A Color Target for Museum Applications

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Abstract

All museums engage in preventative conservation to insure the longevity of their collections for future generations. One aspect is lighting where there can be a tradeoff between light damage and color appearance. A second aspect is imaging where excessive light exposure reduces accessibility and where digital surrogates increase collection access and reduce handling by maintaining fragile objects in storage. Color fidelity is a critical quality criterion for both aspects. A color target was formulated for museum applications using the absorption and scattering properties of artist acrylic dispersion paints and retouching paints representative of historical and modern paintings. One component of the target was 12 samples varying systematically in CIELAB hue at the maximum achievable chroma. A Euclidean color-difference space based on CIE94 was used to determine chromatic gamut area as a measure of color preference and clarity while color differences weighting hue were a measure of color distortion. Four grays were formulated with a range of color inconstancy under Illuminant A while matching under D65 and four metameric pairs were formulated to represent examples of restorative inpainting with poor pigment selection with respect to metamerism. These samples were very sensitive to changes in spectral power distribution and spectral sensitivity. The target, at this stage only computational, was tested for museum lighting and imaging applications, the results indicative of superior performance to conventional color targets.

Introduction

Preventative conservation is defined as, "the mitigation of deterioration and damage to cultural property through the formulation and implementation of policies and procedures for the following: appropriate environmental conditions; handling and maintenance procedures for storage, exhibition, packing, transport, and use; integrated pest management; emergency preparedness and response; and reformatting/duplication" [1].

Museum lighting is a key component in preventative conservation and there are international recommendations on illuminance levels and minimizing optical radiation below 400 nm [2]. Although there are not standards on correlated color temperature (CCT) or color rendering, it is clear that maintaining a visual experience that is consistent with the artist's intent is a critical component of lighting design [3, 4]. The main way to assess lighting quality is through the visual experience and the use of the CIE general color rendering index [5], well known to be a poor indicator of perceived quality [6].

Another aspect of preventative conservation is the use of digital surrogates and when imaging, minimizing light exposure and excessive handling. Although a digital image is not equivalent to an actual viewing experience, it enables greater access to a museum's complete collection and has obvious benefits for scholarship and conservation. One important property is color accuracy. The main way to assess color accuracy is visual evaluation on calibrated displays, proofing prints, and evaluating calibration targets, exemplified in reference 7. In some cases, custom targets representing the spectral properties of the artwork are evaluated [8], but this is the exception rather than standard practice. Both applications would benefit from a color target designed specifically for museum applications.

Reference Conditions

Lighting, both in galleries and imaging studios, include both natural daylight through windows, skylights, and diffusers, and electric lighting such as tungsten halogen, HMI, ceramic high-intensity discharge, Xenon, and fluorescent. Correlated color temperatures range from about 2,500 K (reduced voltage tungsten) to above 10,000 K (blue sky). The reference condition was defined as D65 and the 1931 standard observer in order to align this research to lighting applications.

Target Development

Based on previous analyses of artist materials [9], the goal to maximize chroma while minimizing the number of pigments in a mixture, and known problems with cobalt blue caused by its long wavelength reflectance "tail" [10], the following Golden Matte Fluid acrylic dispersion paints were selected: cobalt blue, phthalocyanine blue (green shade), permanent green light, hansa yellow light, hansa yellow medium, pyrrole orange, napthol red medium, quinacradone magenta, dioxazine purple, carbon black, and titanium white. The two blues span the spectral properties of many artist blues including ultramarine, Prussian, indigo, and cerulean [9]. Hansa yellow light is a greenish yellow while hansa yellow medium is a reddish yellow. For these two hues, a "cool" and "warm" shade was selected, an approach used with modern painting palettes [11]. The remaining colors filled in the hue circle.

Two opaque (complete hiding) drawdowns were prepared of each paint: a masstone and a tint with titanium white such that maximum chroma was approached (excepting yellow paints). Spectral reflectance factor, $a^*_{94} = 3.1, b^*_{94} = -24.8$, was measured using a Macbeth XTH integrating sphere spectrophotometer in its specular excluded mode. The method described by Berns and Mohammadi was used to estimate each paint's absorption and scattering properties [12]. Because the instrument geometry was specular excluded and the tints were near maximum chroma, the Saunderson correction for refractive index discontinuity was not used.

Using nonlinear optimization, the concentrations, c, of two chromatic pigments adjacent in hue plus white were determined that maximized chroma for a defined hue angle:

$$Z = \text{minimize}\left(1/C^*_{ab}\right)$$
$$\text{subject to}$$
$$h_{ab} = 0, 30, 60, \ldots 330 \tag{1}$$
$$0 \le c \le 1$$
$$c_1 + c_2 \le 1$$

The 12 samples ranged in CIELAB chroma from 37 to 90 and in lightness from 42 to 85. Because of the importance of cobalt blue and maintaining the long wavelength reflectance tail, it was not mixed with phthalocyanine blue, resulting in a hue of 277°. The green at a hue of 150° was reduced in chroma slightly to have a chroma intermediate between 120° and 180°. Otherwise, chromas achieved produced a reasonable ovoid when plotted in CIELAB. Their reflectance factor spectra are plotted in Figure 1.

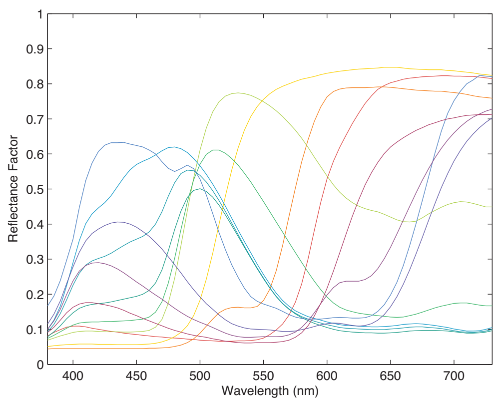

Figure 1. *Reflectance factor spectra of 12 hues at maximum chroma, color-coded using sRGB*

Producing neutrals using complementary colors is a common practice in painting. Furthermore, chromatic-colorant neutrals are sensitive to lighting and non-colorimetric cameras. These paints were formulated in all combinations to achieve a colorimetric match for $L^*=70$, $a^*=b^*=0$. For each spectrum, a color inconstancy index (CII) between illuminants A (test illuminant) and D65 (reference illuminant) was calculated, shown in Eq. 2. The color-difference space, Eq. 3, was based on line-element integration of CIE94, in similar fashion to seminal work by Chasseur in 1989 [13].

This color inconstancy index ignored the well-known lack of performance in CIELAB including its chromatic adaptation transformation and hue linearity [14]. However, because the goal of this research is an evaluation by the museum community, familiarity with CIELAB was considered more important than accuracy. Hue was given twice the weighting because hue differences are more noticeable than chroma or lightness differences for this application. Four samples were selected having a range of color inconstancy. Their spectra are plotted in Figure 2.

Many easel paintings require treatment as they age including removing aged varnish, consolidation of delaminating paint layers, inpainting (retouching), and a variety of structural treatments on the support (e.g., canvas or panel) [15]. Sometimes, the inpainting is metameric to the surrounding area and when the gallery or imaging lighting is different than the conservation studio, a color mismatch may be highly visible, especially if the passage has low spatial frequency. The classic example is bluish sky [10]. The gray complements exemplify this effect where the spectral variation is greatest at long wavelengths. If the imaging input system has its red sensitivity at longer wavelengths than about 600 nm, inpainting will be visible, even if the taking illuminant is similar to the conservation studio lighting. Sets of metamers at low chroma were formulated using 43 colorants dispersed in a urea-aldehyde resin designed for inpainting [16]. For each pair of metamers, ΔH^*_{ab} and a metameric index (MI) was calculated for illuminant A using Eq. (2) except the two samples were compared rather than two lights. The degree of metamerism was greatest for blues and browns and three pairs were selected. The fourth pair was a metameric formulation to a measurement of aged lead white dispersed in linseed oil from the 19th century. The spectra are plotted in Figure 3 and their spectral differences were greatest at long wavelengths, a result of maximizing metamerism for illuminant A. The spectra for the first and second pairs of metamers were very interesting and reminiscent of ink and textile metameric pairs produced for the U.S. Inter-Society Color Council during the 1960's.

$$CII = \sqrt{\left(\frac{\Delta L^*_{94}}{2}\right)^2 + \left(\frac{\Delta C^*_{94}}{2}\right)^2 + \left(\frac{\Delta H^*_{94}}{1}\right)^2}$$
$$\text{where}$$
$$\Delta L^*_{94} = L^*_{94,test} - L^*_{94,reference} \tag{2}$$
$$\Delta C^*_{94} = C^*_{94,test} - C^*_{94,reference}$$
$$\Delta H^*_{94} = \frac{a^*_{94,test} b^*_{94,reference} - a^*_{94,reference} b^*_{94,test}}{\left[0.5\left(C^*_{94,test} C^*_{94,reference} + a^*_{94,test} a^*_{94,reference} + b^*_{94,test} b^*_{94,reference}\right)\right]^{1/2}}$$

$$L^*_{94} = L^*$$
$$\begin{pmatrix} a^*_{94} \\ b^*_{94} \end{pmatrix} = \begin{pmatrix} a^* f\left(C^*_{ab}\right) \\ b^* f\left(C^*_{ab}\right) \end{pmatrix}; C^*_{ab} > 0$$
$$\begin{pmatrix} a^*_{94} \\ b^*_{94} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}; C^*_{ab} = 0 \tag{3}$$
$$\text{where}$$
$$f\left(C^*_{ab}\right) = \frac{\ln\left(1 + 0.045 C^*_{ab}\right)}{0.045 C^*_{ab}}$$

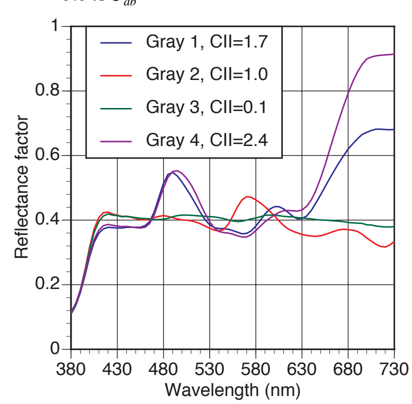

Figure 2*. Reflectance factor spectra of complementary grays. Listed color inconstancy indices compared illuminant A with D65*

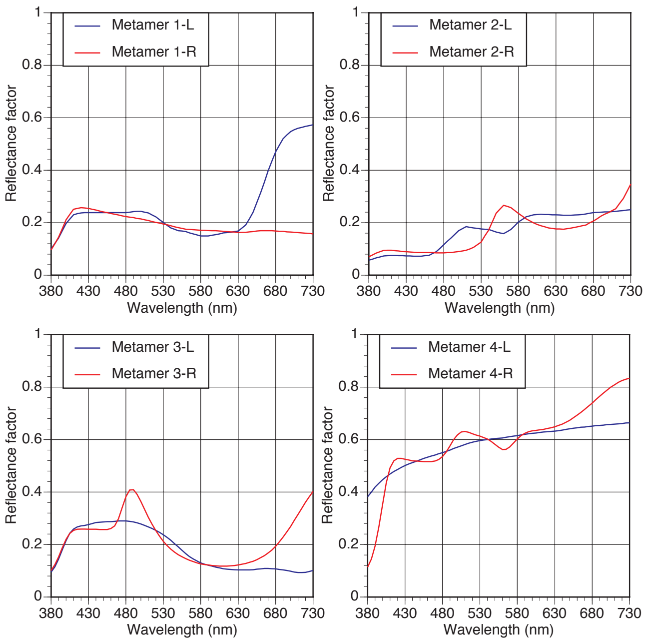

***Figure 3.** Reflectance factor spectra of metameric pairs*

The final target consisted of 24 colors: 12 high chroma colors sampling hue, four grays with a range of color inconstancy (as well as metamers), and four metameric pairs. An sRGB visualization is shown in Figure 4.

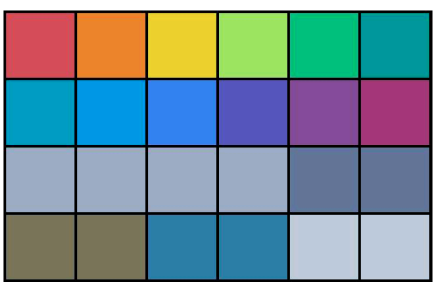

***Figure 4**. sRGB visualization of target for D65 and the 1931 standard observer (Colors outside the sRGB gamut were clipped to 255.)*

Lighting Applications

Suppose that the artist's intent is to display the work under natural daylight, which for this example, was assumed to be equal to D65. If the artist considers color a critical aspect, then it is important to evaluate how the lighting might change appearance if the museum uses electric lighting of either the same or different CCT. Two lights were evaluated, one, a theoretical three-primary white LED [17] composed of three 50 nm bandwidth Gaussian distributions with chromaticities equal to D65, and the second, CIE Illuminant A. LED lighting has the advantage of controllable geometry and the absence of UV and IR optical radiation; this source was designed to render artist paints similar to D65, that is, minimize color inconstancy. Illuminant A has a similar spectrum to tungsten PAR lighting used commonly in museums. The three spectra are plotted in Figure 5, normalized to equal luminance.

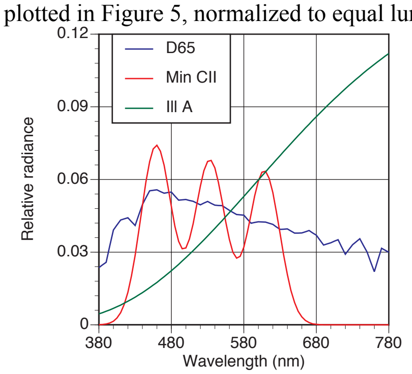

***Figure 5.** Relative radiances (normalized to equal luminance) of reference D65 and two test illuminants ("Min CII" and "Ill A")*

The area encompassed by the hue circle projected onto the a^*_{94}, b^*_{94} plane relates to chroma, contrast, and clarity [18]. Enhancing these perceptions may be preferred and can compensate for very low illuminance levels, sometimes required when displaying artwork that is highly light sensitive. The gamuts are compared in Figure 6 and relative to D65, the source simulating D65 had a gamut of 100% while Illuminant A had a gamut of 95%. The same approach was used by Davis and Ohno using samples from the Munsell Book of Color when evaluating color rendering [19]. The primaries and secondaries (CMYRGB) of the Macbeth ColorChecker were also designed to evaluate color gamut [20]. This type of metric would be more valuable for sources designed to enhance chroma [17] than for these two illuminants.

It was also observed that Illuminant A changed the appearance of most of the hue circle. The color inconstancy indices of the hue circle are listed in Table I. These large values indicate that paintings with a large color gamut would have a very different appearance with incandescent museum lighting compared with their daylight appearance.

Cobalt blue (row 2, column 3; $a^*_{94} = 3.1, b^*_{94} = -24.8$) is well known to take on a reddish quality under incandescent lighting. However, the limitation of CIELAB's chromatic adaptation transformation resulted in this color shifting towards green under illuminant A.

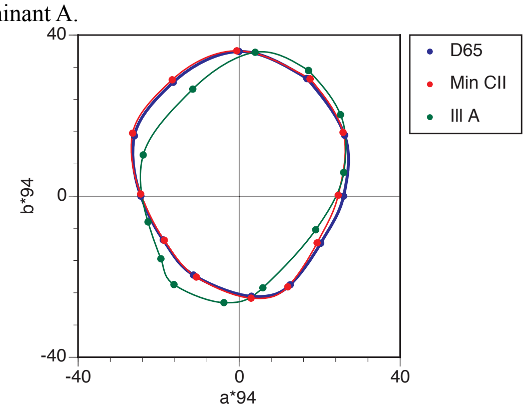

***Figure 6.** Rendering of hue circle for each listed illuminant*

Table I. Color inconstancy (Lighting) and observer metamerism (Imaging) indices for the hue circle spectra

	Lighting		Imaging	
	Min CII	Ill. A	5 Channel	RGB
Hue 30	0.9	6.1	2.1	1.4
Hue 60	0.7	3.5	4.9	2.7
Hue 90	0.6	4.3	3.6	1.7
Hue 120	0.3	4.0	2.1	2.8
Hue 150	0.5	4.2	1.2	3.2
Hue 180	0.5	7.0	1.0	7.5
Hue 210	0.2	4.5	0.7	7.2
Hue 240	0.9	4.4	2.3	2.7
Hue 270	0.4	7.1	6.9	0.4
Hue 300	0.8	6.7	4.9	2.7
Hue 330	0.5	3.1	1.6	1.5
Hue 0	0.7	6.5	0.7	2.3
Average	0.6	5.1	2.7	3.0
95th percentile	0.9	7.0	5.8	7.3
Gamut area	100%	95%	92%	91%

The color inconstancy indices of the grays and metamers are listed in Table II. The target was quite sensitive to slight differences in rendering as the daylight simulator had a general color-rendering index of 94. The 95th percentile is listed because observers are sometimes more critical of large errors than average errors. The poor performance for Illuminant A was expected, particularly for three of the four grays, since they were designed to have poor color constancy for this illuminant. One sample of each metameric pair had poor color constancy, again, as expected.

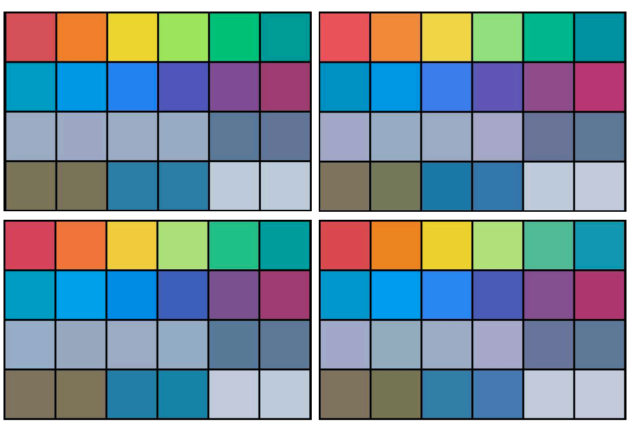

***Figure 7**. sRGB visualization of the spectral target for the daylight simulator minimizing color inconstancy (top left), illuminant A (top right), the five-channel camera (bottom left), and the RGB camera (bottom right)*

As stated in the introduction, inpainting can sometimes result in appreciable metamerism. These metameric pairs evaluated whether a test light will reveal the retouch, desirable to detect the presence of treatment, but undesirable if a color mismatch affects the artist's intent and is distracting. These pairs were quite sensitive to lighting differences, in similar fashion to the gray samples.

Table II. Color inconstancy (Lighting) and observer metamerism (Imaging) indices for the complementary grays and metamers (considered individually)

	Lighting		Imaging	
	Min CII	Ill. A	5 Channel	RGB
Gray 1	0.2	1.7	0.8	2.4
Gray 2	0.6	1.0	0.2	1.4
Gray 3	0.1	0.1	0.1	0.2
Gray 4	0.4	2.4	1.1	3.0
Metamer 1-L	2.0	0.8	2.9	2.6
Metamer 1-R	0.2	2.4	1.8	1.0
Metamer 2-L	0.3	4.6	2.4	3.1
Metamer 2-R	0.5	1.0	1.2	2.3
Metamer 3-L	0.2	2.4	1.9	1.2
Metamer 3-R	0.3	2.4	2.9	6.0
Metamer 4-L	0.1	2.0	1.3	0.8
Metamer 4-R	0.4	3.0	0.9	2.0
Average	0.4	2.0	1.5	2.2
95th percentile	1.2	3.7	2.9	4.4

Table III. Illuminant (Lighting) and observer (Imaging) metameric indices for the metameric pairs

	Lighting		Imaging	
	Min CII	Ill. A	5 Channel	RGB
Gray pair 1	0.6	5.1	0.9	7.0
Gray pair 2	0.7	2.3	1.4	4.1
Metameric pair 1	1.8	3.2	1.0	3.6
Metameric pair 2	0.6	4.1	1.3	5.4
Metameric pair 3	0.5	2.9	1.0	4.8
Metameric pair 4	0.5	1.0	0.4	1.2
Average	0.8	3.1	1.0	4.4
95th percentile	1.5	4.9	1.4	6.6

A visualization of the target for these two illuminants is shown in Figure 7. The CIECAM02 chromatic adaptation transform was used to calculate corresponding colors for Illuminant A. The change in appearance for the hue circle is an approximation as many of the colors are outside the sRGB color gamut.

Imaging Applications

Most digital cameras have spectral sensitivities that are not linear transformations of color matching functions and use color management to improve color accuracy [7]. Two imaging systems were evaluated. The first is a typical color filter array (CFA) RGB camera. The second is an LED system where five chromatic LEDs were used for illumination with a monochrome camera. For this analysis, the monochrome sensor's spectral sensitivity multiplied by each LED's spectral radiance and divided by illuminant D65 was used to represent this camera as a five-channel device. The division enabled treating the system as a monochrome camera with five colored filters with a taking illuminant of D65. A pseudo-inverse spectral calculation was performed to transform both cameras to colorimetric devices minimizing RMS spectral error. The estimated color-matching functions were normalized to equal area. The results are plotted in Figure 8, clearly indicating that neither device is inherently colorimetric. Certainly, there are better approaches to color management, but for the purpose of this example, this simple spectral approach was deemed sufficient.

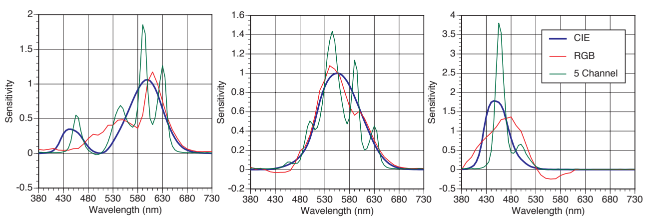

Figure 8. Spectral sensitivities of the CIE 1931 standard observer and its estimate using an RGB and five-channel camera. Each channel is normalized to equal area

Floating-point camera signals were calculated for the target using D65 as the taking and rendering illuminants. Both camera systems distorted the hue circle and reduced area to about 90%, plotted in Figure 9. Rather than color inconstancy, observer metamerism was evaluated where the reference observer was the 1931 standard observer and each camera was the test observer, the usual approach when evaluating camera accuracy. These values are listed in Tables I – III. The two cameras had similar average errors for the hue circle, however, the 95th percentile was 1.5 units larger for the RGB camera, suggesting that images using this camera would be more objectionable.

The degree of observer metamerism for the grays and individual samples comprising the metameric pairs are listed in Table III. Similar to the lighting analysis, these samples were sensitive to observer differences. Note that the third gray, nearly spectrally flat, had very small error for both cameras. This would be equivalent to achieving good gray balance for a Color Checker. Yet, the color-inconstant grays had poor performance for the RGB camera.

When conventional color photography was the main image capture media, poor pigment selection when retouching would be revealed dramatically because film's red spectral sensitivity was shifted towards much longer wavelengths than the eye's L cones. A similar problem was observed using the RGB camera. The poor color reproduction accuracy for this camera was equivalent to illuminating the target under Illuminant A. Even if more sophisticated color management was used, these errors would still result [21]. The target visualization for these cameras is shown in Figure 7.

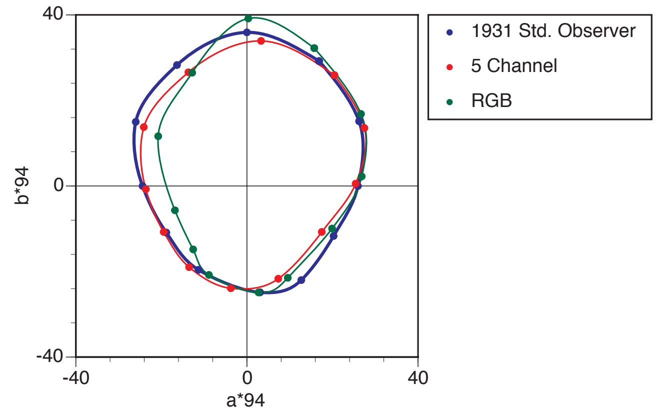

***Figure 9.** Rendering of hue circle for each observer for D65*

Comparisons with the ColorChecker Classic

The X-rite ColorChecker Classic [20] remains an indispensable target and visualizations for D65, illuminant A, the five-channel camera, and the RGB camera are shown in Figure 11. Because the gray scale was designed to be spectrally flat, using Munsell papers, it does not exhibit color inconstancy. The target also does not include metameric pairs. Blue flower (row 1, column 5) was designed to reveal limitations in film spectral sensitivity for the red layer. However, current CFA cameras do not have this limitation to the same extent and this sample has reduced effectiveness compared with the color inconstant grays in the new target. The third row of the ColorChecker remains an effective tool to evaluate changes in gamut; plots in identical fashion to Figures 6 and 9 would reveal the same trends (and limitations of CIELAB).

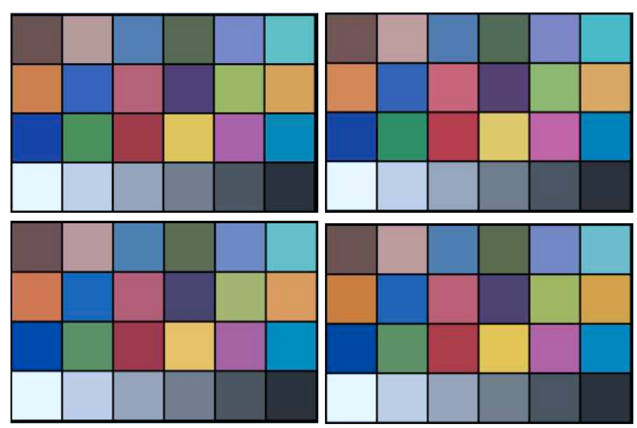

***Figure 11**. sRGB visualization of the Macbeth ColorChecker for D65 (top left), illuminant A (top right), the five-channel camera (bottom left), and the RGB camera (bottom right)*

Conclusions

A color target was formulated for museum applications using the absorption and scattering properties of artist acrylic dispersion paints and pigments dispersed in a urea-aldehyde resin used for inpainting. The target has a number of advantages compared with typical commercial targets. It includes cobalt blue, known to have sensitivity to changes in lighting and image capture. This blue is not used in any commercial targets. It includes a set of grays formulated with chromatic colorants, similar to common painting practice. These grays are color inconstant and are sensitive to changes in lighting and image capture. It includes metameric pairs, also sensitive to lighting and image capture. In particular, this target can reveal potential problems when imaging artwork that has undergone preventative conservation including inpainting where pigment selection did not consider metamerism.

This research also demonstrated the known limitation of CIELAB's chromatic adaptation transformation (CAT) where cobalt blue's corresponding color between illuminants A and D65 was greenish rather than reddish. Although CIELAB can be readily modified to include a more accurate (CAT), first suggested in 1983 [22], a new simple color space may be more appropriate for the art community.

At this stage, it is not possible to suggest quality thresholds, partly because the degree of color inconstancy or metamerism depends on the tradeoff between color appearance and preventative conservation [23]. This might also apply for imaging if the amount of light exposure necessary to achieve high color accuracy limits accessibility.

One possible area for improvement is the hue circle. The design goal was maximizing chroma, assuming colors of high chroma were most susceptible to changes in lighting and camera properties. However, cobalt blue, for example, has poorer color constancy as a lighter tint [24]. It would be interesting to reformulate the hue circle balancing chroma, lightness, and color inconstancy.

Future research will include creating and testing such a color target.

Acknowledgments

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Marissa Haddock earned her B.A. in Film and Video from Columbia College Chicago in 2007 and is completing her M.S. in Color Science at RIT. She is interested in color reproduction methods in various media and became interested in cultural heritage while working in library and museum settings. Her current research interests are related to color matching and paint formulation in the treatment of paintings, and future research will involve restoration of motion picture film.

