Color Accurate Digital Photography of Artworks

Robin D. Myers
Better Light, Inc.
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Introduction

In the world of photography, some colors are not reproduced accurately by either film or digital photography. Colors can change hue, lose or gain saturation, lighten or darken in appearance. For example, some blues turn purple on film or in a digital file and some greens become gray. This article will explain why this problem occurs in the field of digital photography of artworks and propose a solution. While film photography is still a large business, for reasons that will become apparent, digital photography offers better a solution for reproduction photography. The techniques developed here for color accurate artwork photography are also applicable to many other situations where color accuracy is a prime requirement.

The Problem

To understand the issues involved in artwork photography, an especially problematic watercolor painting, *Summer Breeze* by Ann Langston, was borrowed from the artist. This painting contains large amounts of cobalt blue in a wide variety of tints. Cobalt blue is one of the colors that is extremely difficult to reproduce accurately. Ann Langston had this painting photographed with film and then printed on offset presses with varying results.

Figure 1. Different renditions of the watercolor "Summer Breeze" by Ann Langston using traditional photographic reproduction methods.

None of these reproductions is close to the original. When an exposure is made to reproduce cobalt blue correctly, the image becomes too dark or the other colors are incorrectly reproduced (Figure 1, upper-left). An exposure that renders the painting's tonal range correctly results in the cobalt blue turning purple (Figure 1, upper-right and bottom). The problem with correctly imaging this painting is metamerism of the cobalt blue pigment.

Metamerism

The phenomenon where colors match under one set of viewing conditions but they have different spectra is called metamerism.

Viewing conditions are primarily defined by the observer and the lighting. For normal viewing, the observer is usually a human viewing the colors. In the case of photography, the observer is the film or digital sensor. For artwork reproduction photography, the human observer is the reference by which all the other observers are judged. In the most common situation for these observers, color is sensed by three types of color sensors, each sensitive to certain portions of the visible light spectrum.

Since the entire spectrum of visible light is reduced to only three sensors, when any two colors produce the same set of signals from the sensors they then appear to match. It also means that as the differences in the spectra of the colors increase, the probability increases that they will not match if one or more of the viewing conditions changes. For digital photography the viewing conditions related to metamerism are the spectral reflectances of the subjects, the lighting and the sensor.

The concept of metamerism is very important in the practical application of color. The entire color industry is based on the ability to produce metameric matches between colors with different spectra. Every catalog that has a colored item that matches the appearance of the original item is a metameric match between the spectra of the printing inks, the color response of the image recording system (film or digital) and the colors used in making the original object (e.g. dyes or pigments). This is the goal of artwork photography; to reproduce accurately colors on a digital camera that match the colors seen by the human observers.

Observers

When two observers see the same color and it does not match, the reason can be traced to differences in the spectral responses of the observers. Compared in the following graphs are the spectral sensitivities of the standard observer (human response) to those of a typical digital sensor.
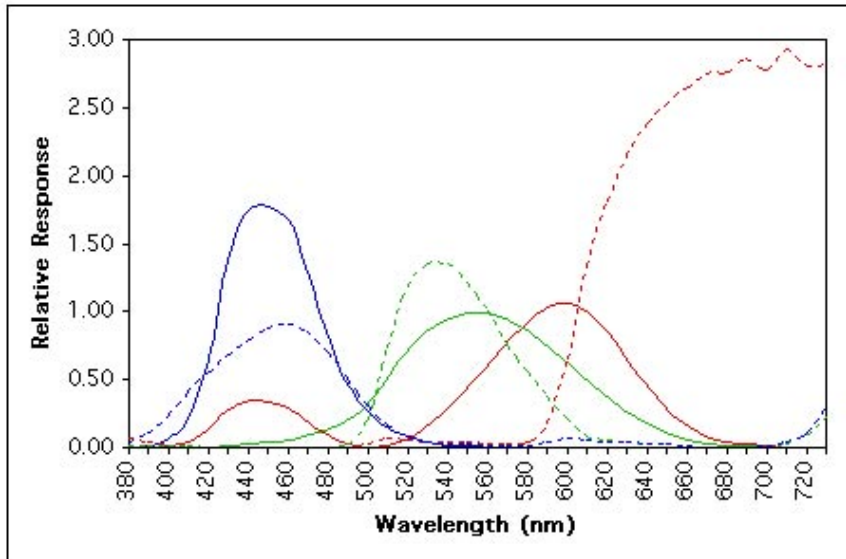

Figure 2. Relative spectral responses for the CIE 1931 standard observer (—,—,—) and a typical CCD sensor (- - -, - - -, - - -).

One of the biggest differences between the standard observer and the digital sensor occurs in the red region of the spectrum. The human observer's red sensitivity peaks about 600 nm with the digital camera peaking much further toward the infrared portion of the spectrum, near 700 nm.

A change in illumination can also lead to metamers no longer matching. The different spectral distributions of the lighting combines with the different spectra of the colors to produce different observer responses. A common example of this phenomenon is having a car fender painted to match the car body with the repair shop's fluorescent illumination, then finding the fender does not match the body in daylight illumination.

Pigments

Cobalt blue

It is well known that certain pigments cause metamerism problems for reproduction in both film and digital photography. One of the most notorious pigments in artwork reproduction is cobalt blue. The spectrum of cobalt blue (Figure 3) gives a clue to the problem. Notice the peak that starts in the far red about 650 nm and extends into the infrared.
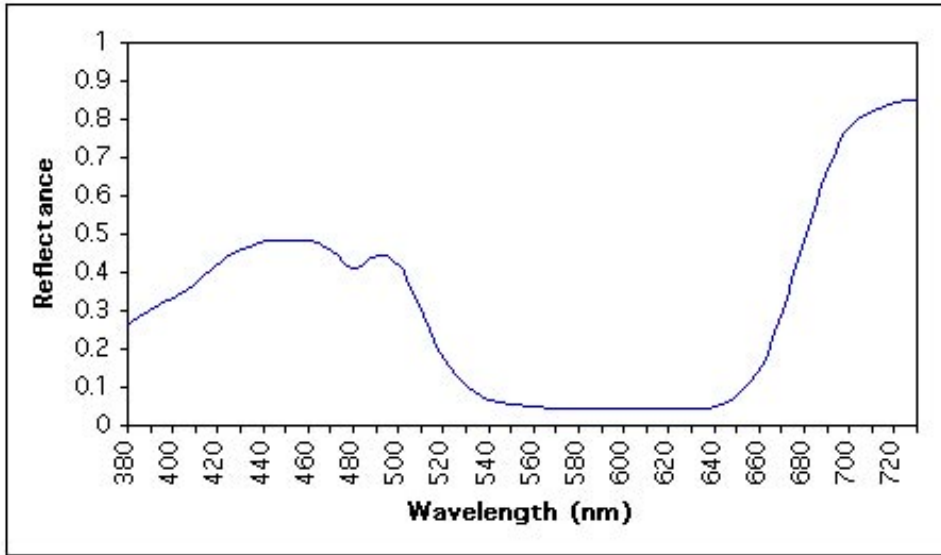
Figure 3. Cobalt blue spectrum.

When the spectrum of cobalt blue is compared to the human visual response (Figure 4), the section of the spectrum above 670 nm does not create a large response, while the blue portion, below 520 nm, has a more significant role in the perception of the color.
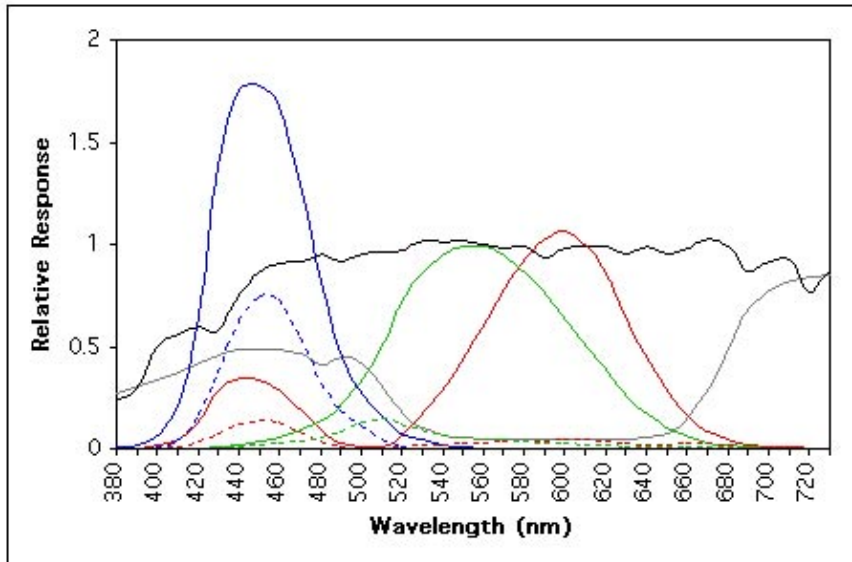

Figure 4. Comparison of standard observer (——,——,——), D-50 daylight illumination (——), cobalt blue (——), and the resulting perceived spectra of cobalt blue (- - -, - - -, - - -).

The spectral response of film is different than the human spectral response (Figure 5). Film has a higher spectral sensitivity in the portion of the spectrum where cobalt blue has a high red reflectance. This results in a larger response to the red portion of the cobalt blue spectrum and thus the purple result on film.
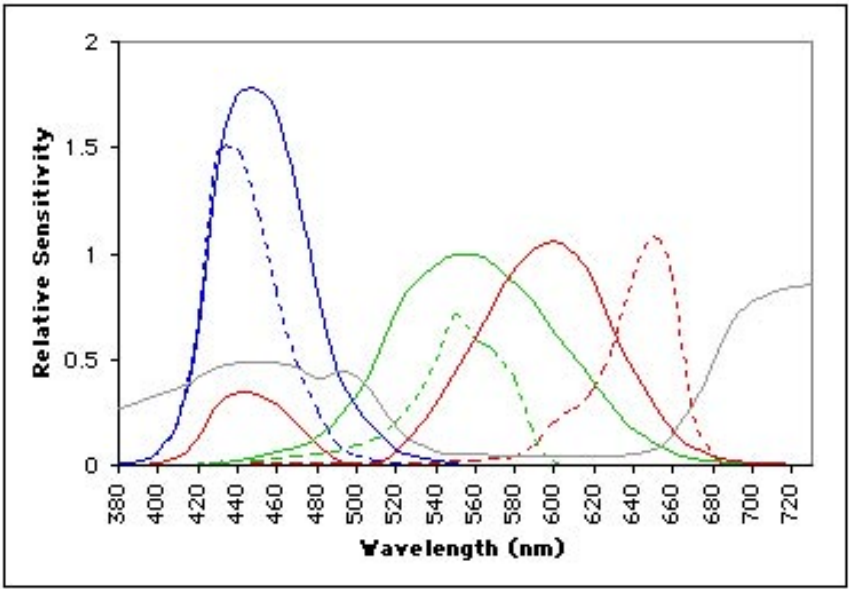
Figure 5. Comparison of standard observer(—,—,—), cobalt blue (—), and the spectral sensitivity of a typical transparency film (- - -, - - -, - - -).

The digital camera also responds to cobalt blue's red reflectance. The silicon sensor is much more responsive to red and infrared light, also resulting in a purple appearance for cobalt blue.
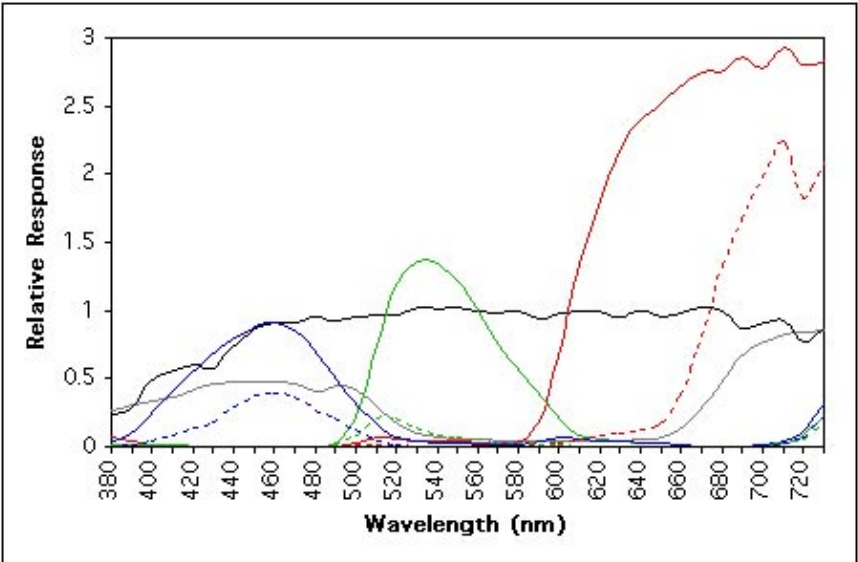

Figure 6. Comparison of silicon sensor (—,—,—), cobalt blue (—), and the resulting spectra of cobalt blue (- - -, - - -, - - -).

Lighting

The primary camera used for this research was a Better Light digital scanning camera. A scanning camera captures an image by moving a sensor consisting of rows of pixels across the image area. Since this exposure is not instantaneous, it requires a continuous light source. The common continuous light sources for photography are natural daylight, tungsten, fluorescent and HMI lamps.

For light sources, the emitted color is often given as the equivalent temperature for a black body radiator of a similar color and is reported on the Kelvin temperature scale. The lower the Kelvin number the redder the light, and correspondingly, the higher the Kelvin number the bluer the light. For reference, daylight ranges from about 5000 to 7500 Kelvins (symbolized as K).

Daylight

Sunlight illumination is a continuous spectrum from the UV to the infrared. It includes direct sunlight and light scattered by the atmosphere. The color temperature of daylight varies with the time of day, the amount and location of clouds, the type and amount of atmospheric pollution, and the location of the subject, among other variables.

When illuminated by direct sunlight the color temperature is taken as 5500 K when the sun is higher than 30° above the horizon. As the sun approaches the horizon, the color temperature drops, producing a much warmer light. When shooting on cloudy days, the amount of blue light scattered by the atmosphere is a larger component of the total illumination and the color temperature rises. Shooting in shade or indoors, not illuminated by direct sunlight, the color temperature is usually taken as 6500 K. The daylight color temperature can go much higher, depending on the atmospheric conditions and the shooting situation.
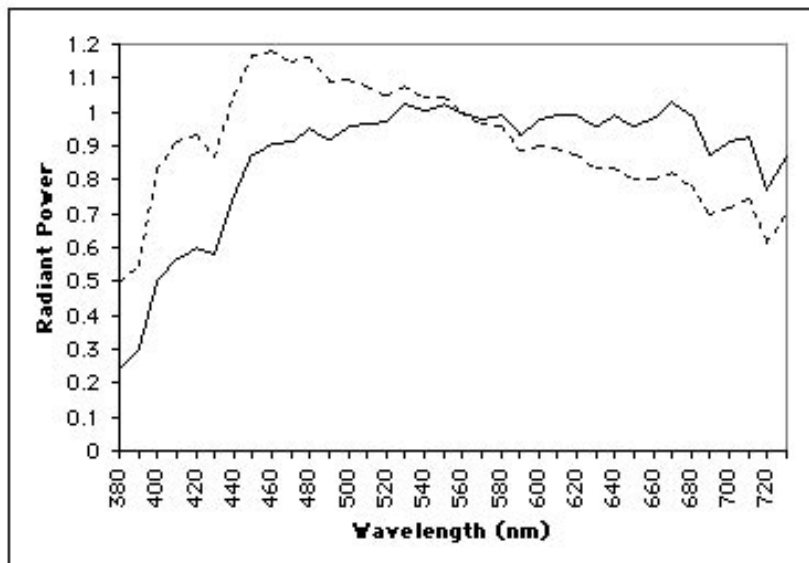

Figure 7. Daylight spectra; D-5000 (—) and D-6500 (- - -) standards.

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Daylight is the reference illuminant by which all the other illuminants are judged. The color for lamps is often compared to daylight as a measurement of the lamp's quality. For all its wonderful visual attributes, daylight is difficult to work with in many photographic situations. It varies widely with atmospheric conditions, latitude, time of day, etc. Other than reflectors, shades, and diffusers, there are very few options for controlling or shaping daylight.

Tungsten

A tungsten light, also known as an incandescent light, makes light by heating a tungsten filament inside a glass envelope containing either a vacuum or an inert gas. When the tungsten filament gets hot, at its temperature of incandescence, it emits a continuous spectrum of light with more light at the red than the blue wavelengths. The color temperature range for Tungsten lamps is typically around 2600 to 3000 K; thus, they produce a very warm appearance with their light.
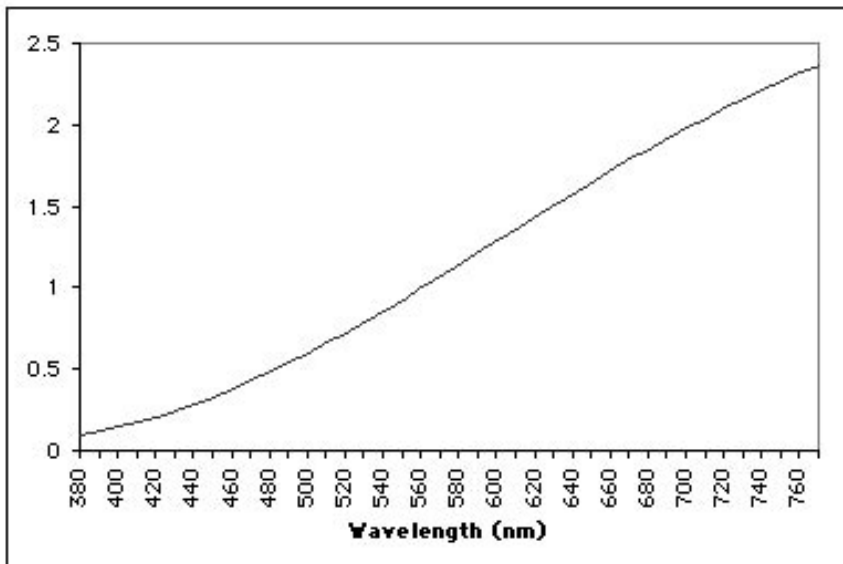

Figure 8. Tungsten lamp emission spectrum.

As shown in Figure 8, there is a large amount of red and infrared light emitted by an incandescent lamp. Correspondingly, there is a very small amount of ultraviolet and blue light emitted so the light has a yellow-red appearance.

Due to the high amount of light at the red end of the spectrum and the sensor's increased sensitivity to red light, digital cameras must turn down the gain of the red sensors and turn up the gain of the blue sensors to achieve a neutral color balance with tungsten lighting. As the sensor gain is increased the signal is increased but the noise is also increased. For tungsten lighting the noise in the blue channel for a digital sensor is more than the other channels. Also, since the red gain is lowered and the blue raised, the yellow and orange colors are reduced in saturation in the resulting images.

Tungsten-Halogen (Quartz-Halogen)

The tungsten-halogen lamp is a tungsten light with a halogen gas added to the gases inside the lamp envelope. The envelope is also made closer to the surface of the filament and is made of quartz to withstand the higher temperature. The combined effect of the halogen gas and the close envelope allows the lamp to be operated at a higher temperature, producing a whiter light than the standard tungsten lamp. The color temperature range for tungsten-halogen lamps is from 3000 to 3400 K.

Solux Tungsten-Halogen

There is a new wrinkle to the choices among tungsten-halogen lamps. The Solux lamp is a 50 watt tungsten-halogen lamp with some characteristics that overcome many deficiencies of standard tungsten-halogen lamps. They have been designed with special dichroic filters that reflect over 50% of the infrared light out the back of the lamp away from the subject. The filters also convert the spectrum of the light to closely match the spectrum of daylight at a color temperature of 4700 K. With special power sources, the lamps can be driven up to 5500 K, a color that correlates with the color balance of daylight film. The 50 watt output of the Solux does not make them suitable for large area illumination but their daylight color makes them very effective for small area lighting applications such as illuminating artworks.
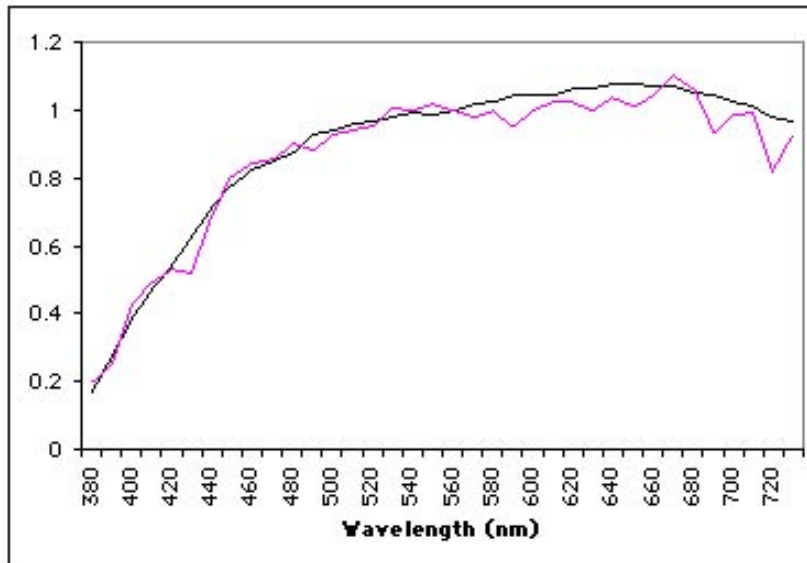

Figure 9. Solux 4700 K lamp emission spectrum (—) compared to 4700 K daylight (—).

Tungsten and tungsten-halogen lamps have been around long enough for a large number of light shaping devices to be available. By their nature, these lamps are point sources with very directional lighting characteristics. The addition of diffusion devices allows them to double as diffuse light sources. Fresnel lenses, parabolic reflectors, barn doors, snoots, honey comb filters, etc. are available to shape the light from small localized accents to large area fill lights. These light shapers allow tungsten light to be used specularly, diffusely or in various combinations of the two.

The low cost, wide range of lighting options and the higher color temperature make tungsten-halogen lighting currently the most commonly used type of continuous illumination source. For this reason it is one of the types of lighting used for these tests.

HMI

HMI is an acronym for hydrargyrum medium-arc iodide, a difficult to pronounce name for a mercury-halogen lamp. Mercury, iodine and other gases in the lamp are excited by electric discharge with light being emitted across the spectrum. A significant amount of light output is in the ultraviolet region and also in the infrared region. HMI lamps run hot with color temperatures of 4500 to 6500 K.
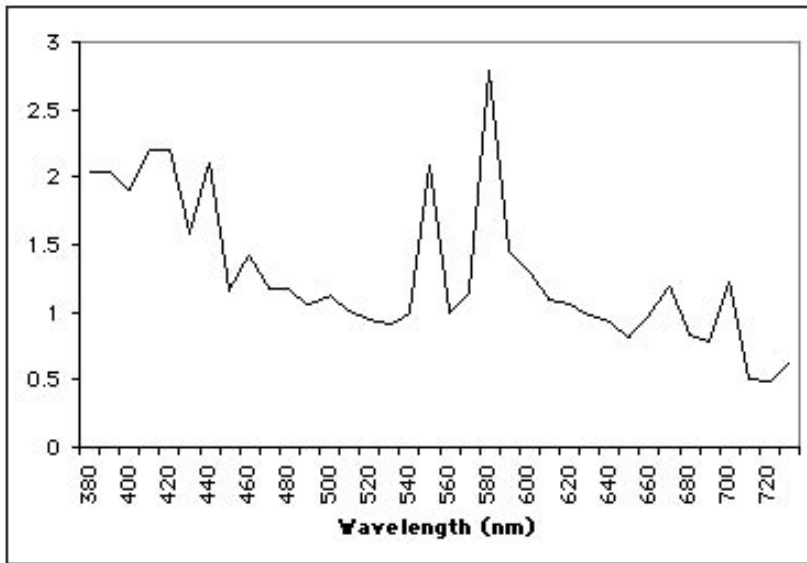
Figure 10. HMI lamp emission spectrum.

HMI lamps are very bright lights with a high lumens per watt output. Because their color balance is close to daylight, they are widely used in the movie industry and are being used for some digital scanning applications. The high ultraviolet and infrared output makes them undesirable for fine art reproduction since these two areas of the spectrum can cause appreciable damage to the artwork.

Since HMI lamps are directional light sources similar to tungsten lamps in their usage and housings, the same type of light shaping devices are available. The higher light output of HMI lamps (compared to tungsten) enables the use of diffusers and polarizers while maintaining acceptable exposure levels. This capability makes this type of lighting popular with some photographers. The high cost of HMI lamps, fixtures and power supplies makes this type of lighting the least commonly encountered in photographic studios. HMI lighting was not considered for this research due to its unsuitability for artwork reproduction owing to its high ultraviolet and infrared emissions, which could be very injurious to the art.

Fluorescent

A fluorescent lamp consists of a glass tube that has a coating of a phosphor material on the inside surface and is filled with gas containing a small amount of mercury vapor. When the mercury is excited by the electric discharge in the tube, it emits light with a high concentration of ultraviolet light. The ultraviolet light excites the phosphors which radiate light in the visible spectral region. Variations in the phosphors allow fluorescent lights to be made in a variety of spectral distributions with typical color temperatures from 3000 to 7500 K.
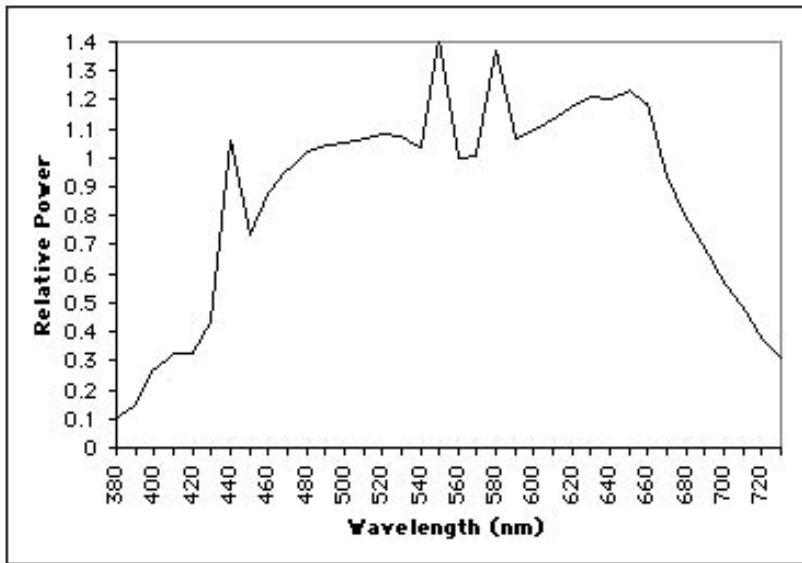
Figure 11. CIE standard F8 (5000 K) fluorescent lamp emission spectrum.

Since a fluorescent lamp works by converting ultraviolet light to visible light, it is only natural to find that some of the ultraviolet is not converted and is output along with the visible light. There is also some infrared light from a fluorescent lamp, but not nearly as much as a tungsten or HMI lamp. Fluorescent lamps have a very high lumens per watt emission with most of the light falling in the visible portion of the spectrum. Experience has shown a two exposure value increase in illumination over tungsten-halogen for the same wattage.

Fluorescent lamps are diffuse light sources that are generally found in fixtures that illuminate large areas, compared to tungsten lamps. There are a few fluorescent lamp fixtures that cluster several lamps with a conical fixture to shape the light into a more directional configuration. It works to some degree, but not as effectively as the tungsten and HMI fixtures. There are some fixtures with filters, honeycombs and reflectors that allow for limited shaping of the light.

Because of the widespread availability of daylight balanced fluorescent lamps their large area illumination capabilities and low infrared emissions, fluorescent lamps are the third type of lighting considered for this research.

Sensors

Human

As shown in Figure 2, the human visual system is sensitive to light from 380 to 780 nanometers (nm), however, the sensitivity from 380 to 400 and above 700 nm is so low that the practical range for the eye is usually reported as 400 to 700 nm.

There are three basic color responses approximately corresponding to red, green and blue wavelengths. Especially notice the peak of the red response, corresponding to about 600 nm.

CCD

The basic digital camera sensor is a panchromatic sensor; it responds to light from the ultraviolet, through the visible, and well into the infrared spectrum. To produce a color sensor, filters are applied to its surface to give the sensor color selectivity. Each filter limits the panchromatic response of the silicon sensor to a small portion of the spectrum.

In Figure 2 it is apparent that silicon sensors are sensitive to visible light and also wavelengths in the infrared portion of the spectrum. Notice that the color sensor filters do not block all the infrared light, resulting in the color sensor having a response to infrared wavelengths. To overcome this, normal visible light digital photography requires an infrared blocking filter to be placed in the light path before the sensor to reduce or eliminate infrared sensitivity.

On some cameras, this filter is manufactured as part of the sensor, on others it is permanently affixed behind the lens in front of the sensor. The Better Light scanning insert used for this research replaces the film holder in a standard 4x5 inch camera. It has a separate infrared blocking filter that can be mounted in front or behind the lens, depending on the mechanics of the 4x5 camera being used.
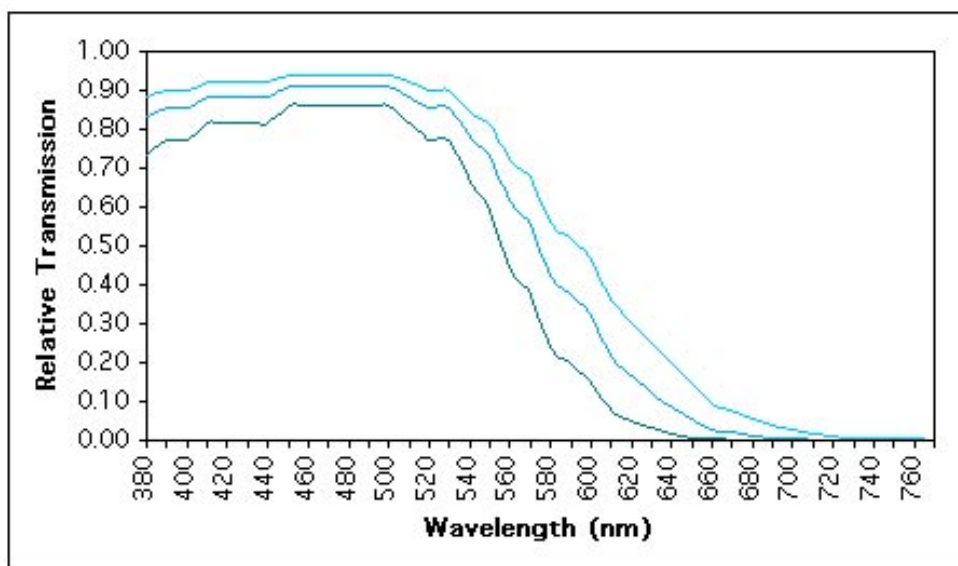

Figure 12. Spectral transmittances of a daylight (——), tungsten (——) and the combined daylight and tungsten filters (——).

For the Better Light camera there are two filters; one for daylight and the other for tungsten lighting. Each filter removes a prescribed amount of infrared light (Figure 12). The choice of which filter to use usually depends on the scene lighting. For daylight and fluorescent lighting the daylight infrared filter is used. The tungsten filter is designed to remove a larger portion of infrared light and is used for incandescent (tungsten or tungsten-halogen) or HMI lighting.

Putting it together

The proper reproduction of artworks depends on the accurate reproduction of the colors in the work. To explain the reason for the metameric effects of some colorants, and devise methods to control those effects to allow for accurate color reproduction, an understanding must be developed of their spectral reflectances and the spectral conditions of the viewing environment. Since cobalt blue is especially problematic for reproduction, it will be used as an example.

As shown in Figure 3, cobalt blue has a large reflectance in the far red and near infrared, in addition to the expected peak in the blue region of the spectrum. To analyze the effect of the these reflectances, the conditions of a standard viewing environment can be simulated by combining the spectra of the lighting, cobalt blue and the sensor.
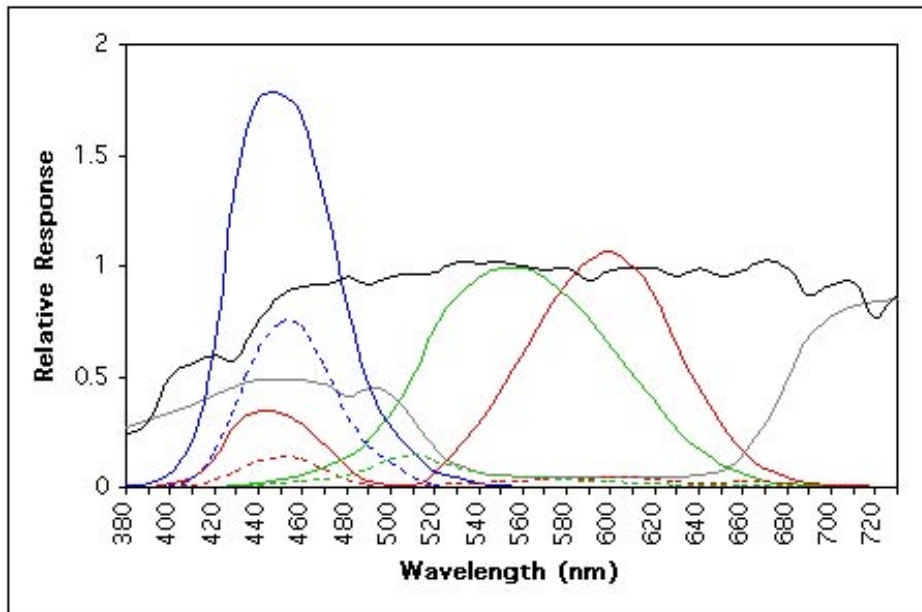

Figure 13. D-50 illumination (—) combined with the reflectance of cobalt blue (—), the CIE 1931 standard observer (—,—,—) and the results (- - -, - - -, - - -).

For a human observer, the cobalt blue appears to be a blue color. The spectral curves in Figure 13 show why this happens. The large red reflectance of cobalt blue in the far red region of the spectrum occurs where the sensitivity of the observer is minimal. Thus, only the blue reflectance of cobalt blue, and a small amount of the blue that is sensed by the red cones in the eye, is sensed by the observer. This red response is small enough not to change the sensation from blue to purple.
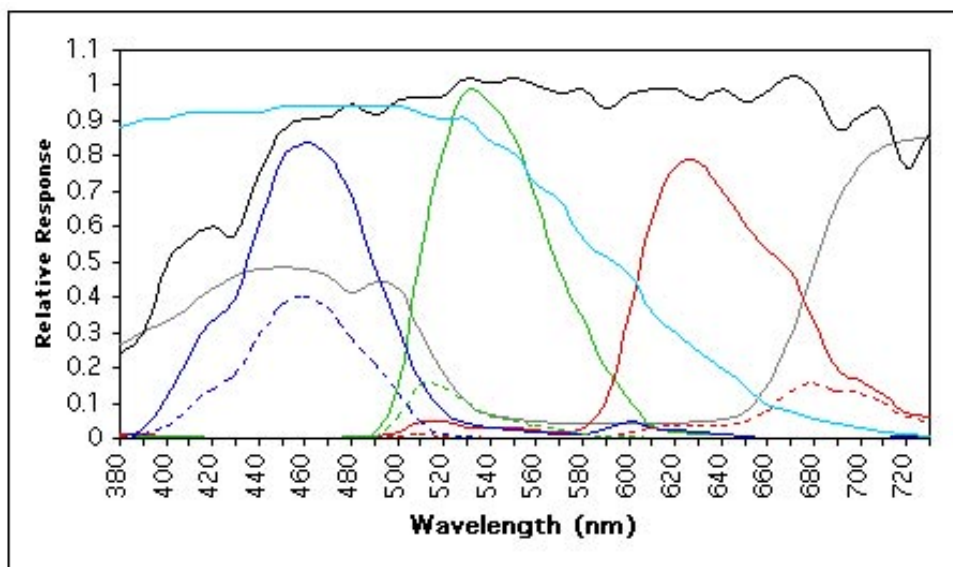

Figure 14. D-50 illumination (—) combined with the reflectance of cobalt blue (—), a daylight filter (—), the silicon sensor RGB responses (—,—,—) and the results (- - -, - - -, - - -).
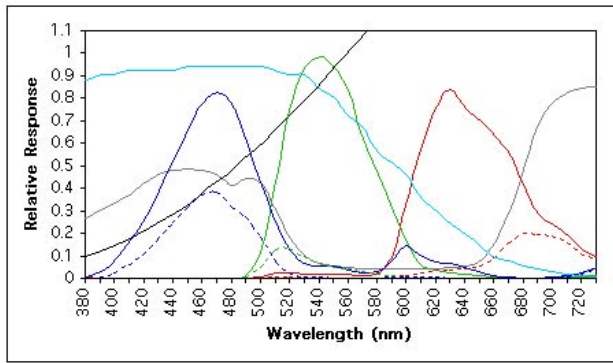
Figure 15a. Tungsten illumination (——) combined with the reflectance of cobalt blue (——), a daylight filter (——), the silicon sensor RGB responses (——,——,——) and the results (- - -, - - -, - - -).
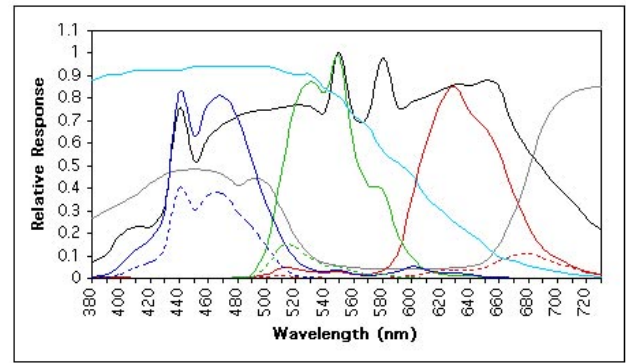

Figure 15d. Fluorescent illumination (——) combined with the reflectance of cobalt blue (——), a daylight filter (——), the silicon sensor RGB responses (——,——,——) and the results (- - -, - - -, - - -).
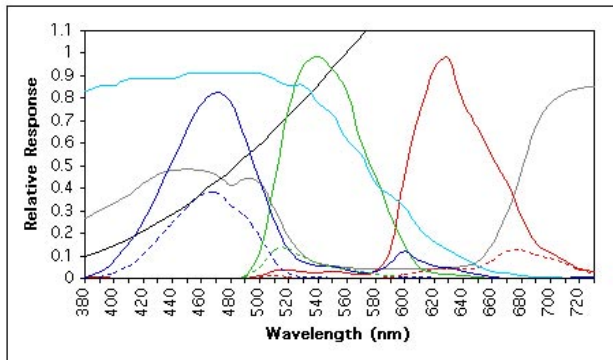

Figure 15b. Tungsten illumination (——) combined with the reflectance of cobalt blue (——), a tungsten filter (——), the silicon sensor RGB responses (——,——,——) and the results (- - -, - - -, - - -).
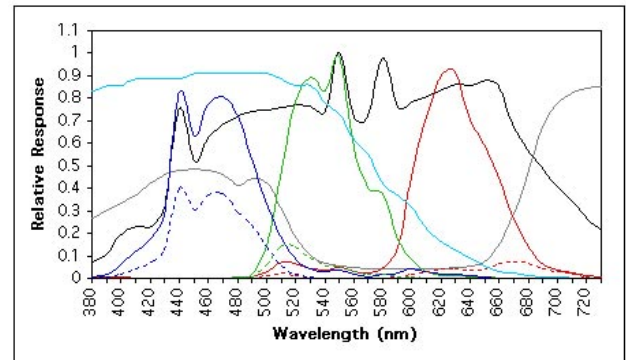

Figure 15e. Fluorescent illumination (——) combined with the reflectance of cobalt blue (——), a tungsten filter (——), the silicon sensor RGB responses (——,——,——) and the results (- - -, - - -, - - -).
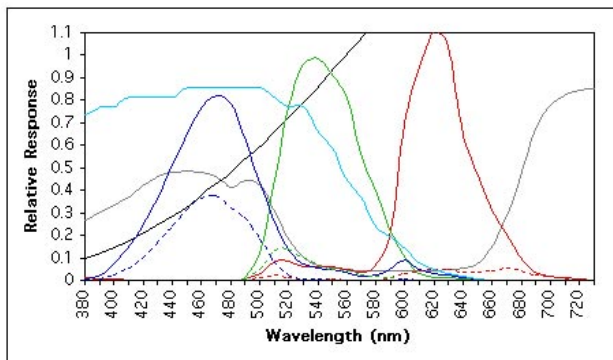

Figure 15c. Tungsten illumination (——) combined with the reflectance of cobalt blue (——), both daylight and tungsten filters (——), the silicon sensor RGB responses (——,——,——) and the results (- - -, - - -, - - -).
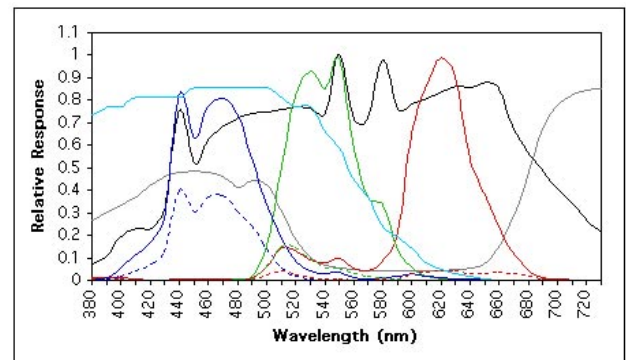

Figure 15f. Fluorescent illumination (——) combined with the reflectance of cobalt blue (——), both daylight and tungsten filters (——), the silicon sensor RGB responses (——,——,——) and the results (- - -, - - -, - - -).

With a different observer, in this case the silicon sensor with a daylight infrared blocking filter, cobalt blue now appears purple (Figure 14). The sensitivity of the sensor to the far red and infrared has given cobalt blue's red reflectance more of an impact on the resulting color.
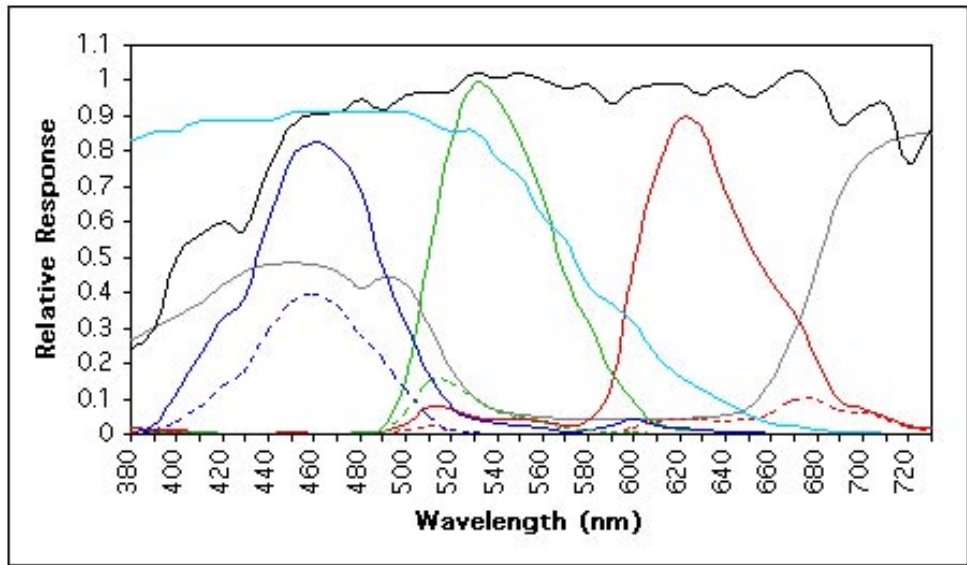

Figure 16. D-50 illumination (—) combined with the reflectance of cobalt blue (—), a tungsten filter (—), the silicon sensor RGB responses (—,—,—) and the results (- - -, - - -, - - -).

By changing the infrared filter from the standard daylight to the tungsten filter more of the red reflectance is removed (Figure 16). The predicted result, with more of the far red and infrared removed, gives a response that correlates closer to the color experienced by a human observer.

One of the major contributions to the viewing environment is the type of lighting used to illuminate the scene. Just as the observer was changed and the predicted results compared, the lighting can be changed between tungsten-halogen and fluorescent with the resulting colors compared.

As shown in the Figures 15a - 15f, the type of lighting has a major effect on the resulting color. Tungsten illumination, with high amounts of red and infrared light, produce a purpler response from the camera than fluorescent illumination (Figure 15a and Figure 15d). By changing the infrared blocking filter from the daylight filter to one with a greater absorbance of red and infrared light (i.e. the tungsten filter), the resulting color is much closer to the one seen by the human observer (Figure 15b and Figure 15e).

The predicted color is still more purple than the color perceived by the human visual system. The tungsten filter by itself will remove all the infrared light, so the light that is producing the purple color for cobalt blue must not be the infrared but instead the far red light beyond 600 nm and less than 700 nm. By placing both the daylight and tungsten filters on the camera, the optical densities of the filters are combined with a greater effect on the far red portion of the spectrum (Figure 15c and Figure 15f).

The tungsten illumination with both filters on the camera is still not giving a fully satisfactory response (Figure 15c). By changing the lighting to fluorescent, which has less red and infrared illumination, the expected result should is closer to the perceived blue color (Figure 15f).

The predictions show a combination of fluorescent lighting combined with both a tungsten and daylight infrared blocking filter on the digital camera will give a blue result for a cobalt blue hue. With such heavy filtration blocking a portion of the far red, as well as the infrared portions of the spectrum, there is the possibility other colors may not be reproduced accurately. To test this hypothesis a set of patches painted with watercolors was photographed with the digital camera and compared visually to the original (Figure 17).

Figure 17. Watercolor test patches photographed with a Better Light Super 6k camera under fluorescent illumination and equipped with two filters.

The results show that the colors imaged with fluorescent light and the double filtration correctly reproduces the cobalt blue hues without causing detrimental effects on the rest of the colors. As a final test, the Summer *Breeze* watercolor was digitally photographed using the technique developed in this paper.

Figure 18. "Summer Breeze" imaged with a Better Light digital scanning camera utilizing two filters to control the far red reflectance of cobalt blue.

The images show that the combination of lower far red and infrared emitting fluorescent illumination, combined with filtration that eliminates the infrared and reduces the far red spectral response of the camera sensor results in a color accurate reproduction.

The issue then arises as to why the camera is not supplied with infrared blocking filters that are the equivalent of the combined daylight and tungsten filters? As the amount of filtration is increased, the amount of light coming through the filter decreases. This means the gains for the camera sensors must be increased to give a reasonable image exposure. Increasing the gain on a digital camera also increases the image noise. The filters supplied with the camera are designed for a wide range of situations to filter out the infrared for their designated lighting (i.e. daylight or tungsten) and to result in images with low noise levels.

Summary

The accurate reproduction of color with digital photography often depends on controlling the factors effecting the metameric viewing conditions. For the case of cobalt blue, this may involve using a light source with low far red and infrared emissions, combined with applying filters to the sensor to reduce the sensitivity in these regions of the spectrum. The methods outlined here have also been successfully applied to digital photography of difficult to reproduce colors in rugs, papers, and artists' pigments.

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