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Comparing oil paintings and their true color holograms from a painter’s perspective.

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Abstract. Several researchers have used holography for museography and art conservation. It is often stated that 3 or 4 laser wavelengths are sufficient to create a visual duplicate of any two dimensional work. This claim is tested specifically for the domain of oil painting. Like holograms, oil paintings convey information through a three dimensional light field. In many cases, this is an intentional effect of the painter’s process of creating the painting. An overview of related fields is provided since there are dependencies. Classical techniques and palettes are subjected to holographic duplication. The results are classified and may be surprising to both holographer and the gallery owner.

1. Introduction

Using Munsell color space, painter's perspective and leveraging state of the art equipment and media, our goal is to determine if museum quality duplication of oil paintings (over the full visual field of observation) is possible using color reflection holography.

- Claims of holography to create exact color duplicates do not always seem to be accurate
- The full visual field is sometimes ignored in analysis of duplication quality
- Measurement criteria are not always clearly presented and so are not easily reproducible
- Mathematical simulations are not always correlated with actual results
- CIE 1931 is nonlinear across dimensions – but this is not usually mentioned – making error factor appear smaller than visually apparent; object luminance is not explicitly compared
- Munsell color theory can be applied directly at all stages of analysis – to select test cases and subjectively evaluate matches
- Color opponent theory should be leveraged in deciding illumination requirements (special consideration for purple, yellow)
- Illumination requirements are correlated between recording, processing and playback – and should be explicit
- Some paintings are better exemplars than others
- Palette 'primary' pigment spectra should be correlated with the resulting overall spectrum
- Test cases should include representative and reproducible pigments, mediums, techniques, finishing (lead white, lindseed oil, glazing / impasto, varnish, high chroma, etc.)
- The same concepts should be applicable to other forms of painting (watercolor, acrylic, etc.)

2. Relevant Painting Concepts

Reputedly, oil painting was discovered by the stained glass and tempera artisans Jan (and Hubert) van Eyck of Flanders, circa 1400. Between then and now a series of technical improvements have resulted in commercially available paints of consistent high quality.

Each academic school of thought since then has promoted different sets of base pigments/colors to be used as a ‘palette.’ Different methods of color mixing have been employed ranging from three or four colors to complete grids of premixed colors. Black may be straight from the tube, or may be created with four complementary colors. Sometimes the colors are mixed on the palette, other times on the canvas, some times by layering transparent glazes and yet other times they are simply placed next to each other on the canvas and mixed by the human visual system. Complementary colors may be intentionally placed in proximity of each other to ‘vibrate’ the HVS (see detail from painting).

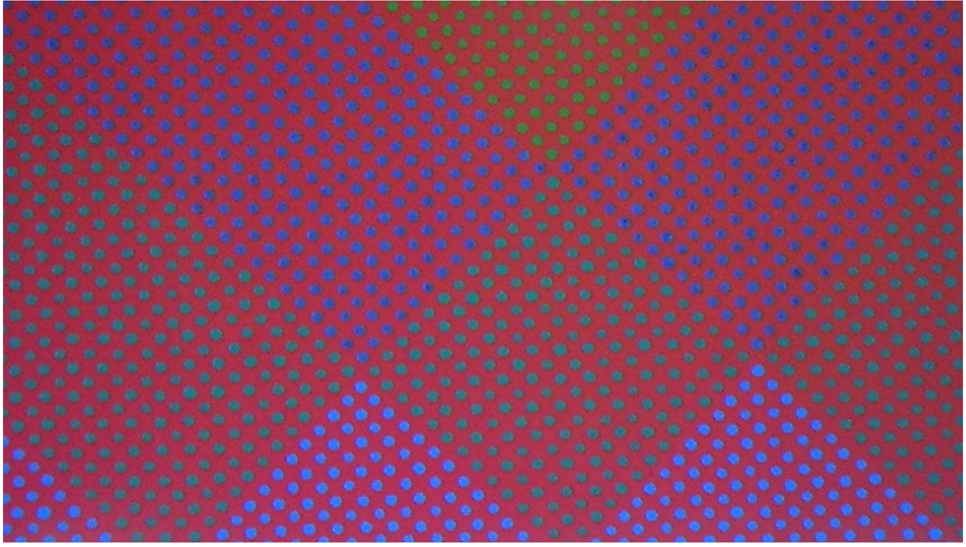


Figure 1 – Color Function Painting: ALL THINGS DO LIVE IN THE THREE (Anuszkiewicz)

Studying with Jack Faragasso at the New York Art Students’ League introduced me to the premixed grid approach of Reilly and Faragasso. It is distinguished from other premixed grids in that it is based on Munsell Color Theory. Hue selection is performed at constant Value. Value selection is performed at constant Hue. Chroma selection is performed at constant Hue and constant Value. In an advanced variant, the grid can be reduced to a small subset of spectral colors which are sufficient to recreate the full grid. It is primarily aimed at flesh tone reproduction for all ethnicities under all lighting conditions. Additional colors can used independently of the grid primaries to match atypical colors.

Particularly with oil paint, light can be partially absorbed and reflected by the various layers of the painting. This results in a more complex reflection of light and individual wavelengths than highly reflective opaque painting.

The surface of a painting can range from smooth as glass to deep troughs and bare canvas or board. The paint may have additives, such as sand, that create unusual textures. Sometimes this surface is sealed with a varnish and other times not.

So, the light reflected from a painting is not the same as reflected from a photograph. The surface is not uniform in texture or material or reflectance and may even create shadows on its own surface due to deep texture. Finally, the colors may be composed of a wide variety of natural, mineral or synthetic pigments with different absorption spectra.

As a result of the above complexities, some accidental and others intentionally created by the artist, the painting may appear very different from various viewing angles and distances. The illumination of the painting is intimately related to the viewing experience and can sometimes have a negative impact (glare, non-uniform lighting, etc.).

The elements mentioned above have led me to believe that true color holography might be the only way to duplicate the viewing experience of a specific painting and that Munsell Color Theory could be applied to the task.

3. Relevant Lighting Concepts

Lighting is critical at all stages of the creation and enjoyment of an oil painting. Each painter has a specific preference depending on the subject, mood and destination of the painting. Ideally the painting is displayed in the same light as when it was painted. However, even in paintings of the 17th century one can detect instances where part of a painting was finished indoors and part was finished outdoors. Furthermore, many museums used mixed modes of lighting, for a variety of reasons. So it is difficult to point to an ideal historical viewing standard for lighting. Many feel early morning light is perfect, and some museums have tried to adopt this by using slightly warm, broad spectrum, lighting.

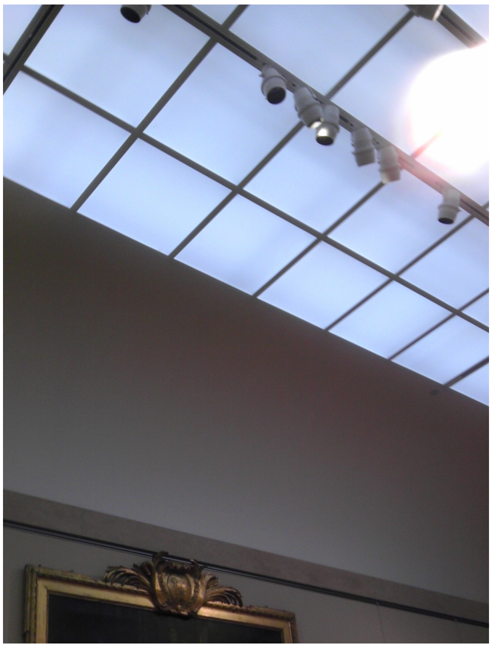


Figure 2 Typical Museum Gallery

Lighting is typically muted in the gallery except for spotlights focused on individual artwork. Recently, LED lighting has come to the forefront and some museums are starting to switch over, gallery by gallery, to warm white LED from incandescent Halogen. The museum LED have a spectrum very similar to existing Halogen, but with long life, lower cost of ownership, lower temperatures, etc. In a recent study, the lamps selected by the museum were determined from qualitative assessment by staff and visitors of color samples and artwork. The better LED spotlights were favored over Halogen. Halogens are (subjectively) described as stronger in red hue but weaker in blue and purple hues than LED.

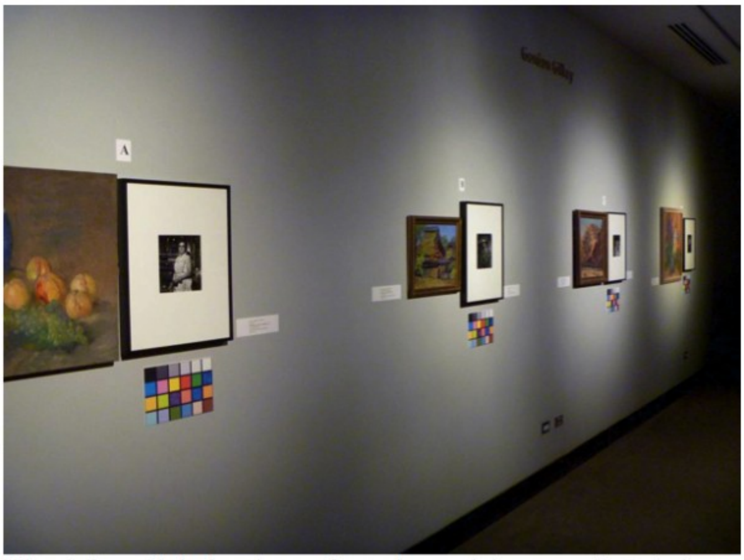


Figure 3 U.S. DOE study at Jordan Schnitzer museum

The technologies used for current LED lighting is not always as would be expected. One of the vendors provides ‘white light’ using two different technologies. While the result is white in both cases, the color accuracy is likely very different. There has been discussion in some of the lighting studies that color accuracy metrics used to categorize the quality of LED (CRI for example) do not actually correlate well with qualitative assessment.

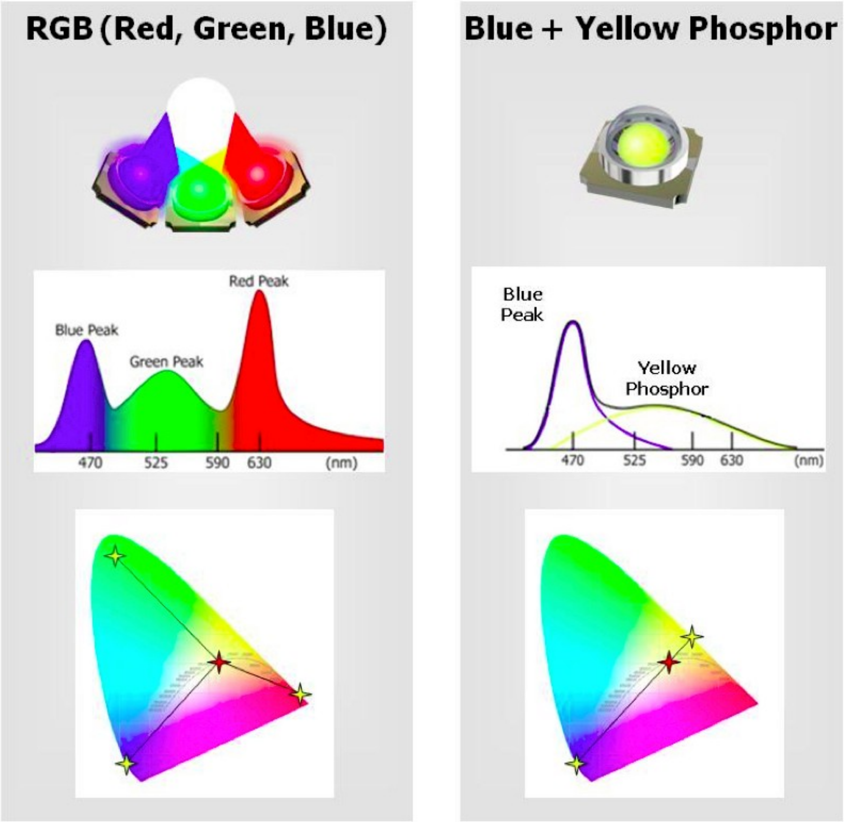


Figure 4 – from CREE: "Two ways to get white"

4. Relevant Holography Concepts

A color reflection hologram (Denisyuk/Lippmann/Bragg) captures the standing waves created between object and emulsion for each laser wavelength used. When processed and illuminated with white light, all colors are filtered out except the wavelengths originally reflected by the object. If the illuminant is the original laser light source, or equivalent wavelengths, with identical geometry then the reproduction quality should be the maximum possible. One criteria for perfect reconstruction is that 50% of observers could not distinguish between hologram and original. Another criteria is color difference in the CIE color space.

Denisyuk has written that the dynamic range of brightness recorded by such a hologram should exceed the dynamic range of photographic film. The ‘S’ curve typical of film is presented to show that two bright points on film (E2, E3) may actually record the same value (D2), whereas they would not for a hologram since the value for any point on the surface is recorded across the entire hologram and will not over saturate at any point in the holographic film. No mention is made if this will also hold true at the dark end of the brightness range. Intuitively, the answer is no since a very small value would be recorded at each point in the hologram when the object surface is dark. At some point it will be comparable in magnitude to noise.

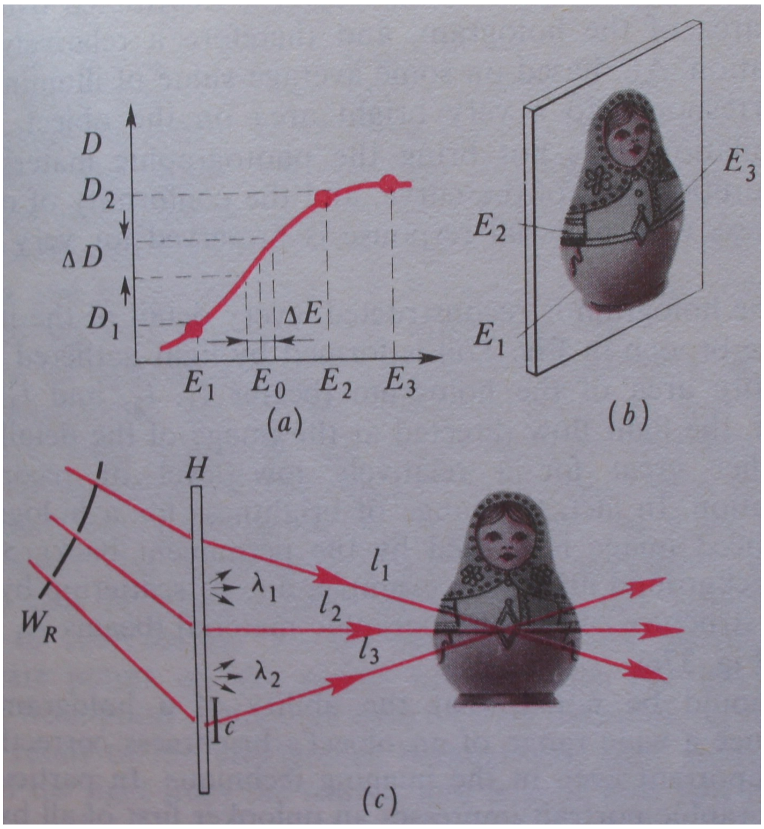


Figure 5 – from Denisyuk: dynamic range comparison

Several authors (Hubel, Bjelkhagen, etc.) have documented issues specific to multi-color reflection holograms, including the reduction in diffraction efficiency as the number of discrete wavelengths are increased. The limit/effect is dependent on the recording material. The same authors have also investigated using the CIE (1931) color space to analyze which, and how many, discrete wavelengths are required to sufficiently cover the space of recordable colors. In many cases, numerical simulations have been used to derive the optimal choices. In others, the evaluation criteria depend on some aspect of the material or its processing. Most of the CIE based analyses ignore the non-linearity of the 1931 CIE color space. None appear to match Luminance explicitly. Many of the emulsion issues are now historical, as current high quality holographic emulsions do exist without the issues mentioned (Gentet emulsion for example).

Flourescent and diffraction effect colors are not recordable with holography, although for some cases they can be illuminated with white laser light.

5. Relevant Neurophysiology Concepts

The Human Visual System (HVS) has two modes – night (scotopic) monochromatic vision using rods and daylight (photopic) color vision using cones. The HVS uses three different ‘cone’ cells to detect respectively red, green and blue light. The detection is not independent however (they overlap in broadly detected wavelengths). There are more red cones than green cones, and more green than blue. This has led to opponent color theories that describe the further abstraction of color by the HVS. An internal value of yellow (not directly detected as yellow) is synthesized from the red, green and blue inputs. These four values are then used to creed opponent color channels, namely Blue versus Yellow and Red versus Green. There is speculation that this decomposition is the most efficient from an information theory perspective as various reductions in data transfer and processing result.

Yellow is sensed when equal input of Green and Red are present. More interesting than the apparent redundancy of yellow is the existence of purple, which is a unique color only in our mind, resulting from equal Red and Blue inputs. When R-G and Y-B are balanced we sense Gray.

Also, additive color and subtractive color stimulate the HVS slightly differently. For subtractive color the complementary colors must balance. Lasers combine as additive color and light is reflected from a painted surface as subtractive color. For this reason, superposition calculations for color on CIE chart are predictable. Subtractive colors for similarly colored pigments are not predictable. As the spectrum of illuminant changes two pigments that were identical in color may have very different colors as their absorption can change with wavelength. This defines metamerism – colors that are identical only under certain lighting conditions.

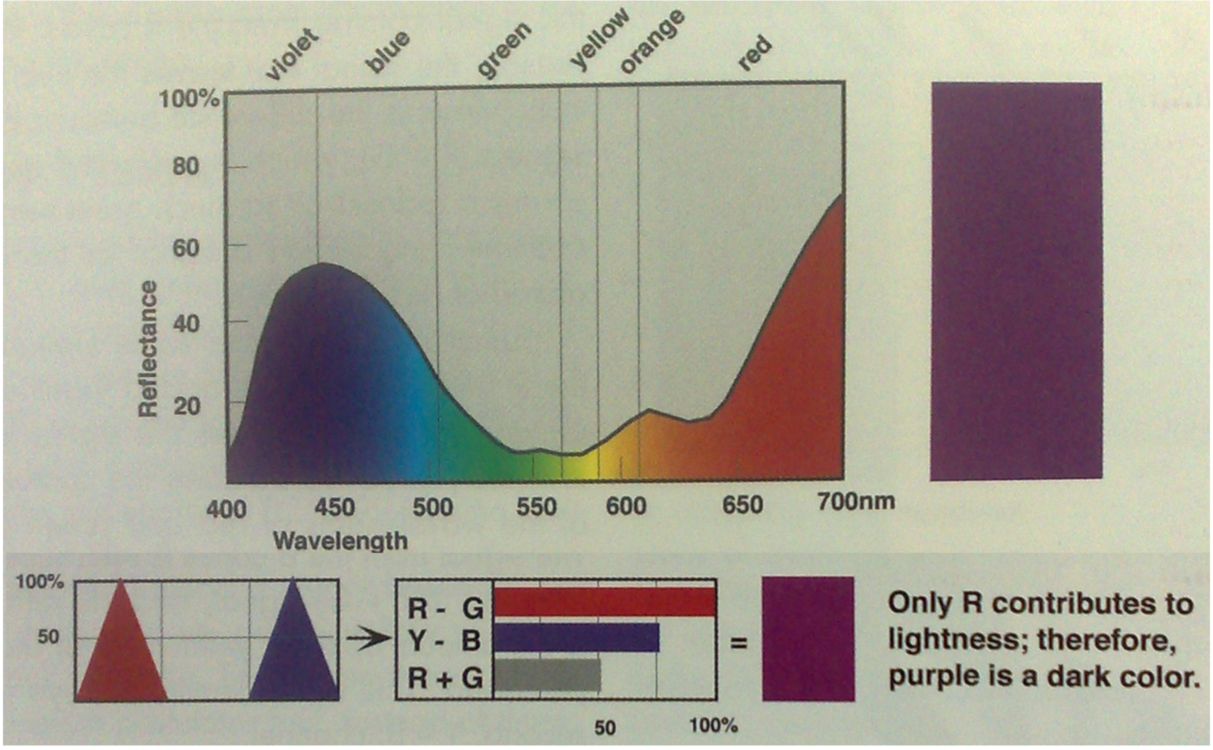


Figure 6 - from Munsell Student Color: Blue containing Chromas are darker

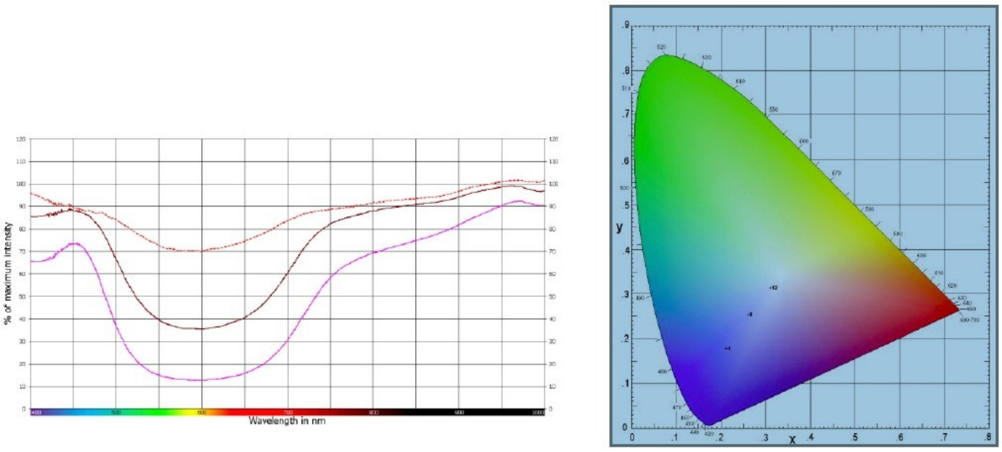


Figure 7 – from Aambø: As Yellow is increased Ultramarine looses Chroma

From these facts one can see that the HVS does not perceive a uniform color space and that chroma can be independent of luminance.

6. Relevant Colorimetry Concepts

6.1. Colorimetry

Colorimetry is the measurement of color specifically as related to HVS perception and typically leveraging CIE color space.

There are several CIE standards. NIST recommend using CIE 1976 L*a*b* since it represents an ‘object color space’ as opposed to a (source) ‘color space’ like CIE 1931. The primary differences are the addition of an object with reflectance of the source light, additional dimension of Luminance, and a predefined reference white (X_n, Y_n Z_n). For painting analysis Luminance must be considered along with Hue and Chroma in measuring a difference.

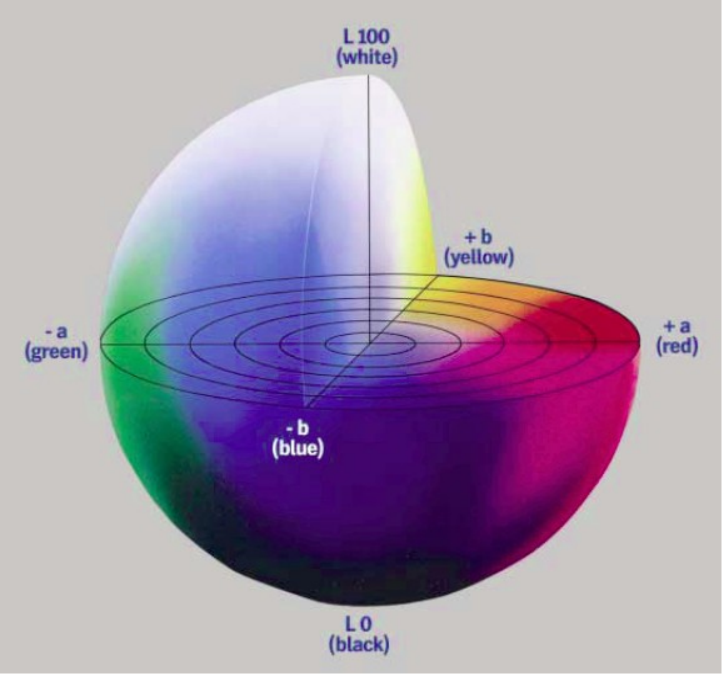


Figure 8 - from Heidelberg: L*a*b* object color space

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

Figure 9 - from NIST: XYZ conversion to L*a*b*

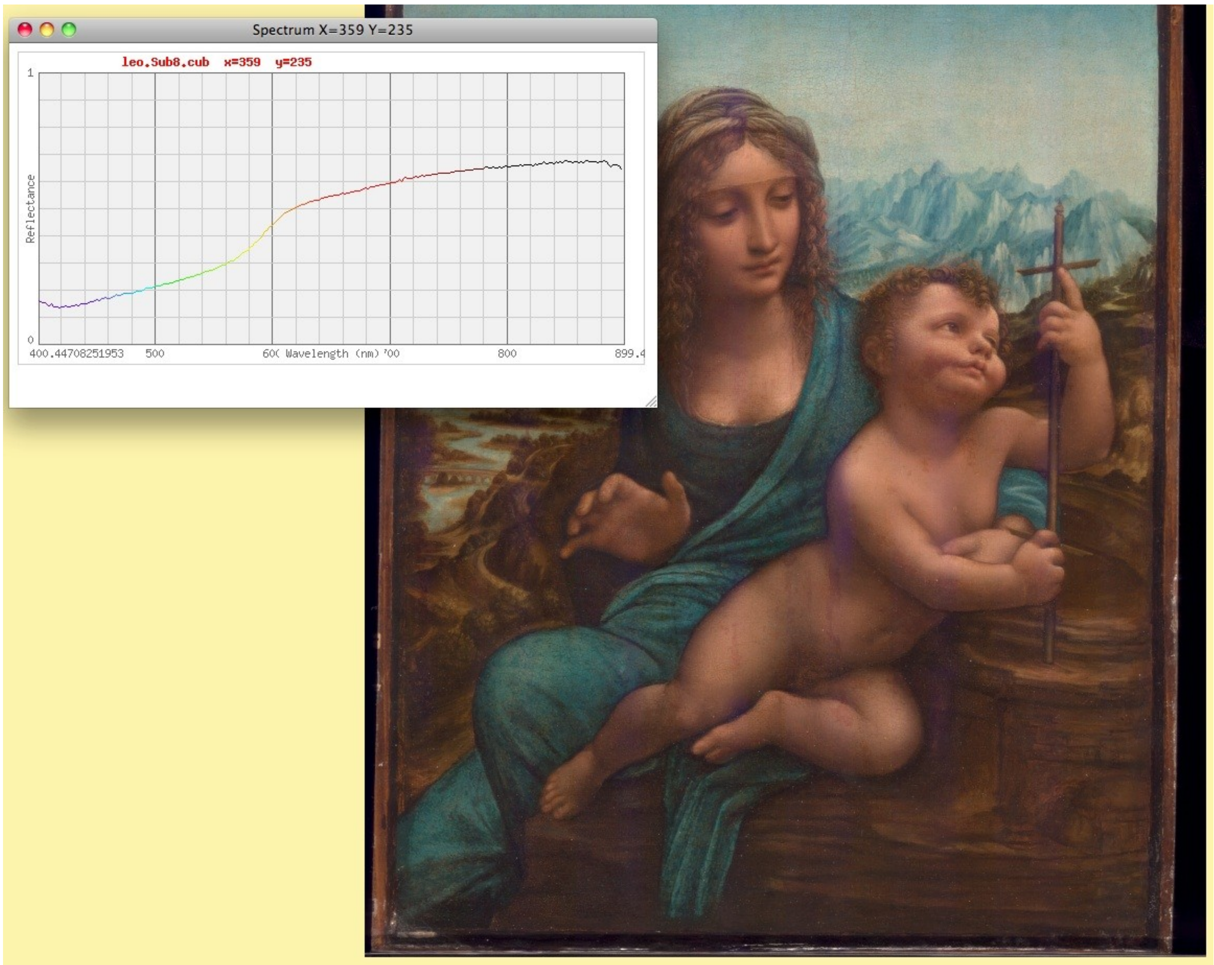
6.2. Spectrophototometry

Spectrophototometry is the physical measurement used as input to Colorimetry. The output is a CIE value for each measured spot (X, Y, Z for example).

Most all Spectrophotometry measurement devices require control over the reference source illuminant. Some provide for a nanometer by nanometer wavelength scan and provide extremely precise measurement.

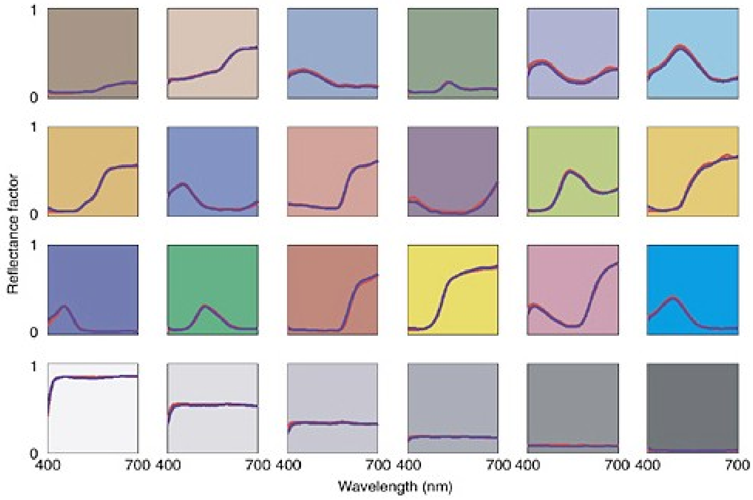
An example specific to oil painting conservation is shown below; the entire painting has been measured and the data is available to researchers on the internet.

http://www.ifac.cnr.it/webcubview/demo/leofull.php



Unfortunately, there does not appear to be such a device that provides for white laser light to image a broad area and then allow for x,y coordinate scanning of the sample. It might be possible to use a very quality digital camera to compare color histograms of two samples under constant laser illumination, and at a next level of detail perform pixel by pixel registration and comparison. Several spectrophotometry manufacturers mention that the spectral response of cameras is not precisely defined enough to allow the same level of quantitative analysis. But one suspects it would provide a reasonable preliminary validation to perform Mean Square Error analysis on the two images once registered for rotation, scale and translation.

GretagMacbeth ColorChecker Color Rendition Chart.



Typical spectral-measurement accuracy

Figure 10 - from Sackler NAS Colloquium (R Berns): Color Sample Spectrum

Some of the papers reviewed leveraged custom equipment to achieve some level of Spectrophotometry, but as mentioned above did not seem to compare Luminance. Above is shown a color test pattern and corresponding measured subranges of spectrum using a hybrid imaging system. Possibly this approach of filtered sampling could be leveraged for reflection holograms.

7. Approach

Compare existing samples visually and if a perfect match occurs, continue analysis with imaging and numerical techniques.

- Select sample art work that would benefit from true color holography; not all work needs
- Apply Munsell Color Theory where feasible
- Correlate cross constraints across holography, museum, artist and testing perspectives
- Prepare testable exemplars that exercise constraints for all parties
- Evaluate existing painting holograms
- Create viewing stage – used for both recording white laser light and playback display lights

- Pre-screen targets under white light
- Compare targets and holograms under white light and display lighting
- If possible create holograms of one or more exemplars
- Film / photograph viewing stage for all media; evaluate subjectively or with software
- At first stage leverage manual white balance on camera for bright white printing paper
- Document wavelengths, media, illumination and setups used; any issues
- Document findings / recommendations

7.1. Viewing Stages

Two viewing stages were used: sample and duplicate with shared illuminant; two different illuminants for one or more samples / duplicates.

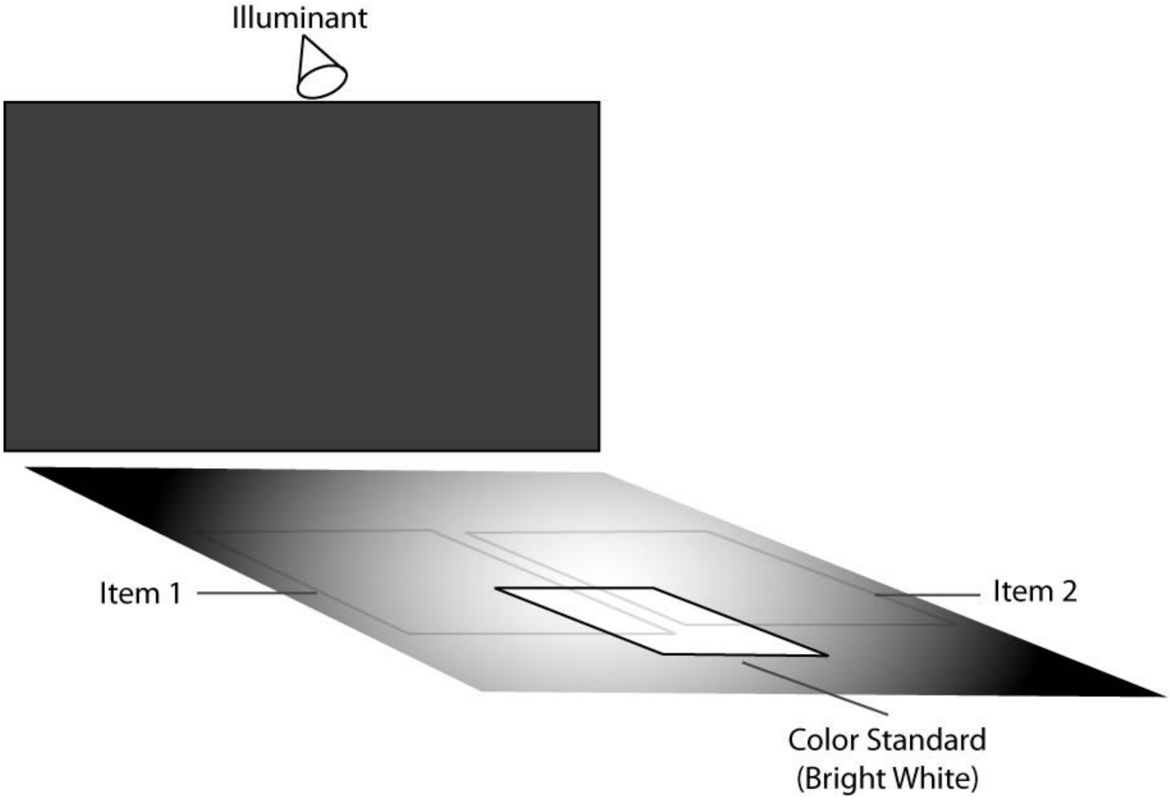


Figure 11 Same Illuminant

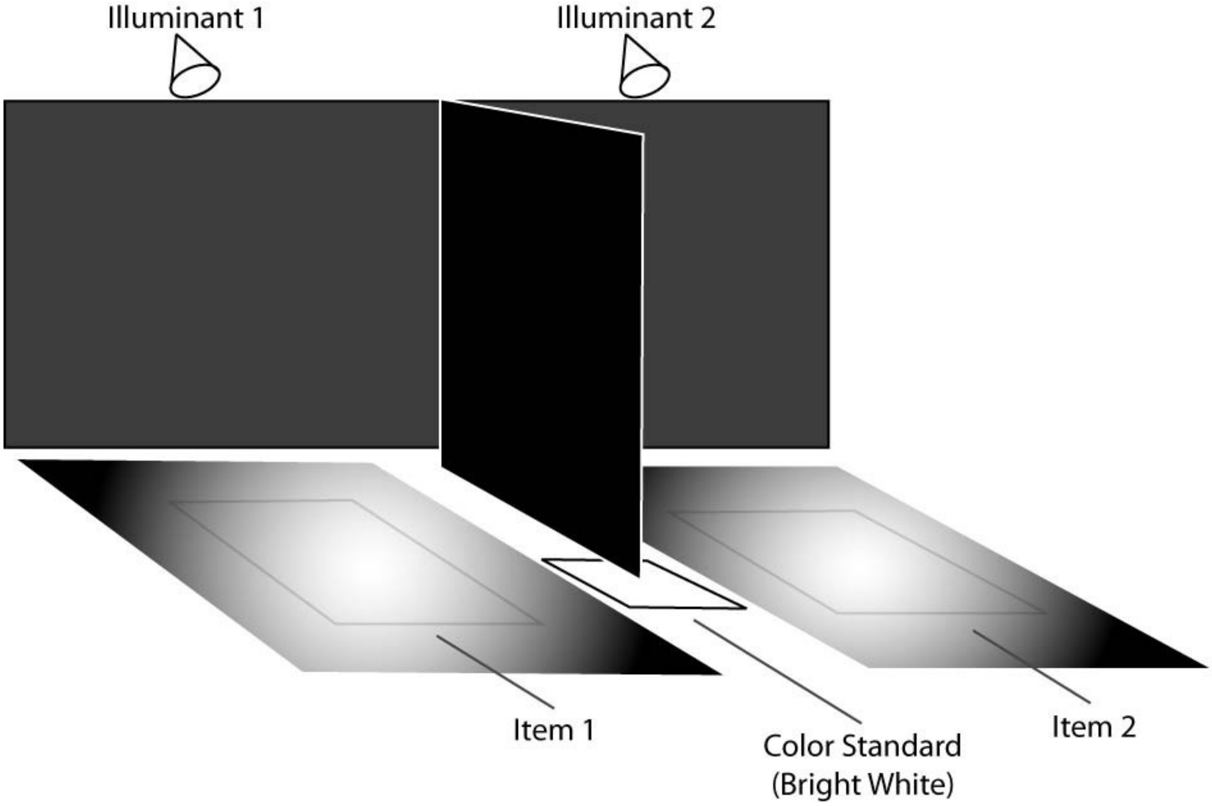


Figure 12 Different Illuminants

8. Issues

The initial expectation was to quickly move from preliminary analysis to detailed computational analysis. This did not occur. However the initial stages of analysis did uncover issues and alternative approaches that will be investigated in the future.

Several independent fields of study require color analysis, each with open issues directly impacting this research.

Media / pigment issues – the color standards are typically highly reflective and of unknown material. It would be useful if the color standards were not proprietary and leveraged several luminance targets. One solution for Oil Painting is to create a set of easily reproducible standards using a consistent manufacturer of oil paint as a reference (for example Windsor Newton Artist Colors).

Holography result is behind glass – most oil paintings are shown without glass. While this impacts display acceptance it does not impact comparison.

Laser issues – glare, reflectance, etc. – Laser illumination for reflection holography involves tangential lighting and is not ideal for viewing of textured surfaces. Initial solution is to tilt the object slightly, but could also include polarization and other modifications if required.

Practical issues – a color holography lab is not always accessible for research

Validation issues

- Simulations and statistical models do not seem to result in equivalent low error results
- Other fields have issues with CIE 1931 and some of the ‘standard’ color tests, etc.
- Some results are strictly numeric, using CIE metrics
- Many researchers only evaluate hue and seem to ignore luminance and its dynamic range
- Most results are not shown with original
- Failures are not typically discussed – it would simplify testing to share failure modes
- Display and lighting issues – Halogen and LED lighting is targeted to consumer point of sale. This can be contradictory to holography as increased noise, ghosting, and color shift.

- Colorimetry issues – there is not an easily accessible instrument to do high precision colorimetry of holograms, especially for white laser light illumination.

9. Results

The results are preliminary as mentioned above. Lab time was not available to create a sequence of new holograms and some of the existing holograms seem to have color balance issues related to changes in equipment. Based on recent non-painting examples the problem is resolved.

- No existing examples were indistinguishable between original and duplicate.
- For texture and geometry they were visually identical; geometries were identical.
- Color is not a perfect match and the overall reflectance is much lower: particularly for display lighting and in some cases for white light laser illumination (one laser changed as mentioned above).
- Glare is an issue – once locked in it is permanent. It appears polarization and tilt can eliminate.
- Dark values and earth tones have lower value than original; dark hue difficult to judge.
- Display and recording wavelength mismatch; power balance / reflectance mismatch
- Test approach (viewing stages) useful
- Laser color primary combinations visualization / checking useful
- Laser illumination and previsualization helpful

9.1. Images

Test patterns under white laser light are shown first, to validate their use for holographic duplication. These are followed by the two test paintings for which holograms were available in three viewing stages. In future work a subset of the test patterns / paintings will be compared with their holograms.

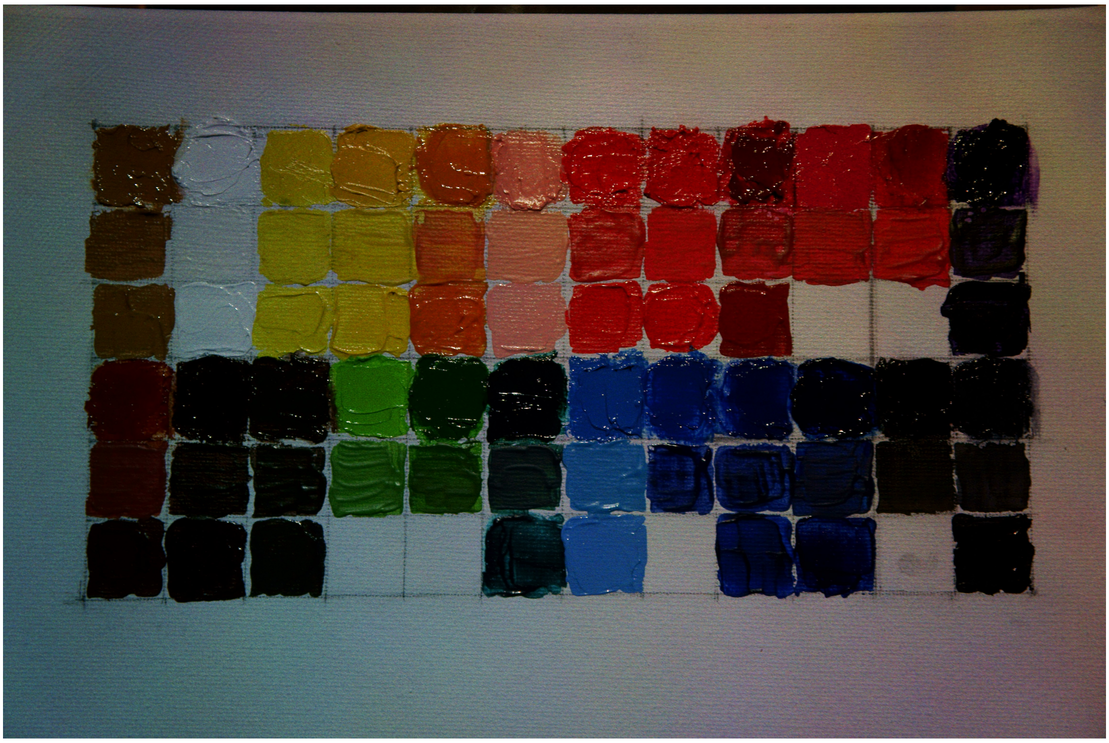


Figure 13 - Test Color Spectrum: Oil; Aquarelle; Acrylic (repeats)

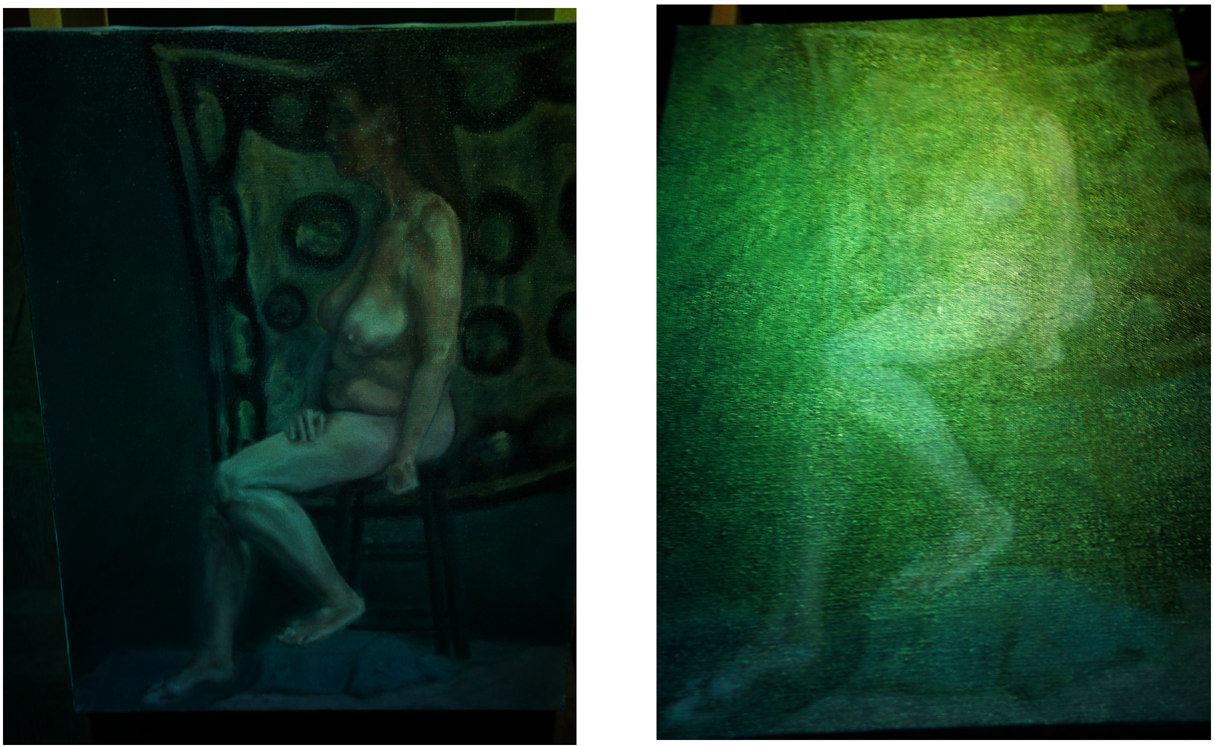


Figure 14: Traditional oil techniques; damar varnish; note glare at some angles

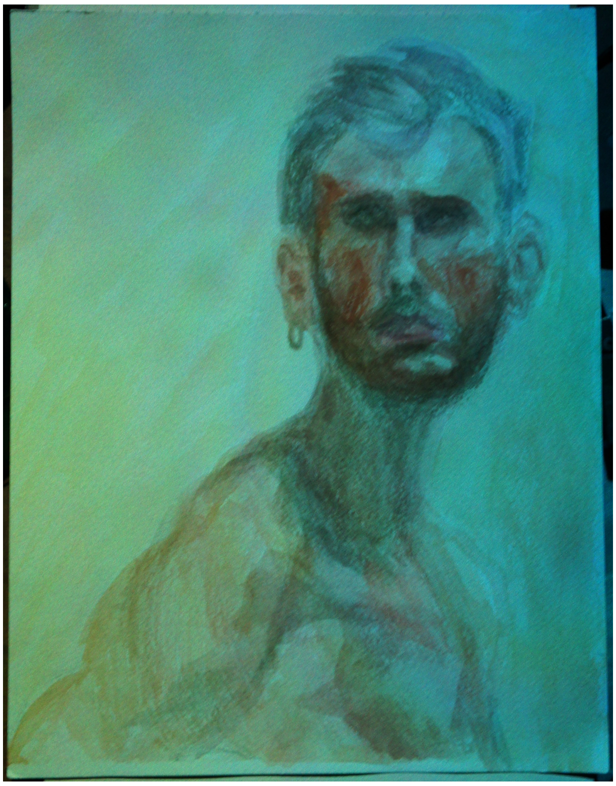


Figure 15 - watercolor sketch

Figure 16 - Still life with RGBYP and B/W

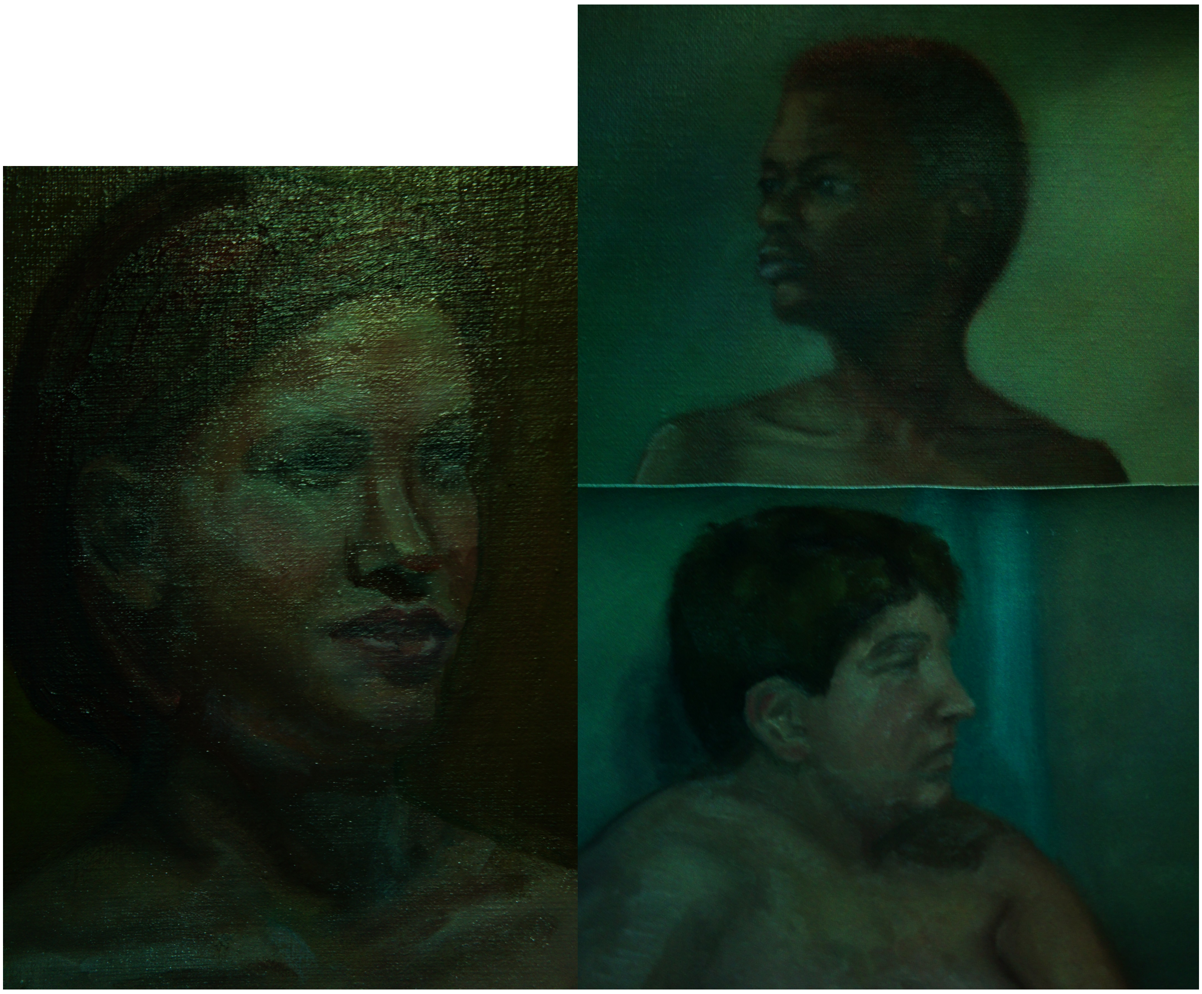


Figure 17 - High Chroma; various skin tones

Figure 18 - Painting 1 and Hologram; White Laser Illumination

Figure 19 - Painting 1 and hologram; warm LED

Figure 20 - Painting 1 and hologram; Halogen

Figure 21 - Painting 2 and hologram; White Laser illumination

Figure 22 - Painting 2 and hologram; warm LED

Figure 23 - Painting 2 and hologram; Halogen

Figure 24 - Kaolin painted Native Indian Kachina doll

10. Conclusions

The conclusions are preliminary based on issues above.

- The claims of greater dynamic range than photography (film) do not seem justified for color holography (at least not yet)
- Analyzing white light reflectance, spectrum and number of wavelengths must be practical and not via simulation.
- Ideal test exemplars should be created and shared; 8 highly reflective color chips are not sufficient; take approach similar to other fields (24 or more)
- An approach that leverages high quality digital camera and ICC profile would simplify process even if a preliminary stage of colorimetry
- Holography will not be identical unless reflectance is ‘dimmed’ on original
- Dark areas of hologram appear to have less dynamic range than bright areas. Note that the above hologam shows a bright black – but this is because the Kaolin paint used has extremely high reflectance (Kaolin / China Clay is used for porcelain and for glossy print stock).

11. Future Work

The initial need is to resolve the issues mentioned above. Subsequent to that the following is suggested:

- Create (or join) controlled environment focused on true color holography for museography
- Solicit sponsors from Laser, Lighting, Colorimetry and Museum fields
- If possible get access to two or three wavelengths for each primary (RGB); evaluate color accuracy separately from noise minimization; it seems that CIE color space can be covered as a polygon with red to green being a straight line and green through blue requiring additional wavelengths; digital TV is now leveraging 4 laser displays – research what wavelengths Mitsibushi recommends
- Create standard exemplars leveraging Munsell color with CIE equivalent using most uniform and available commercial pigments and with value range and wash/varnish for each pigment
- Get input from museums on standard pigments that correlate with old masters, try different era of paintings (or palette of that era with recreation) to see if they are each reproducible

- Research options to 3 wavelength LED and museum selected Halogen replacement (warm broad spectrum LED)
- Add pastel to the pigments tried? Good usage due to fragility of media and behind glass
- Continue original intent of evaluating subtleties of visual duplicate over full visual field

12. Acknowledgements

The author wishes to acknowledge and thank Atelier d'Art en Holographie for providing access to existing works, material, equipment and assistance in preparing test samples.

The author also wishes to thank Jack Faragasso for providing insight into the use of Munsell color system to match paint colors, Hans Bjelkhagen for sharing research papers and Kremer pigments for providing sample color charts.

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