Kimberly Frost
Preventive Conservation
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50 Shades of Blue:
Exploring the Impact of Color Temperature on Color-matching and In-painting

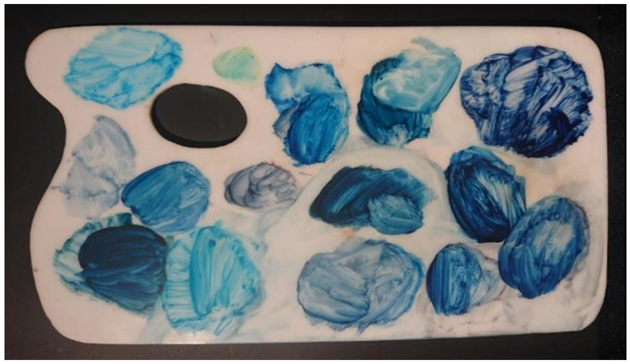

Image by Kimberly Frost

INTRODUCTION

The perception of color results from the interaction of a light source, an object, and the observer's eye-brain system. Changes in these three factors can cause shifts in the perceived color. In some cases, colors may appear to match under one condition, but mis-match under different conditions; this is called metamerism. Changes in both the observer and the illuminant can result in metamerism.

Conservators are often tasked with creating seamless color matches to create invisible in-painting for repairs. The interactions between the structure of an artist's materials, various illuminant sources, and variation in the viewer's visual system make color-matching and in-painting a challenging task. Since museum objects are on view to a wide audience, there is no way to control variation in the observer. Artworks are also frequently moved to different viewing environments, each with its own combination of illuminants. All light sources emit visible radiation, but we do not perceive their light as the same color. Radiation emitted from the source varies across the visible spectrum and results in a different spectral power distribution and perceived color temperature for each source.

Though color temperature is frequently discussed when considering gallery lighting, the color temperature of illuminants used during conservation treatment has garnered less attention. This experiment will consider the color temperature of illuminants used during typical conservation in-painting and evaluate their impact on the conservator's ability to create in-painting which remains color constant across a wide range of illuminants with different color temperatures.

Research Questions:

- Does the color temperature and spectral power distribution of an illuminant impact the conservator's ability to create acceptable color matches?
- What level of light intensity is acceptable for color matching?
- Is the traditional preference for daylight conditions during in-painting justified?
- Is the design of this experiment reproducible for testing these parameters?

EXPERIMENTAL DESIGN

Materials, methods and preferences for in-painting are as diverse as conservators. In this experiment selected pigments were used to create painted samples with intentional losses. Color matches were then mixed and in-painted on the samples at four different illuminant color temperatures. Though conservators may prefer to in-paint with multiple illuminants, for this experiment lighting conditions were controlled by using a single illuminant. In this way, any benefits or deficiencies during color matching should be more noticeable, and could not be attributed to factors outside the illuminant. Finally, the in-painted samples were compared side by side, under a wide range of color temperatures to judge the color constancy of the in-painted matches.

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Why Blue?

Blue has long been known as a problematic color during in-painting. In her article *Retouching and Colour Matching; The Restorer and Metamerism*,[1] Sarah Staniforth suggests that selecting a modern pigment with the closest spectral reflectance curve to the original pigment's can help a conservator avoid metamerism and make matches with good color constancy. Conservators who wish to make a distinguishable in-paint using modern pigments often find this a challenging task for two reasons. First, historical blue pigments often have different spectral reflectance curves than modern blue pigments. Second, because of their variation in reflectance curves at the red wavelengths of the visible spectrum, blues are also very sensitive to changes in color temperature and illuminant metamerism, see Image 1. For these reasons, blue pigments and paints were selected for this experiment since they should be good indicators of changes experienced due to variation in color temperature.

Staniforth recommends that original pigments with a rise in red reflectance, genuine ultramarine and smalt, should be matched with modern cobalt, cerulean or French ultramarine, which also have a peak in red reflectance. Conversely, azurite has a low red reflectance and its recommended matches, Prussian blue and manganese blue are also low in red reflectance. In this experiment 4 modern pigments were used. Two were high in red-reflectance: ultramarine blue, cobalt blue; and two were low in red-reflectance: Prussian blue and manganese blue.

Though the matching scheme suggested by Staniforth was generally helpful, it did not always create successful matches and in some cases the pigment chosen for in-painting varied across lighting conditions, see Table 2. Recent research by Berns, Krueger and Swicklik[2] shows that calculations can be used to find a pigment mixture with an exact spectral reflectance match. Because it relies on reflectance measurements, the method avoids removing sample material, however, it does require the use of a spectrophotometer and the creation of a stock pigment database. Although it may be helpful in specific cases, calculating spectral matches lays beyond the current reach of many conservation departments and professionals.

Sample Preparation

The color of a painting depends on the interaction of superimposed paint layers and the refractive index of their binding medium. A variety of blue pigments, pigment/binder mixtures and layer structures were used to create samples which would emulate those commonly found in traditional paintings. Paint samples were made in three testing groups: lapis pigment (also called genuine ultramarine), azurite pigments, and mixed or manufactured paints. To limit variation in pigment grinding and paint mixtures the four sample swatches were painted at the same time with the same batch of paint or pigment, see Image 2. A temporary liquid rubber masking was applied to a prepared gesso canvas to create reserve losses in the paint layers. After test samples dried, the reserve areas were unmasked and the matching color swatches were separated to create a sample panel on a neutral background for in-painting.

One significant limitation of this experiment is that color samples were made with freshly painted pigments and surfaces. This can only go so far to recreate the challenges of working with aged pigments and binders. However, if an illuminant improves the ability to make good matches when viewing fresh colors, it should also bring the same improvements when working on aged original materials.

Light Sources: In-painting Illuminants

The experiment tested the use of two LED task lamps for use during color matching and in-painting. Measurements were taken with a Sekonic C-700 spectrometer to record lux levels, color temperature, color rendering index, and spectral power distributions of the illuminants during in-painting. Samples were arranged side by side with two losses in each continuous paint sample, then each loss was in-painted under color temperatures differing by about 2000K, see Image 3.

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[1] Staniforth. "Retouching and Colour Matching" *Studies in Conservation*, Vol 30. No. 3 (Aug 1985) pp. 101-111.
[2] Berns, Krueger, Swicklik. "Multiple Pigment Selection" *Studies in Conservation*, Vol 47. No. 1 (2002) pp. 46-61.

The 2 Connolux Task Lamps have differing color temperatures; one approximating 4000K and the other 5000K. This difference in color temperature correlates to differences in their spectral power distributions; the 4000K lamp has a peak in blue wavelengths and a large broad peak in red wavelengths, while the 5000K lamp has a large narrow peak in blue and a broad coverage of green, yellow and red with no peaks, see Image 4. A color temperature approximating 3000K was also tested by applying a warm filter over the 4000K lamp, which reduced the intensity of its blue peak, see Image 5. An additional illuminant tested was traditional northern daylight, which has a broad spectral power distribution with larger peaks in blue wavelengths; it measured anywhere between 6000K and 12000K in color temperature, see Image 5.

Light Sources: Viewing Illuminants

After in-painting, the completed test panels were visually compared and photographed in each of the 4 tested lighting color temperatures. In addition, the panels were also viewed and photographed under tungsten filament lights with a color temperature of about 2700K. This offered a good comparison to the 3000K LED illuminant as they are close in color temperature; however, the tungsten filament's SPD is low in blue and has a large continuous red peak, see Image 6.

Table 1, reports the overall Color Rendering Index (Ra) for all in-painting and viewing illuminants. A quick comparison shows that all illuminants had a generally acceptable score above 90. The illuminants used at 2700K, 4000K and 6000K all scored 98; however, this does not mean that their differences in color temperature do not impact a conservator's color matching and in-painting.

RESULTS

In-painting Testing

The realistic limitations of studio conservators were forefront when thinking about testing procedure. Conservators often develop their own preference when choosing retouching materials. In this experiment I chose dry pigments bound in Polyvinyl acetate AYAB resin. This allowed greater flexibility in choosing individual pigments, adjusting gloss, and creating layered structures. During in-painting, the pigment source, quality, and saturation in binding medium all influenced decisions when making a color match. The paint compositions of samples also played a major role. Paints made from a single pigment or tinted with white were usually easy to match. Samples which had two layers added some complexity but could still be matched. Paints or pigments which seemed to combine multiple peaks of high spectral reflectance were the most difficult to match, see Table 2. Since many in-paintings did not have noticeable color shifts, the following discussion will focus on the most problematic sample from each of the three testing groups: azurite, lapis, and mixed paints.

Discussion
Azurite

Samples were made from two sources of azurite pigment: Kremer Pigments Azurite Extra Deep and azurite from a Japanese source. Differences in their particle size lead to slight differences in hue; but more importantly when mixed with an egg tempera binder the pigments' color looks blue with a greenish hue however, in an oil binder the pigments retain a deeper 'true' blue with no shift towards yellow. Because of its expense and in order to achieve a good consistency the Kremer pigment needed to be ground by hand, whereas the finer particles of the Japanese azurite were used whole. This caused the Kremer azurite sample to have more shift towards the green hue then the sample prepared with Japanese azurite.

Because of its deeper color and more purple hue, the Japanese azurite sample had more notable color shifts under the different illuminants. This in turn impacted pigment choices while in-painting. Under the 4000K illuminant, Prussian blue, with its low red reflectance, was chosen as the closest pigment match. However, to achieve a successful match, red and orange tinting colors were added. Under daylight illumination, a mixture of cobalt blue and ultramarine blue, with their higher red reflectance, were chosen as the closest pigment match. It was then necessary to tint this high red color in the direction of the greenish hue, by adding a cadmium yellow pigment.

In this case the painted sample seemed to fall somewhere above the low-red spectral curve usually seen for azurite. Though this is unusual, the higher quality of the pigment stock and its un-aged conditions might contribute to its deeper color. In this case Staniforth's suggested matching pigment, Prussian blue, was not as successful. The Prussian blue did not match well when viewed under cool color temperatures (5000K, 6000K), where the original pigment looked more vibrant with an increased purple hue. Conversely, the daylight Cobalt-Ultramarine match had minimal shifting and still matched when viewed under the warm color temperature illuminants (4000K-2700K).

Mixed and Manufactured Paint

In order to test matching to un-verified and mixed pigments, samples were prepared with Mussini tube oil paints. The sample prepared from their Cobalt-Cerulean Blue proved the most difficult to match with the available pigment palate. According to Staniforth, Cobalt and Cerulean both have large reflectance peaks in blue wavelengths and in red wavelengths, see Image 1. This causes the paint to have notable shifts in appearance under different illuminant color temperatures.

When viewed under a warm color temperature the color appears muddy, with a yellow cast. In-painting under these conditions resulted in matches that were often too yellow; manganese blue was chosen as the base color but even after adding a red tinting color, the match was not very successful when viewed under other illuminants. When viewed under the cooler 5000K illuminant, a successful match was easily established by adding cobalt, with its higher red-reflectance, and a smaller amount of yellow tinting color. However, when viewed under the very warm tungsten illuminant, this match also appeared too blue.

In this case the warm color temperature detracted from in-painting, because it shifted the sample's appearance too far to the warm red side of its reflectance curve. The cooler color temperature illuminant made it easier to establish a match because it avoided this red reflectance, but it also mis-matched under warm color temperatures. For this sample, neither illuminant provided in-paintings with good color constancy. Since both the 3000K and 5000K illuminant scored lower on their CRI, this result is not surprising. A better match might be established by choosing an illuminant with a higher CRI and avoiding extremes in color temperature which distort the sample color.

Lapis

Samples were also made from a Lapis Lazuli pigment marked good quality from Kremer Pigments. Unlike the azurite samples, whether the pigment was bound in egg tempera or oil medium did not significantly change its color. Lapis was used both as a single paint layer and also with a red, rose madder under layer; a technique sometimes observed in traditional panel paintings to create heightened blue or purple drapery. In all of these samples, the lapis showed significant color shifts from changes in color temperature, see Image 7.

The color shifts observed in the original lapis paints also impacted the matching process during in-painting. When in-painting was completed under a warm color temperature (3000K) the in-painting appeared dull and grey when viewed in the 4000K, 5000K and daylight conditions. Conversely, in-painting completed under cool color temperatures of 5000K and daylight appeared too purple when viewed under warmer illuminants. For the pure lapis sample, the most color constant match was made under the 4000K illuminant. Again, avoiding extremes in the illuminant color temperature during in-painting improved the color constancy of the match.

Illuminant Testing

It is clear from the in-painting process described above that color temperature of the illuminant has an impact on both the ease of color matching and the color constancy of matches. Blues with high spectral reflectance curves in red were usually hard to match. Although they seemed relatively easier to match when working under warm color temperatures, these matches were also the most likely to have mis-matching appearance shifts under cool color temperatures.

Though their SPD's are quite different, viewing and completing in-painting with the 5000K LED lamp and daylight gave comparable color matches. In both conditions, matches made to blues high in red reflectance experienced a color shift when viewed under warmer color temperatures (3000K, 2700K). Among the tested illuminants daylight and the 4000K LED had the best results with only one match being unacceptable for color inconstancy. The 3000K LED and 5000K LED were more problematic for both the experience during in-painting and the color inconstancy of the matches generated. Though this trend generally follows the measured CRI of the tested illuminants, it should be noted that not all illuminants of these same color temperatures will have similar CRI scores. It is clear that both CRI and color temperature should be considered when setting up lighting conditions for color matching and in-painting.

Finally, the intensity of each illuminant was adjusted and measured during the in-painting process. These changes in intensity sometimes resulted in decreased intensity of the color samples, or noticeable changes in their relationships to one another. The difficulty of in-painting increased with a noticeable drop in the intensity of colors at about 500-700 lux.

CONCLUSIONS

The traditional preference for Northern facing daylight and its natural variability rendered surfaces under a much wider range of color temperatures than those achieved by the task lamp. However, the variability of daylight can also be its downfall. On a cloudy day, daylight conditions measured regularly as much as 1000K cooler than average, even when sunny, and up to 5000K cooler under cloudy conditions, see Table 2. In these fluctuating conditions, the benefits of the task lamp would be helpful to balance lux levels during in-painting.

The color temperature of a single illuminant was shown to have significant impact on both the process of in-painting and on the constancy of color matches. However, differences in the spectral power distribution of the illuminants did not seem to create any advantages or disadvantages. Among the tested illuminants, the 4000K LED and daylight generated matches with the best color constancy.

Based on color temperature observations, if daylight with its cool color temperature is not supplemented it can lead to problematic matches. When used together, these sources should provide a well-balanced lighting environment for in-painting. For specific instances where daylight causes known color shifting, it may be preferable to complete in-painting under the 4000K color temperature to avoid metameric mis-matching.

Light levels above 500-700 lux, above normal gallery conditions, were necessary to complete satisfactory in-painting. Though individual conservator differ, using a single illuminant source in a controlled lighting environment and specifying lux levels should make this experiment reproducible for other conservators. The experiment might be repeated with different pigments to evaluate if color temperature conditions are equally important for all ranges of color.

REFERENCES

Berns, Roy S. Jay Krueger and Michael Swicklik “Multiple Pigment Selection for Inpainting Using Visible Reflectance Spectrophotometery” Studies in Conservation, Vol 47. No. 1 (2002) pp. 46-61.

Staniforth, Sarah: “Retouching and Colour Matching; The Restorer and Metamerism.” Studies in Conservation, Vol 30. No. 3 (Aug 1985) pp. 101-111.

APPENDIX I: Images

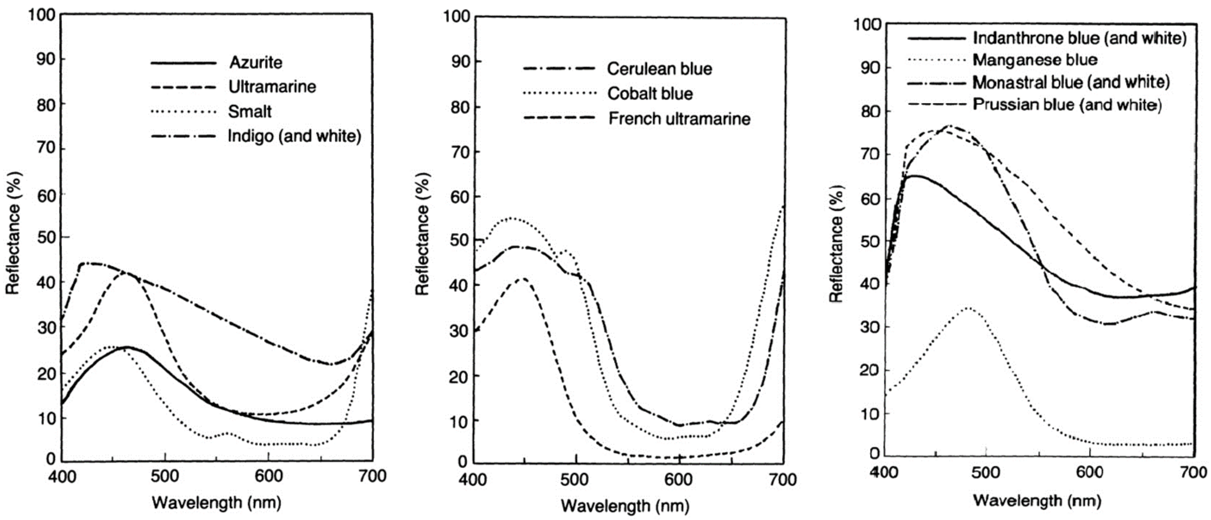

Figure 4a *Traditional blue pigments.*

Figure 4b *Modern blue pigments (high red reflectance).*

Figure 4c *Modern blue pigments (low red reflectance).*

Sarah Staniforth
Studies in Conservation **30** (1985) 101–111

Image 1: Spectral reflectance curves of historic and modern pigments in un-aged paint films, from Sarah Staniforth's article "Retouching and Colour Matching; The Restorer and Metamerism."

Image by Kimberly Frost

Image 2: Painting test samples after liquid rubber masking has been applied to a commercially primed canvas.

4000K 6000K 3000K 5000K

Image by Kimberly Frost

Image 3: Test samples arranged on neutral background and outline of in-painting illuminant color temperature.

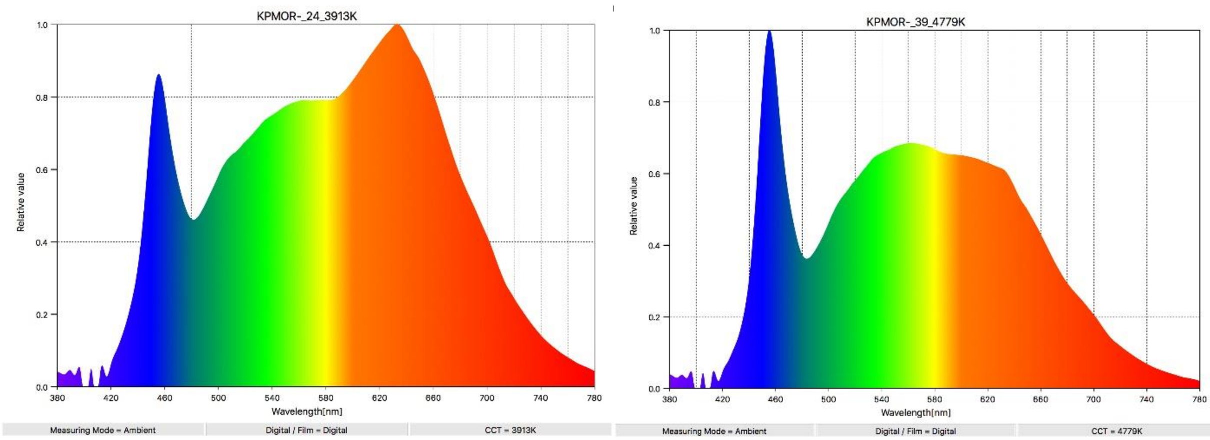

Image 4: Spectral power distrubition of the 4000K LED task lamp on left and 5000K LED task lamp on right. Images courtesy of Chantal Stein.

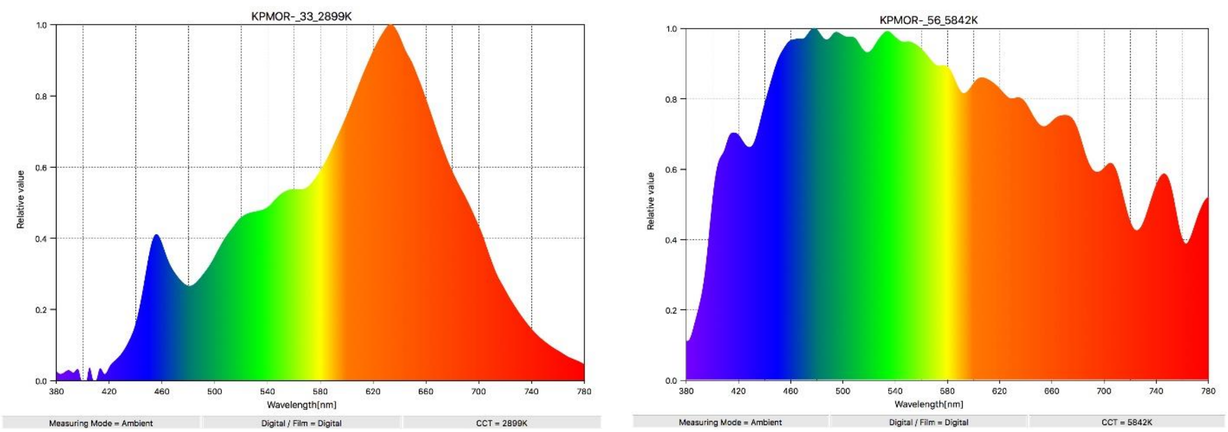

Image 5: Spectral power distribution of the 4000K LED task lamp with warming filter applied on left, and of natural daylight on the right. Images courtesy of Chantal Stein.

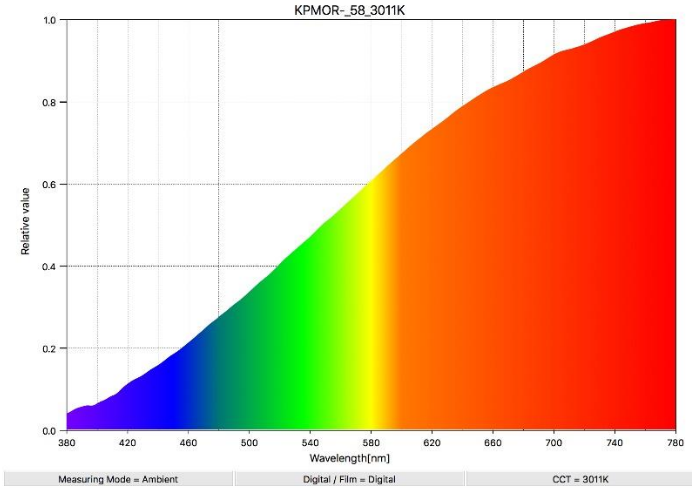

Image 6: Spectral power distribution of tungsten filament illuminant at 27000K, used in photography illumination. Image courtesy of Chantal Stein.

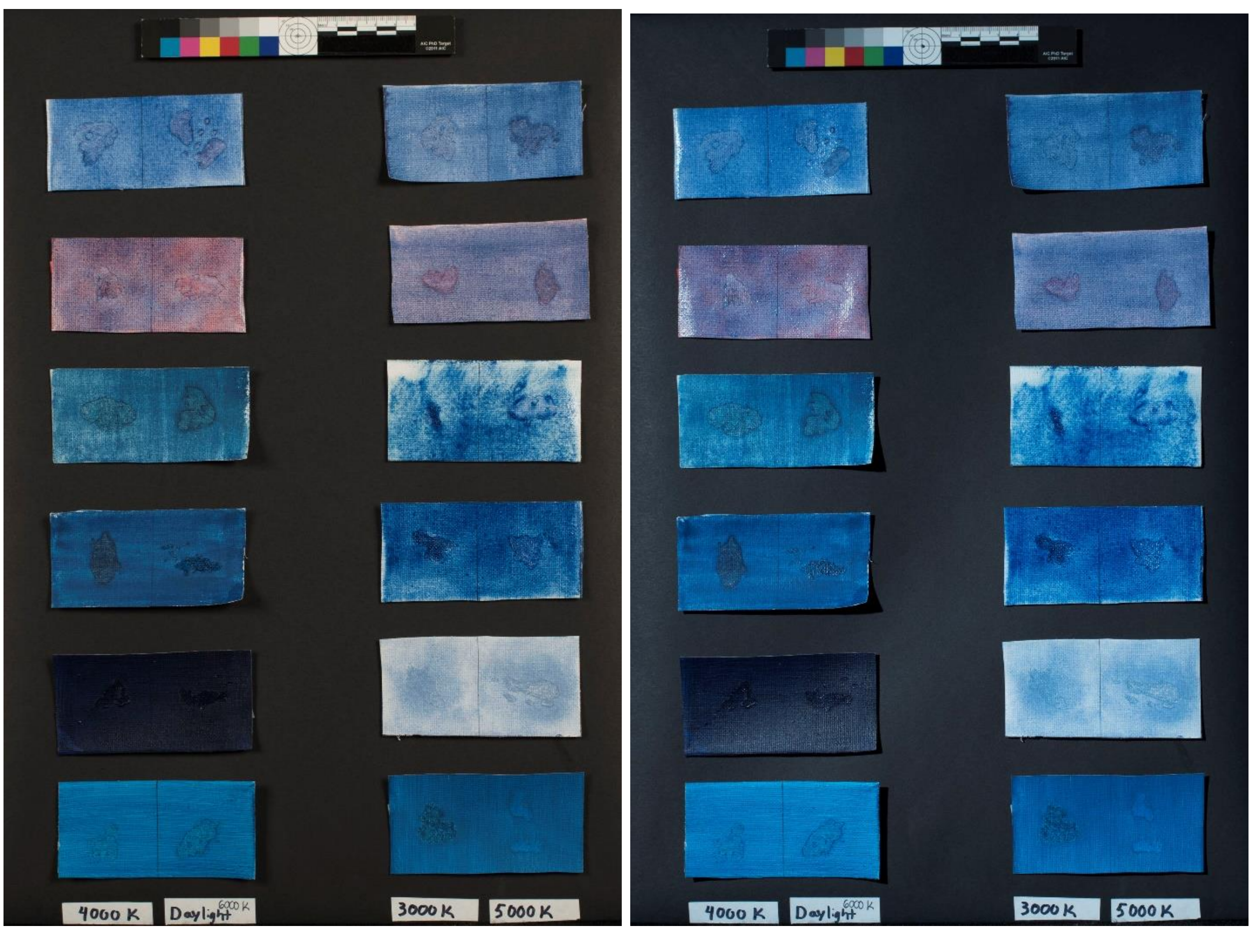

Image 7: In-painted samples photographed with a 2700K color temperature on left and 5000K color temperature on the right. Images by Kimberly Frost

APPENDIX II: Tables

Table 1: Comparison of Illuminant CCT and CRI

Illuminant Source	**Coordinated Color Temperature**	**Color Rendering Index (Ra)**
Photo studio tungsten filament	2700K	98
40 bp LED with filter	3000K	95
40 bp LED	4000K	98
50 LED	5000K	90
Natural daylight	6000K	98

Table 2: Color Matches Recorded During In-painting

Light Source	**40bp**	**Daylight**				**40bp + Filter C**	**50**	
Color Temperature	**4000K**	**Natural Daylight 6000K (variable)**				**3000K**	**5000K**	
Condition Measurements	Lux: 729 CCT: 3862K dUV: -.002	11am Lux: 3630 CCT: 6270K dUV: +0.0051	12:30 pm Lux: 2770 CCT: 5906K dUV:+.0061	2:00 pm Lux: 1370 CCT: 5988K dUV:+.0065	Cloudy Lux: 1170 CCT: 11,136K	Lux: 898 CCT: 2882 dUV: -.0042	Lux: 1150 CCT: 4762K dUV: +0.0039	Lux: 2030 CCT: 4715K dUV: +0.0034
Original paint Composition	**Match A**	**Match B**				**Match A**	**Match B**	
Lapis Kremer oil binder	Ultramarine + cobalt + cadmium red	Patch 1: Cobalt + cadmium red no.1 (good but too purple) Patch 2: cobalt + cadmium red no.1 + cadmium yellow deep (muddy / flat)						
Lapis Kremer egg tempera binder						Cobalt + cadmium red no.1 (easier match but, looks yellow/green in cool lights)	ultramarine + cadmium red no 1 + ivory black +titanium white	
Lapis Kremer + Rose Madder under layer	Layer1: alizarin dark + cadmium red no.1 Layer 2: ultramarine glaze (easy match)	Layer1: alizarin dark + cad. red no.1 Layer 2: ultramarine glaze (easy match)				Layer 1:alizarin dark + cadmium red no.1 Layer 2: Cobalt + alizarin dark + cadmium yellow deep +white (easy to match but looks warm in daylight)	Layer 1:alizarin dark + cadmium yellow deep Layer 2: Ultramarine + titanium white (easy to match)	
Azurite Extra Dark Kremer	Prussian blue + Cadmium red no.1	Layer 1: Prussian blue + cadmium red no. 1 layer 2: Prussian blue + cadmium yellow deep				Ultramarine + cadmium yellow deep +	Ultramarine + cadmium yellow deep + ultramarine glaze	

			ultramarine glaze (easy match)	
Azurite Japan	PB+ alizarin crimson + orange earth	Cobalt + ultramarine + cadmium yellow deep	Ultramarine + cadmium yellow deep (easy match)	Ultramarine + cadmium yellow deep
Lapis Kremer + lead white mixture	X	X	Cobalt blue + titanium white + ivory black (easy match)	Cobalt blue + titanium white + ivory black (easy match)
Mussini Byzantine Blue	Prussian blue + Alizarin crimson dark (2 coats)	Prussian blue + Alizarin crimson dark (2 coats)	X	X
Mussini Cerulean Manganese	Manganese blue + yellow ochre (many coats)	Manganese blue + yellow ochre (many coats)	X	X
Mussini Cobalt Cerulean	X	X	Manganese blue + alizarin crimson dark (very hard to match in warm light; mixes were too yellow)	Manganese blue + cobalt blue + titanium white + yellow ochre