Rejuvenating the Appearance of Cultural Heritage Using Color and Imaging Science Techniques

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ABSTRACT

Many works of art have undergone undesirable changes in color since initial creation. The use of spectral or colorimetric imaging, optical models such as Kubelka-Munk turbid-media theory, sample creation using colorants with similar optical behavior to the artist's materials, and color-image processing has enabled the simulation of a work of art before the color change. This paper describes this approach and demonstrates it use on paintings by Vincent Van Gogh and Georges Seurat.

1. INTRODUCTION

A work of art can change its color over time. Noticeable color changes may include a simultaneous increase in lightness and decrease in chroma (i.e., "fading" or "bleaching"), a decrease in lightness (i.e., "darkening"), or a change in hue (i.e., "staining" or "yellowing"). Surface properties pertaining to roughness may also cause color changes as does changes in varnish properties.

In paintings conservation, the removal and possible replacement of varnish (i.e., "cleaning") leads to one of the most dramatic changes in color. The aged varnish may have significant visible light absorption and scattering compared with a fresh varnish. Because of the controversy surrounding the cleaning of paintings, well summarized by Sutherland,[1] there is a current interest in simulating varnish removal using digital imaging combined with optical models.[2,3]

It is widely known that a number of artist paints may undergo dramatic changes such as red and yellow lakes, smalt, and zinc and chrome yellows. Color changes are not treated, although well documented. Great care is taken to minimize future color deterioration. Thus, simulating the color appearance of a work of art before a color change using digital imaging is a intriguing endeavor.

The simplest approach occurs when the art has passages that have both changed color and remained preserved (e.g., hidden by the frame). One can replace the color in the digital image.[4] When the art does not contain preserved colors, analytical techniques are used to identify the colorants in the passage, samples prepared mimicking the optical properties of the passage, and their spectra and colorimetry measured. Finally, the digital replacement occurs using color-manged imagery.[5]

The author's interest in "digital rejuvenation" resulted from studying Vincent Van Gogh's *Roses*. Van Gogh often used various red lake pigments with extremely poor color stability.[6] (Lake pigments are made by precipitating dyes onto a finely divided inorganic material.) Many of the flowers in *Roses* are light pastels with Munsell Chroma less than /2. Following a microscopic evaluation and the removal of a very small amount of green paint covering the edge of a pinkish-white rose, a vibrant bluish red was revealed (Munsell 1.25R 5/14). Using the color change as a guide, a scanned photograph was rejuvenated using color-adjustment tools in Photoshop. Although not scientifically executed, the image sparked quite an interest at the National Gallery of Art, Washington and beyond.[7] This led to more rigorous digital rejuvenations, the subject of this paper.

2. GENERAL APPROACH

We begin with direct spectrophotometry of the painting in regions where color changes have occurred and if possible, of protected regions. If protected regions do not exist or are not available for measurement, samples are prepared using similar colorants, media, etc. This requires analytical analyses to determine composition. The spectral reflectance data are transformed to a spectral "space" where colorant-mixing behaviour is modelled using linear algebra. Thus far, single-constant Kubelka-

Munk (K-M) turbid media theory for opaque materials has been used. The mixing model is used to create a range of colors between either the protected and degraded regions or between the prepared samples and the degraded regions. Having a range of color choices is important given that the painting, as a whole, has changed color over time. Rejuvenating a color region completely may result in an unnatural appearance in the context of the entire painting. This range of colors is transformed to CIELAB. The painting is imaged using a color-managed imaging system, ideally with spectral sensitivities similar to color-matching functions (or a linear transformation thereof). The image is defined as a CIELAB image. Using Photoshop, image masks are made of the various color regions. Custom Photoshop *Curves* (one-dimensional look-up tables) are created of CIELAB differences between the degraded color (based on the direct spectrophotometry) and a selected color from the range of colors created using the color-mixing model. The custom *Curve* is used as an adjustment layer in Photoshop. This approach maintains the color variability in the masked region. It does assume that the region's color variability is invariant with average color, strictly speaking, impossible since CIELAB is bounded by two points for non-fluorescent materials. It also minimizes inherent differences in geometry and colorimetric accuracy between the spectrophotometer and imaging system.

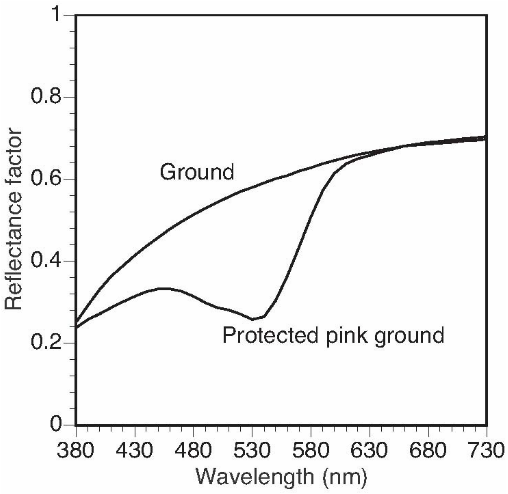

Figure 1. In-situ spectral measurements.

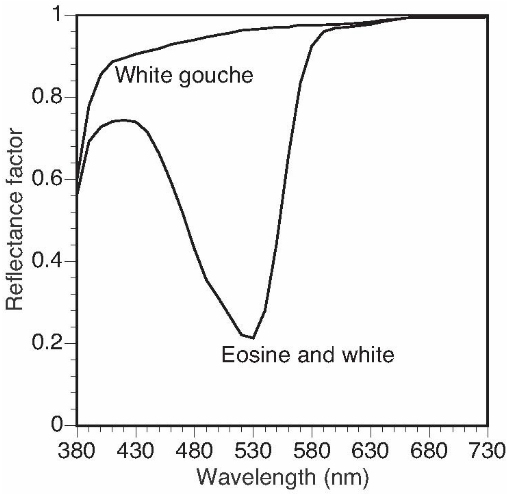

Figure 2. Eosine and white gouche

3. REJUVENATING A FADED PAINTING: VINCENT VAN GOGH'S *DAUBIGNY'S GARDEN*

Daubigny's Garden (F765) is a very interesting painting. Painted in 1890, Van Gogh toned the normally whitish ground layer with geranium lake paint, likely made from the dye eosine, a topical disinfectant. His canvas began as an intense pink color. In regions of grass and foliage, he did not completely paint over the ground layer. This increased the perception of greenness via color contrast. Today, the pink ground is whitish.

On the side of the canvas, a small area of the pink ground has been protected. Spectral measurements of protected and ground areas are shown in Figure 1. For comparison, measurements of a paint out of a white gouche and when mixed with eosine dye are shown in Figure 2. This lake pigment has similar spectral properties to magentas with strong absorption in the middle of the visible spectrum; however, its hue is closer to red than intermediate between red and blue.

Johnston-Feller has shown that the fading of red lake is equivalent optically to changing concentration via K-M theory.[8,9] Using single-constant K-M theory, CIELAB values were calculated that ranged between the faded and protected pink ground of *Daubigny's Garden*.

The Van Gogh Museum does not have colorimetric or spectral imaging capabilities. Instead, medium-format Ektachromes were taken of the painting and of a GretagMacbeth ColorChecker Color Rendition Chart, followed by scanning. The ColorChecker was used to create an ICC profile.[10] Because this approach has poor colorimetric accuracy,[11] in-situ spectrophotometric measurements of the painting were used to make global and local adjustments to the CIELAB image.

The Photoshop image-area selection tool, *Select Color*, was used to create an image mask of the faded ground. Custom *Curves* were created that changed CIELAB coordinates between the faded ground and various concentrations of the geranium red lake. The *Curves* and image mask were used to create a series of adjustment layers that were viewed on a color-managed display by members of the conservation and curatorial staff and the author. The amount of "unfading" had to be subjective because the entire painting has changed color over time, such as changes to the linseed oil medium and varnish layer. The painting in its current state and after digital rejuvenation of the ground color is shown in Figures 3 and 4. As anticipated, the grass looks greener due to color contrast of complementary hues. The appearance of the painting has changed dramatically.

Figure 3. *Daubigny's Garden*, current condition.

Figure 4. *Daubigny's Garden*, digital rejuvenation.

4. REJUVENATING A DARKENED PAINTING: GEORGES SEURAT'S *A SUNDAY ON LA GRANDE JATTE – 1884*

One of the most famous neo-impressionist paintings exemplifying pointillism is Georges Seurat's *A Sunday on La Grande Jatte – 1884*, part of the permanent collection of the Art Institute of Chicago, and the subject of a major exhibition in 2004 including several scientific examinations.[12]

The painting was executed in three distinct campaigns. For the first campaign begun in 1884, Seurat used a palette that included high chroma pigments as well as earth colors and a minimum of black: vermilion, red lake, burnt sienna, iron oxide yellow, chrome yellow, cadmium yellow, viridian, emerald green, ultramarine blue, cobalt blue, lead white and black.[13,14] Seurat's technique was similar to the Impressionists. The second campaign began in the fall of 1885 and incorporated his new divisionist (i.e., "pointillism") technique and ideas about color theory. He abandoned the use of iron oxide yellow, burnt sienna and black while adding zinc yellow and additional hues of chrome yellow, vermilion and red lake. He modified his painting technique employing brushwork in the form of small dots, dabs and dashes (for simplicity referred to as "dots") that were applied next to one another without blending or mixing on the canvas. The painting was exhibited in its revised form in May 1886 at the Eighth and last Impressionist exhibition. The third campaign consists of a border added sometime in 1888-1889.

By 1892, it was reported that the second campaign dots representing colored specular highlights that had initially been luminous yellows, greenish yellows, and oranges had darkened considerably, becoming ochre, olive, and brown, respectively.[15] This was caused by the darkening of the zinc yellow paint[13,14] and became an opportunity to explore digital rejuvenation techniques.[16]

In-situ spectral reflectance measurements were made using a Gretag-Macbeth EyeOne and SpectroEye visible spectrophotometers of brushstrokes containing zinc yellow and a range of colors. Many of the dots and dashes were also sampled to determine specific pigment composition.

A Jenoptik Eyelike Precision M11 digital camera was used to image the painting. Two test targets were also measured spectrally and imaged, the GretagMacbeth ColorChecker DC (CCDC) and a custom target of artist paints. A D50, 2° camera profile was created using the CCDC resulting in average performance of 1.9ΔE_{00} for the CCDC and 2.4ΔE_{00}, for the artist paints.

The first step of the digital rejuvenation involved correcting for natural aging of the painting, which includes the yellowing of the linseed oil, the increased transparency of the lead white and the presence of the underlying paint and ground layers. Using single-constant K-M theory, an "aging spectrum" was calculated using an area of pure lead white (sailboat) and a fresh paint out:

$$(K/S)_{\lambda,\,un-aged} = (K/S)_{\substack{\lambda,\,in-situ\\ measurement}} - (K/S)_{\substack{\lambda,\,aging\\ spectrum}} \qquad minimize\left| L^*_{\substack{fresh\\ white}} - L^*_{un-aged} \right| \tag{1}$$

where $(K/S)_\lambda$ is the K-M absorption (K) and scattering (S) ratio and $(K/S)_\lambda = (1-R_\lambda)^2 / 2R_\lambda$ where R is reflectance factor at wavelength, λ. The aging spectrum was subtracted from each in-situ measurement and CIELAB coordinates calculated. The relationship between the CIELAB coordinates, both before and after un-aging, was modelled empirically and used to create a Photoshop custom *Curves*. *La Grande Jatte* could be un-aged as an adjustment layer.

Fresh paint outs of lead white, zinc yellow, emerald green, and vermilion dispersed in linseed oil and applied to a white board were prepared and measured spectrally. These were used as references for "protected" colors. Differences in opacity between these paint outs and the painting necessitated blending with the spectrum of the underlying paint layers, shown in Eq. 2. Instrumental-based color-matching techniques were used to estimate the background reflectance from CIELAB image data and knowledge of Seurat's palette. Paints outs were estimated for β of 0.5 and 0.75.

$$(K/S)_{\substack{\lambda,\,translucent\\ pa\,int\,out}} = \beta (K/S)_{\substack{\lambda,\,fresh\\ pa\,int\,out}} + (1-\beta)(K/S)_{\lambda,\,background} \qquad 0 \le \beta \le 1 \tag{2}$$

The spectra of several dark-yellow dots, determined to be pure zinc yellow, were averaged, plotted in Figure 5. The darkening affected the long wavelength properties; thus, un-darkening was achieved by interchanging the spectra, once tinting strength differences between Seurat's and the fresh zinc yellow were quantified. Below 470 nm, reflectance was due to absorptions by the yellow pigment and aging. This principle enabled the estimation of the strength of Seurat's zinc yellow. The fresh zinc yellow was scaled so that its spectrum when added to the aging spectrum most closely matched the average in-situ yellow spectrum between 380 and 470 nm, shown in Eq. 3 where *c* defines concentration (strength). The result is also plotted in Figure 5.

$$(K/S)_{\substack{\lambda,\,un-darkened\\ yellow}} = c_{yellow} (K/S)^{\lambda,\,fresh}_{\substack{yellow\\ \beta=0.75}} + (K/S)_{\substack{\lambda,\,ageing\\ spectrum}} \qquad Minimize\left[\sum_{\lambda=380-470} \left\{ (K/S)^{\lambda,\,average}_{\substack{in-situ\\ yellow}} - (K/S)_{\substack{\lambda,\,undarkened\\ yellow}} \right\}^2 \right] \tag{3}$$

Six dark-green dots, containing various proportions of zinc yellow, emerald green and lead white, were measured and their spectra averaged. Previous analyses indicated that emerald green had not darkened significantly;[13] accordingly it should be possible to match this spectrum by a combination of darkened zinc yellow, fresh emerald green, fresh lead white, and the aging spectrum, Eq. 4. The result is plotted in Figure 6. Using the same approach as used to un-darken zinc yellow, an appropriate concentration of fresh zinc yellow with β = 0.75 was determined to replace the scaled in-situ zinc yellow. The final spectrum was calculated by adding the appropriate amounts of each constituent. This process was repeated for dots containing zinc yellow, vermilion, and lead white.

$$(K/S)_{\lambda,\,mix} = c_g (K/S)^{\lambda,\,fresh}_{\substack{green\\ \beta=0.75}} + c_y\Big((K/S)_{\lambda,\,in-situ\,yellow} - (K/S)_{\lambda,\,aging\,spectrum} \Big) + c_w (K/S)_{\lambda,\,fresh\,white} + (K/S)_{\lambda,\,aging\,spectrum}$$

$$Minimize\left[\sum_\lambda \left\{ R_{\lambda,\,in-situ\,green} - R_{\lambda,\,mix} \right\}^2 \right] \quad where\; R_\lambda = 1 + (K/S)_\lambda - \left[(K/S)^2_\lambda + 2(K/S)_\lambda \right]^{1/2} \tag{4}$$

Using Photoshop's *Select Color* and *Magic Wand* editing tools, darkened yellow, green-yellow, and orange dots were selected across the painting. For each color, there was a range of CIELAB coordinates, resulting from differences in pigment concentrations, thickness, and opacity.

Assuming this range was invariant with color, translating their coordinates from darkened to un-darkened values would yield a realistic rendering, that is, retain their natural variability. Photoshop custom *Curves* were created to implement each translation. Following the un-darkening, the image was un-aged, the result shown in Figures 7 and 8. The digitally rejuvenated painting clearly possesses luminosity. The contrast is increased between figures and background. The complementary haloes are more visible, resulting in a greater sense of depth. In the sunlit grass, the dark holes now are points of colored specular highlights.

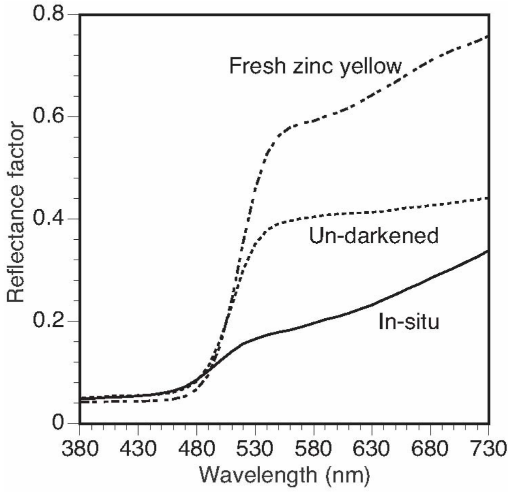

Figure 5. Zinc yellow

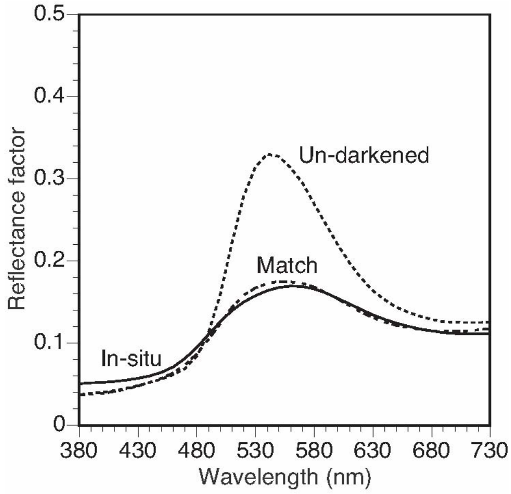

Figure 6. Emerald green and zinc

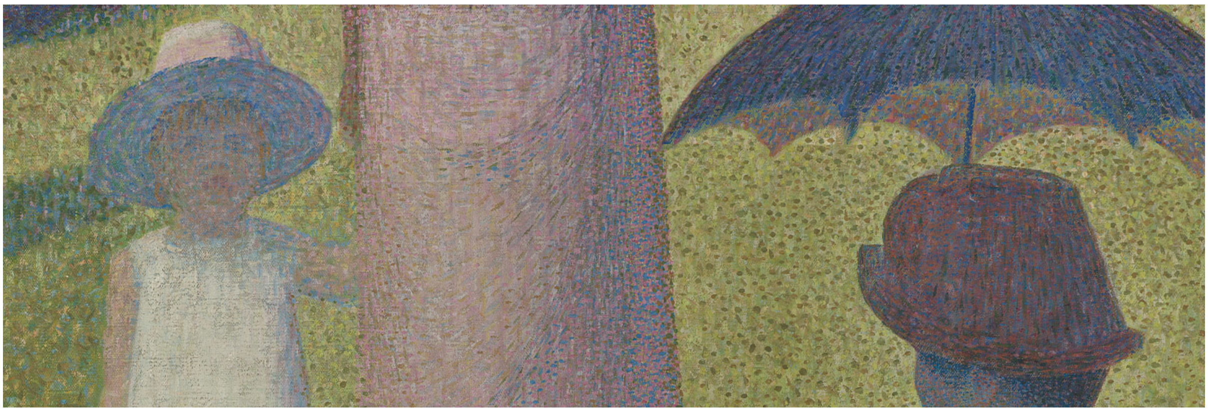

Figure 7. Detail of *A Sunday on La Grande Jatte – 1884* in its current condition.

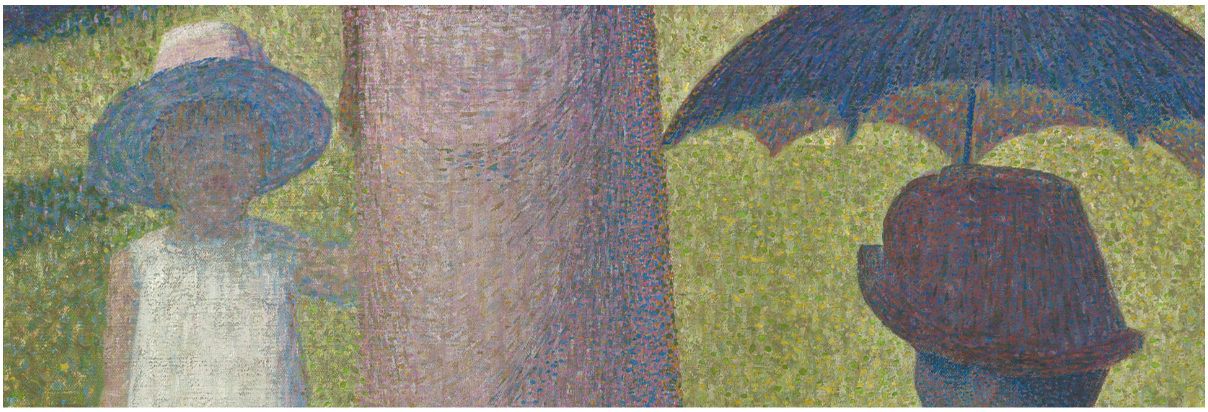

Figure 8. Detail of *A Sunday on La Grande Jatte – 1884* following digital rejuvenation.

5. CONCLUSIONS

Digital rejuvenation provides a glimpse into the past. This glimpse is speculative even adhering to best practices of color and imaging sciences. In the future, the use of spectral imaging and more sophisticated image segmentation should result in a more accurate digital rejuvenation including simulated varnish removal. We also have an interest in creating full-size colorimetric prints that can be viewed by art historians and other connoisseurs, preferably, alongside the actual work of art.

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