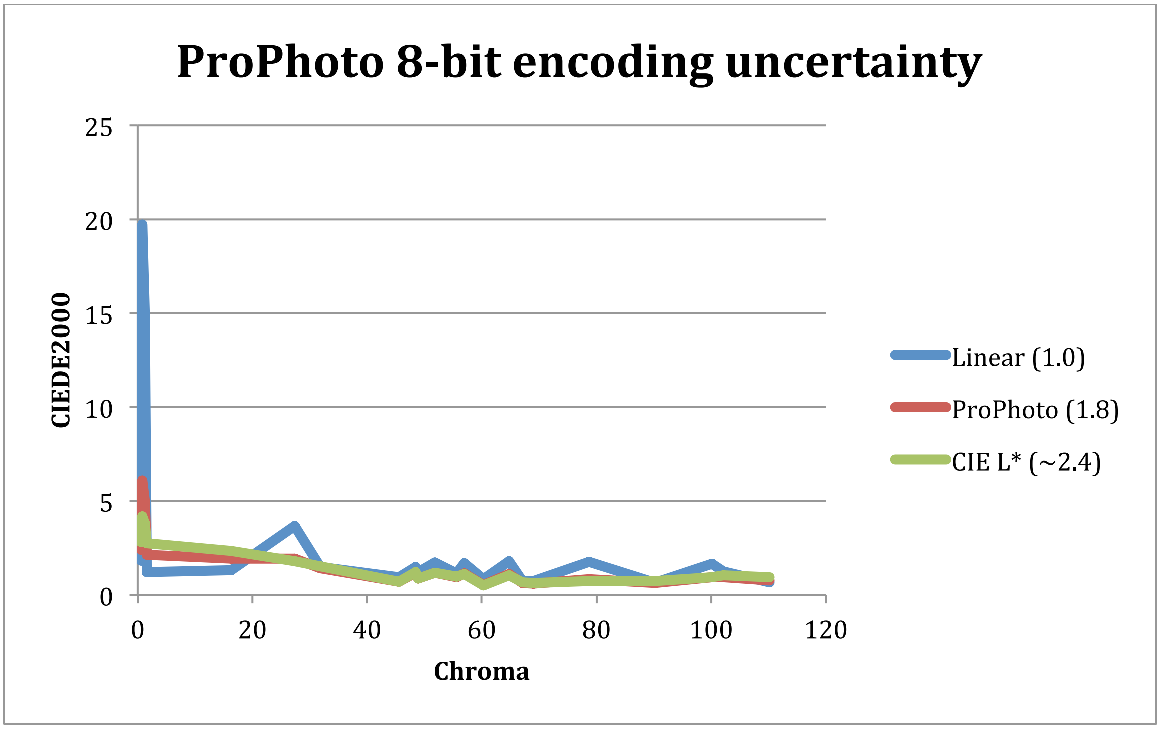


Figure 6. The effect of quantization caused by choice of gamma for 8-bit encoding.

Evaluating Color Gamut Rendering

The encoding schemes listed in Table II were analyzed for color accuracy using the glossy Artist Paint Target. Images can be encoded in CIELAB ("Lab" in Photoshop) in addition to RGB schemes. CIELAB is an obvious choice for color scientists and was included for this reason. The bit depths were selected based on their most common usage. The results are plotted in Figure 7 and listed in Table III.

Table II. Encoding schemes evaluated using the simulated-glossy Artist Paint Target.

Primary set	Bit Depth	Gamma
ProPhotoRGB	16	1.8
eciRGBv2	16	L*
AdobeRGB(1998)	8	2.199
sRGB	8	~2.2
Lab	16	L*
ProStarRGB	16	L*

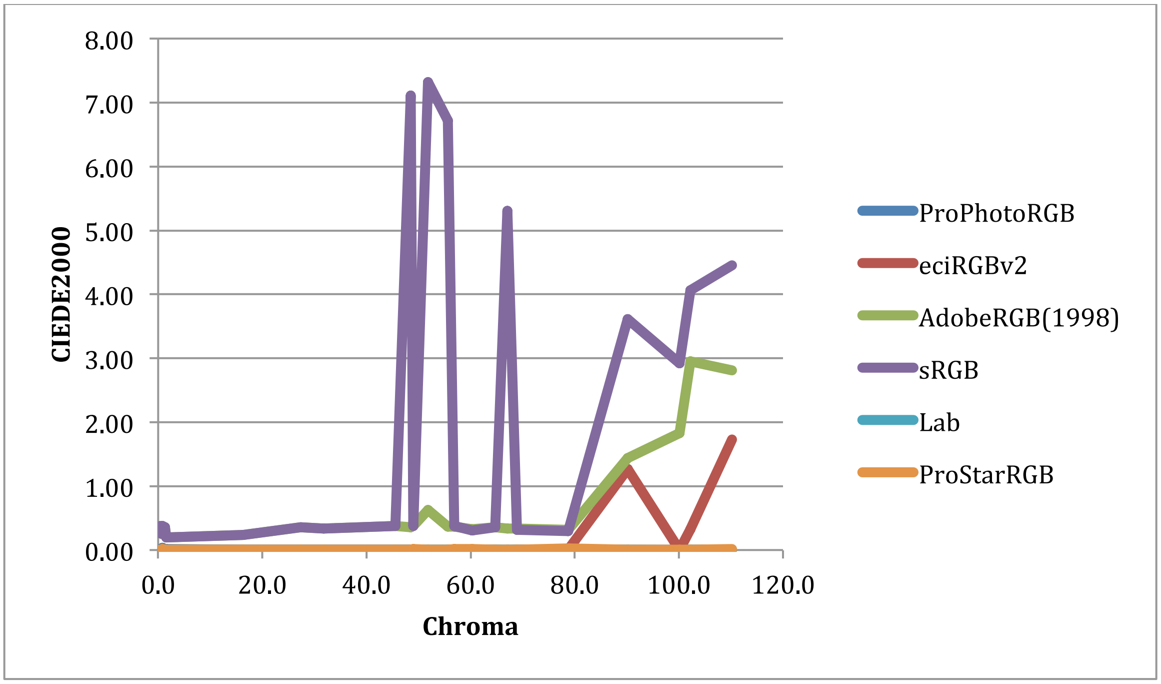


Figure 7. Color gamut rendering errors for each listed encoding scheme.

Table III. CIEDE2000 values for each listed encoding scheme (Table II). Out-of-gamut colors are shown in bold.

Sample	sRGB	AdobeRGB (1998)	eciRGBv2	ProPhoto RGB	ProStarRGB	Lab
A1	0.35	0.36	0.00	0.00	0.00	0.00
A2	0.32	0.34	0.00	0.00	0.01	0.00
A3	0.31	0.32	0.00	0.00	0.01	0.00
A4	0.20	0.20	0.00	0.01	0.00	0.01
B1	0.37	0.37	0.00	0.00	0.01	0.00
B2	**3.61**	**1.44**	**1.26**	0.00	0.00	0.00
B3	0.37	0.38	0.00	0.00	0.00	0.00
B4	0.26	0.26	0.00	0.01	0.00	0.00
C1	**7.32**	**0.63**	0.00	0.00	0.00	0.00
C2	**4.46**	**2.81**	**1.73**	0.00	0.01	0.00
C3	0.38	0.38	0.00	0.00	0.01	0.00
C4	0.38	0.38	0.00	0.01	0.01	0.00
D1	**7.11**	0.36	0.00	0.01	0.00	0.00
D2	**4.06**	**2.95**	**0.32**	0.00	0.01	0.00
D3	0.23	0.23	0.00	0.01	0.00	0.00
D4	0.37	0.37	0.00	0.03	0.01	0.00
E1	**6.72**	0.37	0.00	0.00	0.00	0.00
E2	**2.92**	**1.83**	0.00	0.00	0.00	0.00
E3	0.33	0.33	0.00	0.00	0.00	0.00
E4	0.36	0.36	0.00	0.01	0.00	0.00
F1	**5.31**	0.34	0.00	0.00	0.00	0.00
F2	0.30	0.32	0.00	0.00	0.02	0.00
F3	0.36	0.36	0.00	0.01	0.01	0.00
F4	0.36	0.36	0.00	0.01	0.01	0.00
Mean	**1.95**	**0.67**	**0.14**	**0.01**	**0.01**	**0.00**
90^{th} %	**6.76**	**1.93**	**0.41**	**0.01**	**0.01**	**0.00**
Maximum	**7.32**	**2.95**	**1.73**	**0.03**	**0.02**	**0.01**

The sRGB encoding resulted in the largest errors, the causes both 8-bit depth and clipping. Eight colors were out of gamut producing the large errors readily seen in Figure 7. These colors contained ultramarine blue, phthalocyanine blue, phthalocyanine green, arylide yellow, and pyrrole orange. An insufficient bit depth caused the smaller errors around 0.3CIEDE2000.

AdobeRGB(1998) resulted in appreciable improvement over sRGB because only five colors were out of gamut, and the amount was slight. For in-gamut colors, AdobeRGB and sRGB were nearly identical.

eciRGBv2 resulted in three out-of-gamut colors containing phthalocyanine green, arylide yellow, and pyrrole orange. For the in-gamut colors, the results were excellent with negligible encoding errors. For sRGB, AdobeRGB(1998), and eciRGBv2, clipping occurred for colors near the +b* axis. This is a typical problem using RGB primaries to produce yellows and oranges.

ProPhotoRGB, ProStarRGB, and Lab had identical results with negligible encoding errors. These results support the gamma analysis above where any nonlinear function with 16-bit depth produces excellent results.

Conclusions and Recommendations

It is clear that 8-bit encoding adds quantization errors around 0.3 CIEDE2000 whereas 16-bit encoding did not produce any errors. It is equally clear that sRGB, AdobeRGB(1998), and eciRGBv2 (and v1) cannot encode non-fluorescent paint colors and the Pointer gamut without error caused by insufficient encoding gamut. ProPhotoRGB, ProStarRGB, or CIELAB at 16-bit depth can be used for archiving cultural heritage as long as the artwork does not contain fluorescent colors. None of these encoding schemes can be used for materials that produce luminance factors above 1.0 (L* = 100).

The Studio for Scientific Imaging and Archiving of Cultural Heritage has considerable software with ProPhotoRGB encoding. For this reason, we will continue to use ProPhotoRGB.

There remains a need for a new encoding scheme that is appropriate for artist materials including fluorescent and gonio-chromatic colorants. When such an encoding scheme is available, the Studio will test this scheme and if found acceptable, will replace ProPhotoRGB.