LED Lighting in Museums: Conservation and Color of Textiles

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Abstract

Museums are facing difficulties with textile objects as they begin implementing LEDs into galleries. The damage caused by light is aesthetically and physically damaging to artifacts, and is almost completely irreversible. LEDs have enormously variable SPDs that can cause the color of artifacts to look distorted to viewers. This occurs when the wavelengths reflected by the dyes are absent from the spectrum of the LED selected.

Research to explore the effects of LEDs on early synthetic dyes has been conducted to understand the consequences of implementing LEDs in museum galleries. Findings show that when information from the lamp SPD and textile light reflectance data are used together, that it is possible to select lamps that give the appearance of increased color saturation without harming the artifact.

Introduction

Working together, several conservation scientists, conservators, and lighting designers have examined the overall efficiency of LEDs in conjunction with the Department of Energy, including a seminar at the Smithsonian's American Art Museum in the spring of 2013, looking to reduce the operating costs of museum lighting.[1] Of the 10,000 museums in the United States, the Smithsonian Institution is a federally funded entity with 19 museums and galleries, a zoological park, 9 research facilities, and more than 20 million museum visitors annually.

Overseen by a Board of Regents, but ultimately by Congress, federal funding provides about 57% of the Smithsonian's budget. These are largely spent on (unglamorous) operating expenses, rather than temporary exhibitions or permanent gallery displays which can often be sponsored by donors or developed with grants. Most other local, city, or state museums share the same dichotomy in budgeting. With financial concerns and constraints always paramount, there is a great deal of interest in the potential for energy savings throughout the museum.

Expense and Exposure

A joint study by the Canadian Conservation Institute and the Getty Conservation Institute estimate that the energy cost (in kilowatt/hours) would be reduced by 63% by installing solid-state lighting for a gallery at the Field Museum in Chicago. A more detailed review of the cost of relamping and installing of LEDs for a Getty Museum display area produced a 66% reduction in illumination costs over the lifetime of the LED's luminaire operation (Table I).

Table I. Getty Museum Display Lighting Life-Cycle Cost Analysis (Including Relamping Labor)- Input Data and Summary [2]

	(34) Incumbent Sylvania 60W Halogen PAR38 30 degree Beam, 120V	(34) Cree "LRP38" 12 W PAR38, 20 degree Beam LED Replacement
Initial Capital Costs for All Components	$184.00	$3,398.00
Average Annual Electrical Energy Usage	5410.08 kWh	919.71 kWh
Average Electric Cost per (US Dollars/kWh)	$0.12	$0.12
First Year Energy Consumption Cost	$649.21	$110.37
Study Period	10 years	10 years
Discount Rate	3.00%	3.00%
Discounting Convention	End-of-Year	End-of-Year
Present Value, Energy Consumption Costs	$5,568.00	$947.00
Present Value, Relamping and Lamp Cost	$653.00	$111.00
Annual Value, Relamping and Lamp Cost	$9,076.00	$1,999.00
Present Value, Total Life-Cycle Cost	$1,064.00	$234.00
Annual Value, Total Life Cycle Cost	$14,828.00	$4,985.00
Total Annual Emissions	$1,738.00	$584.00
CO_2 (kg)	1423.00	242.00
SO_2 (kg)	0.35	0.06
NO (kg)	0.58	0.10
Comparative Present Value over 10-Year Study Period		
Net Energy Savings from LED Lamping	4621	Baseline
Net Savings from LED Lamping	9843	Baseline
Savings-to-Investment Ratio	6.31%	Baseline
Adjusted Internal Rate of Return	23.83%	Baseline
Estimated Simple Payback Occurring	3 years	Baseline

An important component in this cost savings is associated with the luminous efficiency of the lamps, which is the ratio of electrical power used to produce light (lumens/Watt). While the typical 60 W incandescent bulb (producing 850 lumens) operates with about 14.2 lumens/Watt expended, LEDs can achieve rates of 60 to 188 lumens/Watt. As a consequence, the radiant power necessary to provide similar levels of brightness for the human eye is greatly reduced. [3]

Such a cost savings can be achieved in part because of the manner in which the human eye perceives light. The wavelengths from 380nm to 750 nm are not perceived individually by the human eye but instead are dependent upon three cone photo-pigments with ‘very broad, continuous and overlapping’ sensitivities to wavelengths that are maximized at 555nm. Thus, white light can be produced for humans by differently shaped spectral power distributions (SPD) across the visible spectrum with enormously different luminous efficacies of radiation (LERs) (Fig. 1).[3, 4]

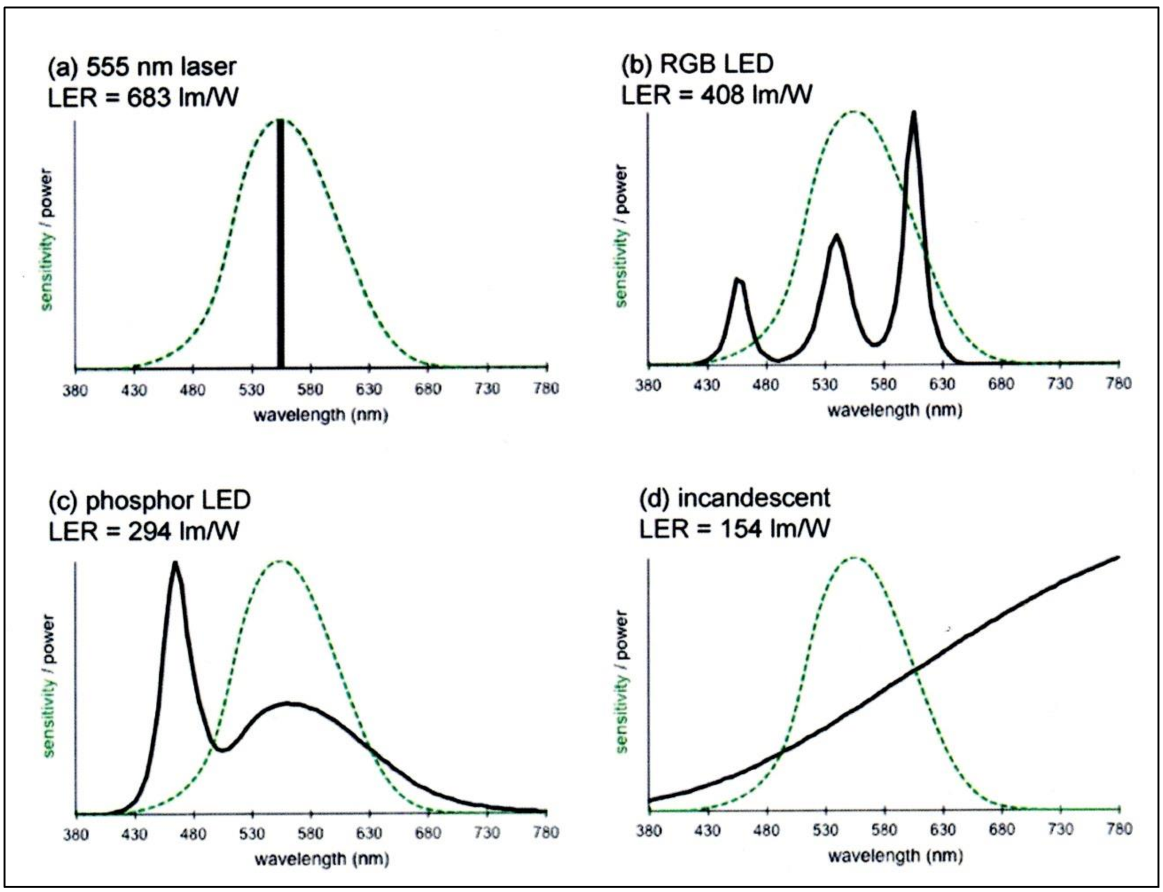

Fig. 1. Luminous Efficacies of Radiation for different lights that all appear white to the human eye but have very different spectral power distributions. The dotted line characterizes the sensitivity of the human eye across the visible spectrum. [3, p.13]

The quantity of electrical power—the area under the curves (in Fig. 1)—are markedly different as well. In addition to the exclusion of ultra violet light and near infrared regions, conservation scientists have sought to limit illuminance generally. With the advent of light sources with defined spectral intensities, the exposure or radiant flux (W/m^2) on a surface could be reduced 30 to 40%. In photometric terms, by changing from a tungsten halogen multifaceted reflector lamp to a three band RGB source, a year's museum exposure for an object—3,000 at 50 lux exposure each hour calculates to reach 150,000 lux-hours per year—could be reduced 41% to 89,000 lux/hours. [5] These savings of money and exposure are impressive, and they have propelled much of the discussion of LEDs at museums.

Indeed the chemical and mechanical damage caused by light on museum objects has been broadly classified into 3 groups within the range of the ISO Blue Wool standards and 1 that is 'irresponsive'—undamaged by light. Despite the desire to formulate a single fixed 'damage factor' to historic textiles, efforts up to now have been unsatisfactory. [6]

For the most part, dyed and undyed textiles are exhibited at the lowest level of gallery lighting (50 lux) for the minimum period of time (3 months). That is, the standard exhibition policy is for textile collections is 37,500 lux/hours—once just every two years. This textile standard represents an 87.5% reduction over a year's normal exposure to lighting at 50 lux. This is an arithmetic reduction rather than the exponential reduction associated with Blue Wool values. Yet, oftentimes, the off-view 'rest' period in dark storage extends to a decade or more. This three-month only policy is logistical as much as it is logical: the effort required for planning, publicity, loans, conservation, and installation does not promote the brokering of an exhibition for less than 3 months duration. The concern for fading and discoloration, loss of tensile strength, and loss of extrinsic value are enough to preclude a prolonged exhibition. Occasionally, susceptible, fragile textiles may be rotated off view and switched with other, complementary examples for a longer exhibition. In extreme instances, the level of lighting on the object may be diminished by successive, darkening corridors that allow the visitors' eyes to adjust to almost scotopic vision at the exhibition.

Color Rendering

Among the 137 million objects accessioned in the Smithsonian collections, a quarter of a million textiles and costumes are extraordinarily popular, iconic, and important: the First Ladies' Gowns, the Star Spangled Banner, the Wright Flyer, the space suits, the quilt collections. The primary issue for textile curators, conservators, and historians at the Smithsonian, as at specialty museums for textiles, carpets, quilts, or tapestry collections, has been fidelity to the artist's original intent, to specific relationships of pattern and color. Technically the focus is upon what is seen by the museum visitor: the quality the light reflected from the object as illuminated by the light source as interpreted by the human eye.

Color rendering and concepts such as LER are linked as photometric concepts by the common use of spectral energy distribution and the sensitivity of the human eye. Two criteria have been appropriated to reference this interplay. First, the correlated color temperature (CCT) is employed to categorize the apparent color of a light source. CCT is not definitive, but gives the observer an idea of the sources appearance or whiteness. In addition, a color-rendering index (CRI) was developed to provide a comparison of the color quality for the spectral reflectance of objects lit by different light sources, including fluorescent lights. [3, 4, 7] More recently it has been adapted for describing the effects associated with an object's color effects of LED lighting.

A new, third system, a color quality scale (CQS) has the potential to incorporate more closely the palette of object color reflectance itself. [8, 9]

Measurement Criteria

The electromagnetic radiation or light emitted by a black body radiator in thermal equilibrium as defined by Planck's Law can be plotted against wavelength to produce the spectral power distribution curves at various wavelengths (Fig. 2). The maximum spectral power of any particular radiator at a specific temperature in degrees Kelvin is used to describe that particular distribution curve. Based on their own λ_{max}, light sources are ascribed to their closest match in nanometers for their particular level of whiteness, their CCT.

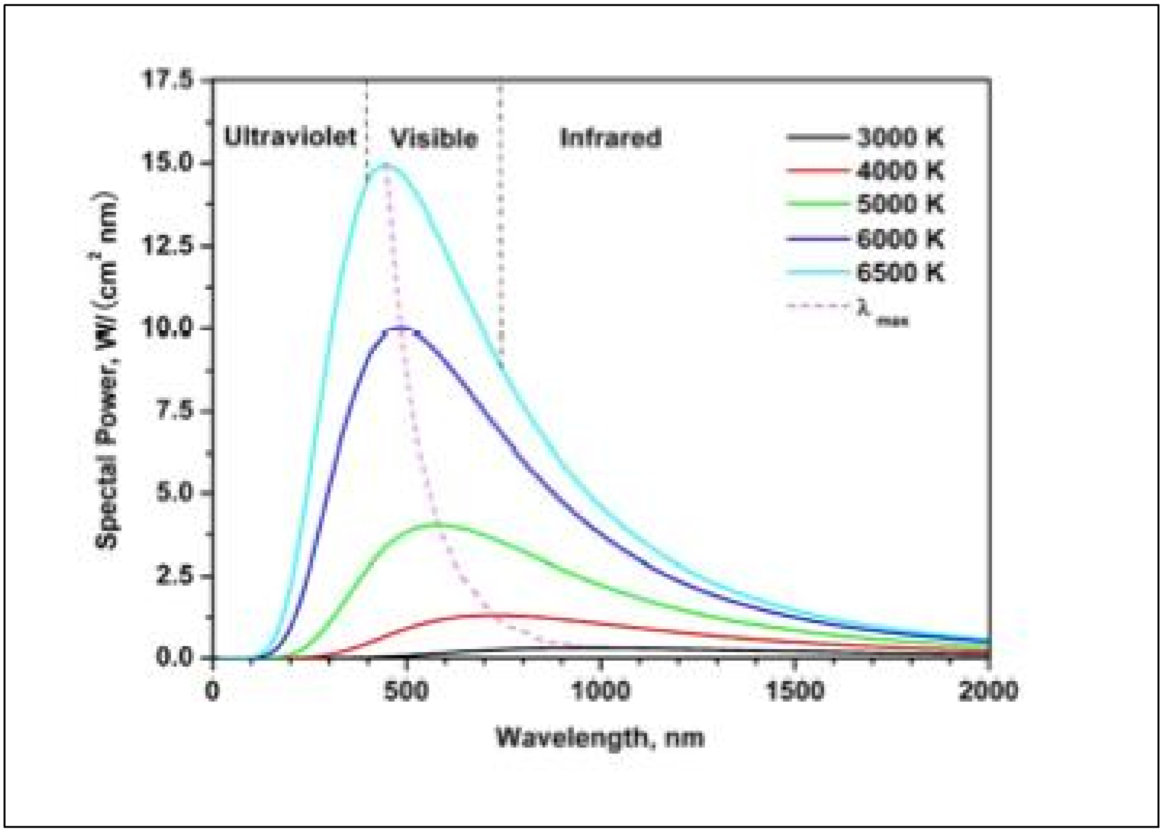

Fig. 2. SPD of Black Body Radiators at Different Color Temperatures

When these light values are plotted within the color matching sensitivities of the CIE tristimulus chromaticity values equidistant from a black zero point, the horseshoe shaped chromaticity diagram with its spectrum locus in nanometers in the visible region appears (Fig. 3, 4 and 5).

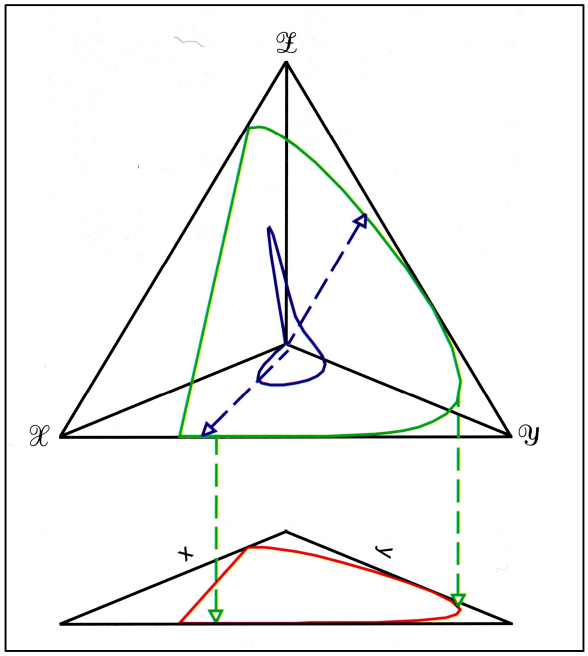

Fig. 3. A sketch of the CIE Tristimulus Space is Expanded Equidistant from the Origin, and that Plane is Sliced and Placed as a Two-Dimensional Graph [10]

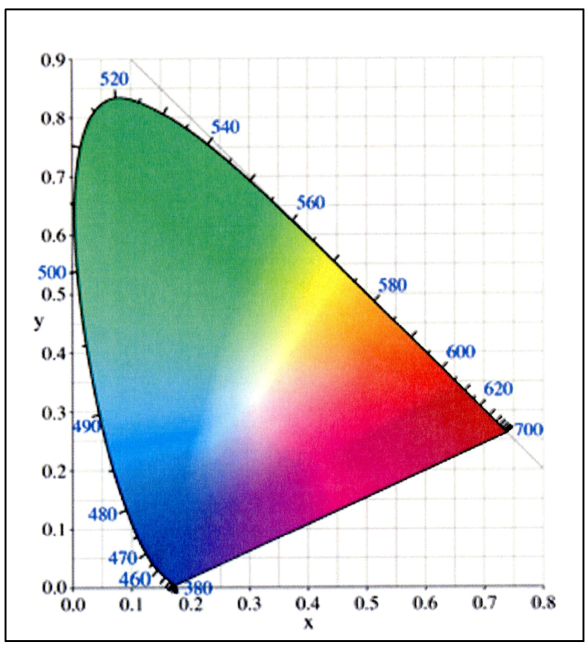

Fig. 4. Depicts CIE Tristimulus Space with the X and Y Coordinates and the Visible Spectrum Positioned and Its Nanometers [10]

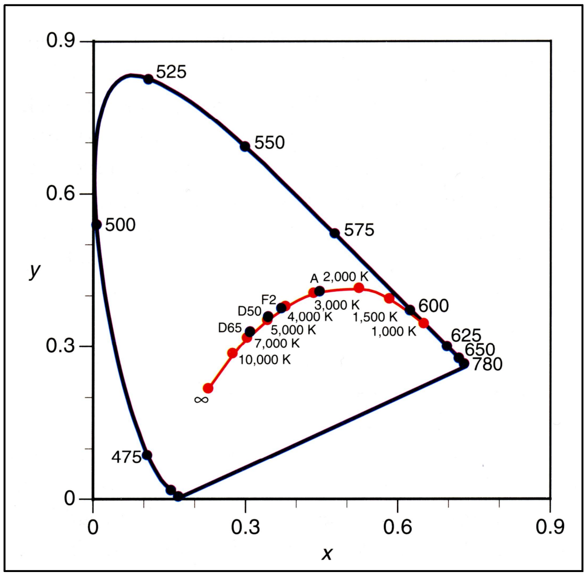

Fig. 5. The Curve of Blackbody Radiator Known as the Planckian Locus [10]

The CIE tristimulus chromaticity values are most commonly depicted as a two dimensional graph though the concept is a three dimensional plot with its illuminance factor set midway. The chromaticity diagram provides a mathetmatical scaffolding upon which to plot both the λ_{max} of light sources and actual visual reflectance values. Modified CIE diagrams were developed to provide chromaticity comparisons that were more uniform for all the hues. These are sometimes called ‘opponent’ systems. The CIELAB 1976 (L*a*b*) and the CIELUV 1976) both provide more constant valuations for hues at the same relative level of chroma (Fig. 6 and 7). Reflected, object colors are most often measured in the CIELAB system while the CIELUV is routinely used with light sources and displays, though both equation sets may be suitable for either use. Over the years, nuances of visual tolerances for the manufacture of materials developed using the L*a*b* metric. [10, p115; 11]

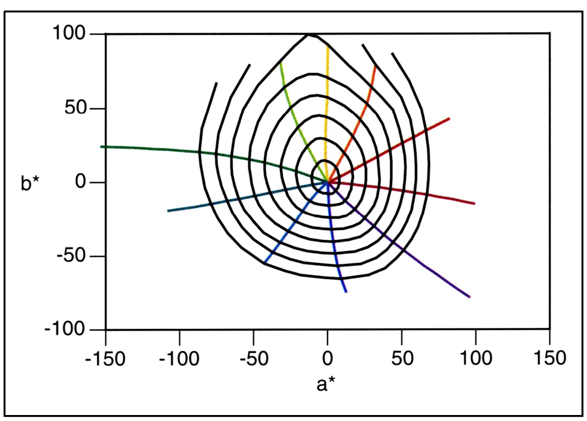

Fig. 6. Example of Munsell Hues using CIE 1976 L*a*b* [10]

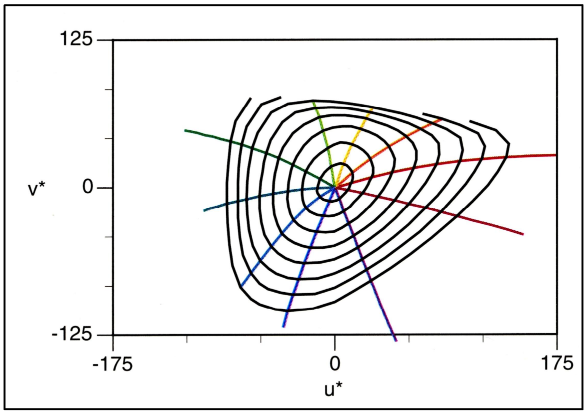

Fig. 7. Example of Munsell Hues using CIE 1976 L*u*v* [10]

Light sources—particularly LEDs lamps—are currently being marketed using these two metrics: by their proximity to a correlated color temperature (CCT) (Fig. 8 and 9), and by their color rendering index (CRI) using an early, 1960 version of the CIELUV. [7]

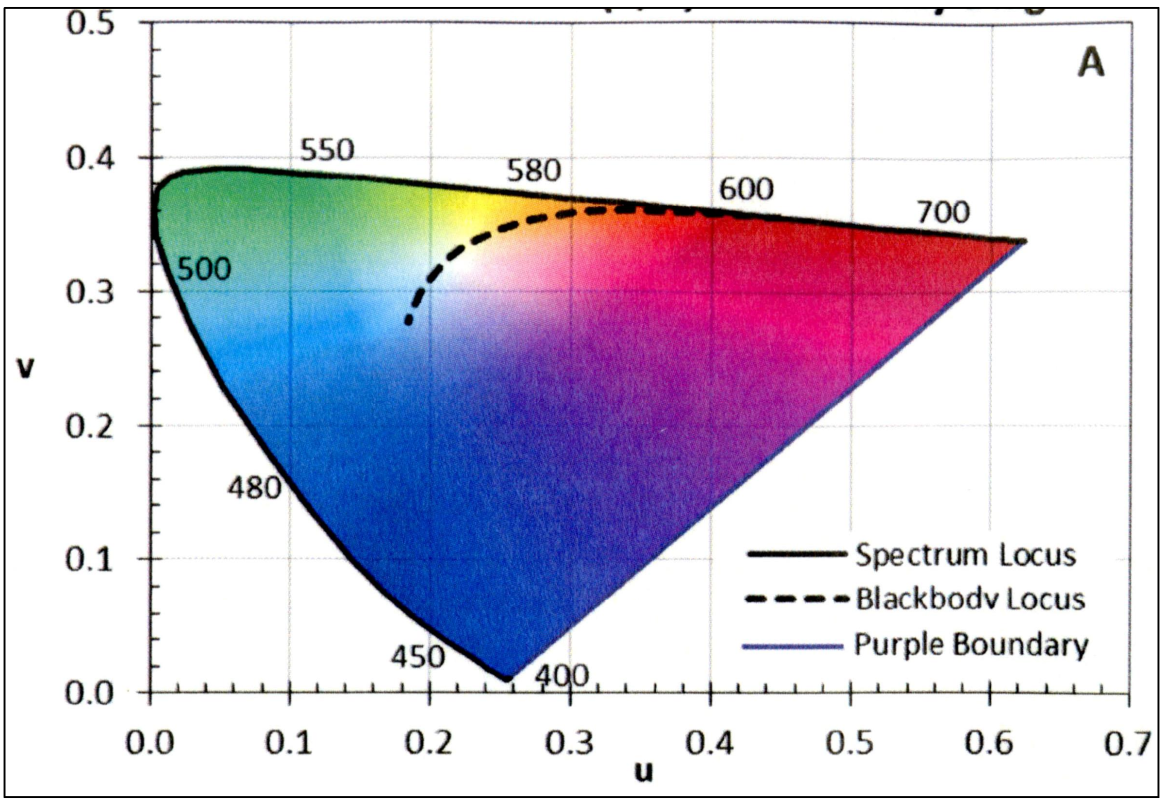

Fig. 8. The location of the black body radiator on a CIE 1960 LUV chart. The temperature ranges from reddish (warm) with a low K value to a bluer (cooler) flare. [7,10]

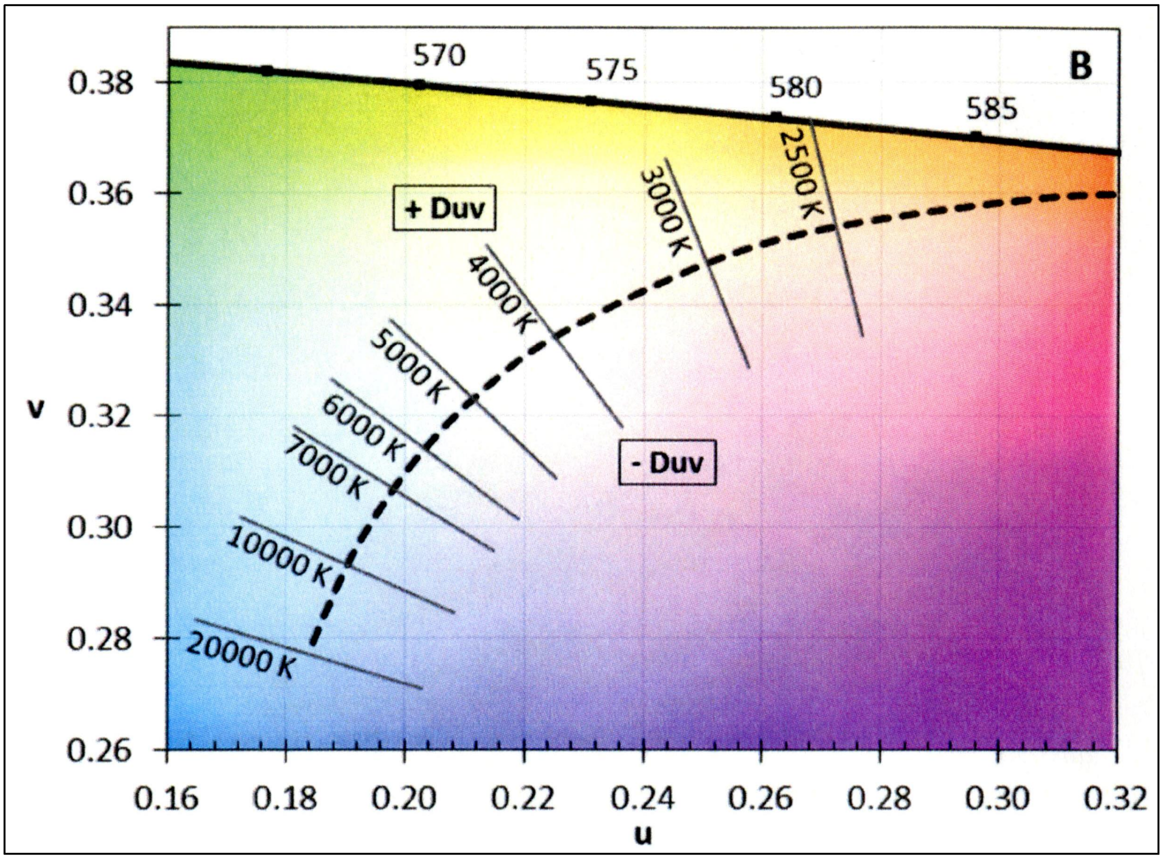

Fig. 9. The location of the black body radiator on a CIE 196 LUV chart. Using a + or – Duv valuation provides a means to designate a yellow/green or purple cast. [7,10]

The CCT metric measures in a blue-yellow direction [3, p.13]. The Duv designation provides a sense of greenish-pinkish light and has been used as a limitation on deviation from the CCT value. Yet, at best, CCT is a generic number, since different light sources with radically different SPDs can be appraised as having the same CCT (Fig. 10).

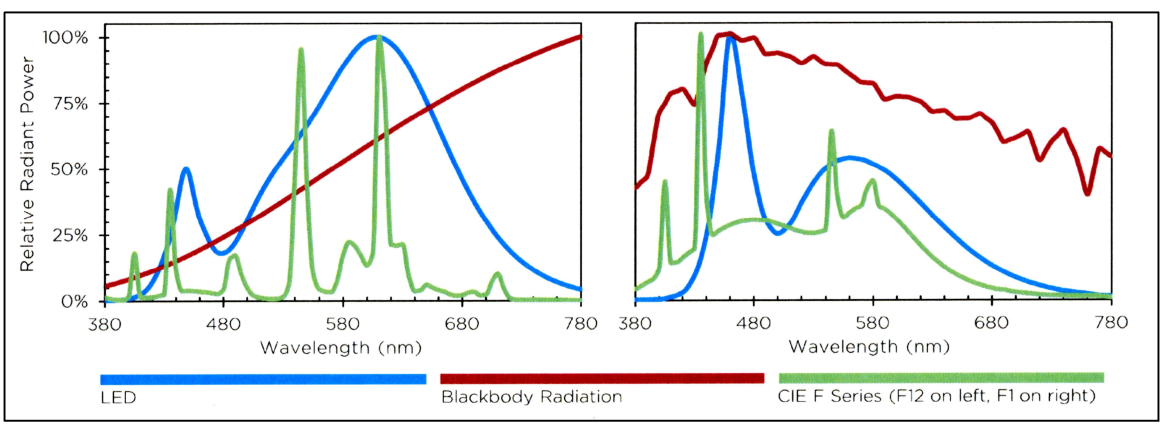

Fig. 10. The SPDs at 3000K (left) and 6500K (right). For human eyes, the white light sources at 3000K look alike as do those at 6500K. Yet they have distinct SPDs as shown here. [12]

For example, two light sources with the same 3000K CCT value may provide very different views of the same color (Fig. 11). Here the same swatch of Crystal Violet on silk (CI Basic Violet 3, CI 42555) do not match when viewed because the actual SPD are of the LED lamps are not congruent.[13]

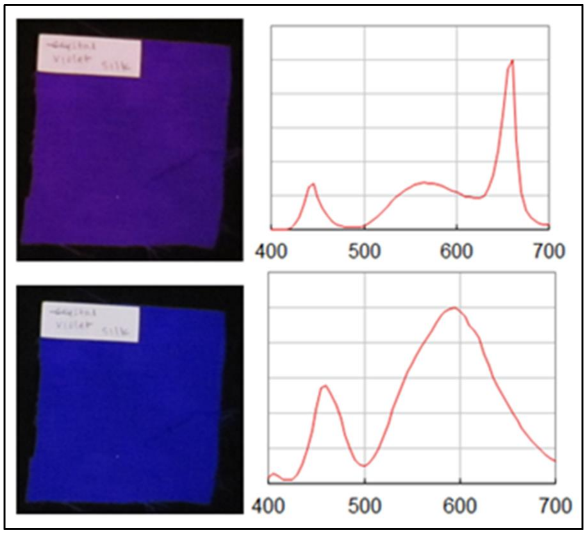

Fig. 11. The same swatch of silk dyed with Crystal Violet (Colour Index Basic Violet 3, C.I. 42555) shown under two different SPDs [13]

Using the same 1960's CIELUV-UVW system, the color rendering index (CRI) provides a numerical measure for the fidelity of an object's reflectance from a given light source compared to its reflectance had it been produced by the reflectance from its designated standard (blackbody radiator). The CRI value generally measures from 0 to 100, with indoor lighting recommended to have a rating 85 or higher. However, it can be a negative number. The CRI keeps the color sample constant and notes the difference in the spectra reflectance between two light sources instrumentally measured for acceptability to observers. There is a reference illuminant and the test illuminant. Eight mid-chroma test color samples (TCS 01-08) are used (Fig. 12, top row), augmented now by six additional tones: a more saturated red, yellow, green, and blue plus 'complexion' and 'leaf green' (TCS 09-14). Because the CRI metric is the average of predominantly mid tones values, R_a, major discrepancies in color-rendering may not be recognized. Hue shifts may or may not be flagged.

For example, a lamp with a low CRI value not need be a poor choice for a bright orange-red. In Figure 13, a silk sample dyed with Congo Red (Colour Index Direct Red 28, C.I. 22120) is shown under two different LED spectra. Both spectra have same CCT and illuminance, but the SPD and CRI are different. The SPD of the low CRI LED affects the range of the color gamut to create a stronger red, a more saturated appearance of the Congo Red sample. [13]

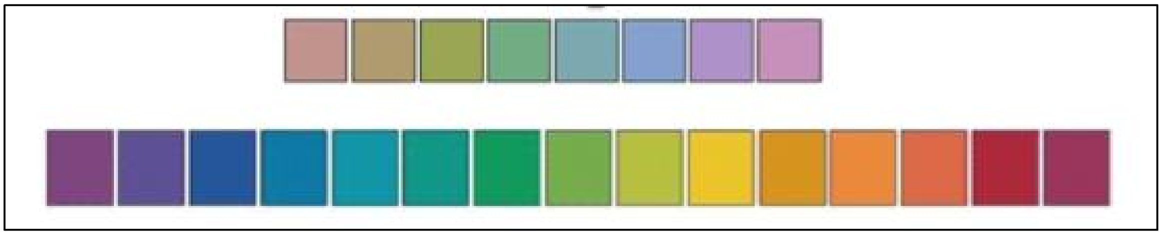

Fig. 12. Top line of Color Samples are used to calculate R_a value for the CRI. Bottom line are the commerially available Munsell Color Chip Samples used for the Color Quality Scale (CQS) [12,8,9]

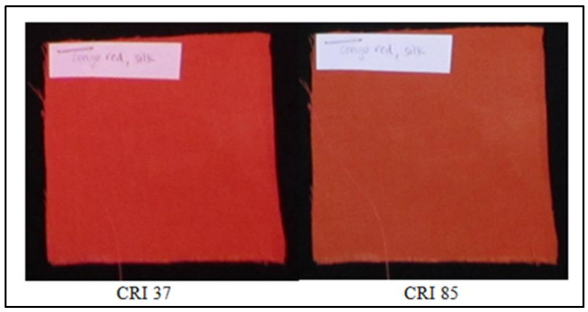

Fig. 13. The same swatch of silk dyed with Congo Red (Colour Index Direct Red 28, C.I. 22120) shown under two LEDs with different CRI Values, low CRI left; high CRI right.

The CRI numeric fails to catch nuances sometimes called fidelity, appeal, discrimination. If there are slight color shifts of hue angle, the viewer may not see them; stronger chroma provide a more pronouced distortion than those with moderate chroma. This deficiency is not captured by the CRI metric. By using muted tones as reference standards, CRI calculations can negate highly saturated hues. At the same time, in some cases a particular light source can enhance the appeal of an object—the reflectance curve may 'flatter' the object viewed under a particular light source by slightly deepening its chroma. Here distortion can have a positive effect.[8, 4, 14, 15, 16, 17, 12]

Textile Color Simulation (TCS) using the NIST Color Quality Scale (CQS)

Recently, another reflectance quality index, the color quality scale (CQS) was developed by the Optical Technology Division at the National Institute of Standards and Technology (NIST) using the CIELAB 1976 metrics and 15 samples possessing a high chroma (Fig. 12, bottom row) again comparing the score of a test source against a standard. In this program, available on the NIST website, the comparison can be shown for each sample, which has been scanned at 5nm intervals. The CIE LAB tristimulus colorimeter formula is used for the NIST Color Quality Scale (CQS). The NIST CQS keeps the color sample constant and notes the difference in the spectra reflectance between two light sources instrumentally measured for acceptability to observers. Again, there is a reference illuminant and the test illuminant. The reflectance value of the color sample constant is measured using a D_{65} xenon illuminant massaged to correspond to the correlated color temperature (CCT). To compensate or adapt the chromatic values, the values for color reference sample are massaged using the CMCCAT2000 formulation. The chroma (C*) value is also determined.

The goal of the NIST Color Quality Scale is to create a single number score for a test illuminant. For this reason, the ΔE_{ab}^* for a test illuminant that leaves the chroma value

$$\Delta C_{ab}^* = C_{ab}^*{}_{test} - C_{ab}^*{}_{ref}$$

unchanged or positive (i.e. ΔC is 0 or a positive number) is left unaltered, but a ΔE_{ab}^* for a test illuminant that leaves the chroma value negative is modified using a 'saturation factor:'

$$\Delta E_{ab}^* = [(\Delta E_{ab}{}^*)^2 - (\Delta C_{ab}{}^*)^2]^{½}$$

In addition, a ΔE_{ab} value is listed for each sample (Fig. 14). An abbreviated visualization of the CRI results compared to those of the CQS demonstrates the greater ability of the CQS to capture critical information for object display.

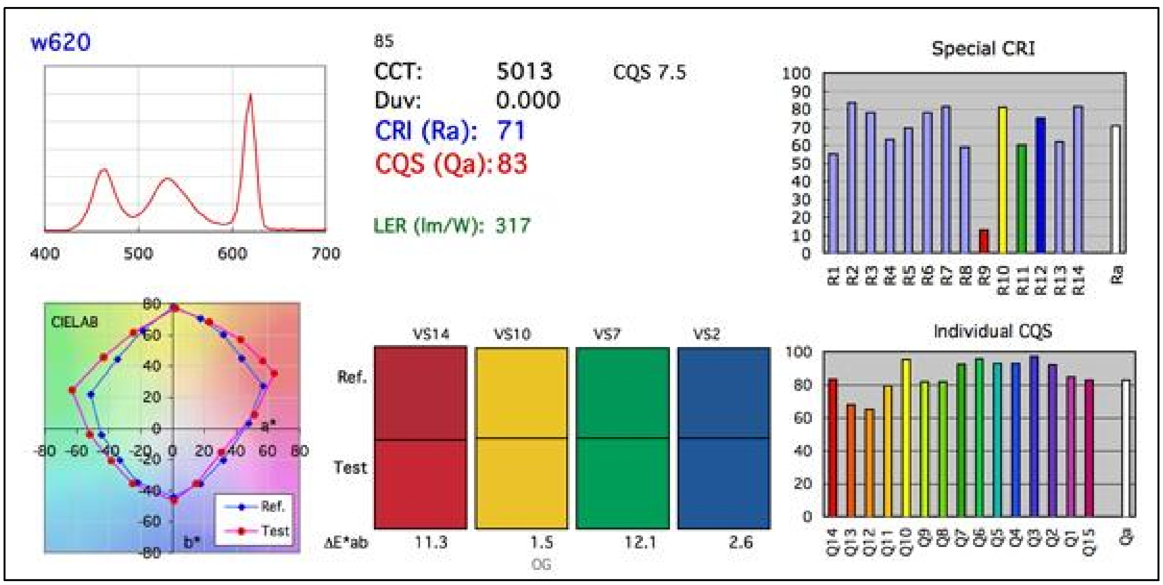

Fig. 14. An abbreviated version of the information found in the CQS program, showing the SPD, LER, CCT, and the results using CRI or CQS. Note the CIELAB depiction of the results and the individual ΔE_{ab} for each CQS sample shown. [14]

Color Quality Assessment at Museums

The Smithsonian Institution does not support an independent color science laboratory, so its proximity to the National Institute of Standards and Technology proved invaluable. The Optical Radiation Group has built a spectrally tunable lighting facility, a studio with variable spectral power distribution across the visible spectrum to work on LED lighting (see Figure 15).

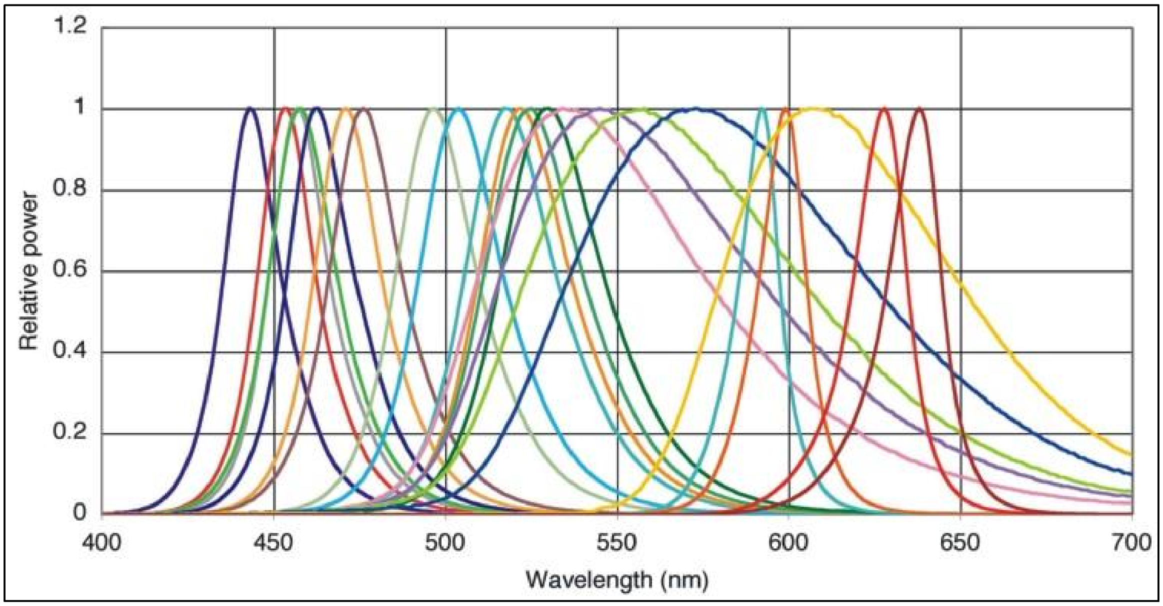

Fig. 15. Spectra of the 22 color channels of LEDs currently installed in the Spectrally Tunable Lighting Studio (SPLS) at NIST

Many of the historically important dyes and colorants are no longer manufactured and employed in commercial textile operations. In order to evaluate how they would be seen under any of the emerging LED systems, a group of dyes popular in the 19th century were dyed (Table II) on silk and cotton following recipes devised by Dr. Helmut Schweppe. [18-21]

Table II. Dyes Used in Experiment

Dyestuff	C.I. Name	C.I.#	Manufacturer/Supplier
Napthol Yellow	Acid Yellow 1	10316	(past mfr: International Dyestuffs Corp.)
			Sigma-Aldrich, Inc.
Uranine A	Acid Yellow 73	45350	(past mfr:Carolina Color and Chemical Corp.) Kremer Pigments
Auramine	Basic Yellow 2	41000	Sigma- Aldrich, Inc. (past mfr: International Dyestuffs Corp.)
Chrysoidine	Basic Orange 2	11270	Sigma- Aldrich, Inc. (past mfr: Passaic Color and Chemical Co.)
Crystal Violet	Basic Violet 3	42555	Sigma-Aldrich, Inc.
Diamond Green B	Basic Green 4	42000	Sigma-Aldrich, Inc.
Magenta	Basic Violet 14	42510	Organic Dyestuffs Corporation and Sigma-Aldrich, Inc.
Rhodamine 6G	Basic Red 1	45160	Sigma-Aldrich, Inc.
Vesuvin BA	Basic Brown 1	21000	Sigma- Aldrich, Inc. (past mfr: Passaic Color and Chemical Co.)

Victoria Blue B	Basic Blue 26	44045	Sigma-Aldrich, Inc.
Congo Red	Direct Red 28	22100	Sigma-Aldrich, Inc.
Safflower	Natural Red 26	75140	Earth Guild
Turmeric	Natural Yellow 3	75300	Earth Guild, Kremer Pigments

Upon viewing under the spectrally tuned light, in several instances the deep chroma or the double bands of the dyes' absorption created more startling differences in color values than even the CQS Munsell pigments (as seen above in Fig. 11 and 13). The CQS program was able to capture those anomalies with ΔE_{ab} values that exceeded the norm. The visual assessment and the CQS prediction correlated well.

During a subsequent visit to the NIST laboratory, the extent of color rendering for museum textiles became clearer: the relationship of tones and pattern were jeopardized as well as the individual dye color (Fig. 16 and 17). For each type of exhibition, the textile palette as a group would have to be characterized in order to define the "best in show" light source, the luminaire assembly that could be predicted to provide the greatest color fidelity.

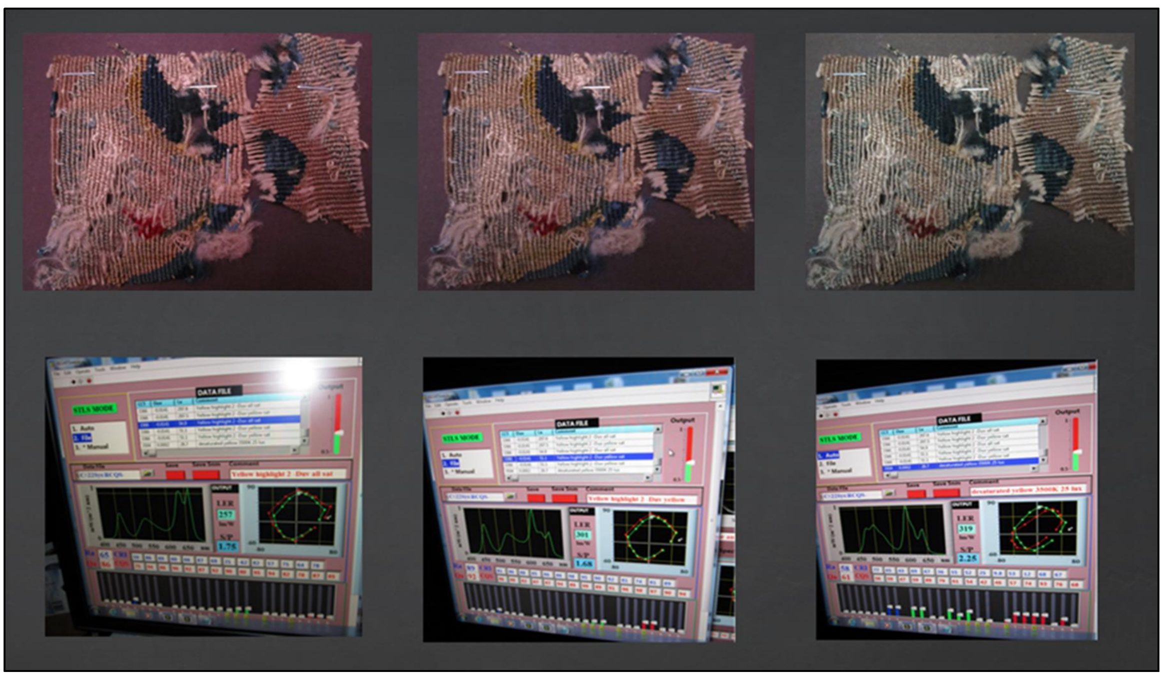

Fig. 16. The three top images show the same, more browned tapestry fragment under the three lights. From left to right, the light changes from all colors being saturated, to only yellows being saturated, to all colors being desaturated. The computer from the STLS with the SPD of the light source and the CIELAB results are shown below. Sample acquired from Dr. Helmut Schweppe.[24]

While the number of natural and early synthetic dyes may be limited, variances in auxiliaries, substrates, recipes, techniques are enormous, even if all the dyes in the Smithsonian Institution were analyzed. The more stream-lined characterization of the spectral reflectance of colors used in a collection of quilts would overwhelm a department, since a single quilt might have 250 patterns with multiple colors.

Instead for this project a single text was chosen with forty-seven specimens of dyed and printed fabrics, William Crookes's *A practical Handbook of Dyeing and Calico-Printing* as a basis for the palette in cotton available for calicos prior to 1874 [22]. These swatches included natural dyes, early synthetic dyes, and mineral colors. These swatches had already been reviewed in an early project by micro-X-ray fluorescence spectroscopy and confirmed by elemental microscopy that the samples were consistent with Crookes's description of them. For the most part, they have the high chroma of fresh commercial samples, stored as they were in a closed book.

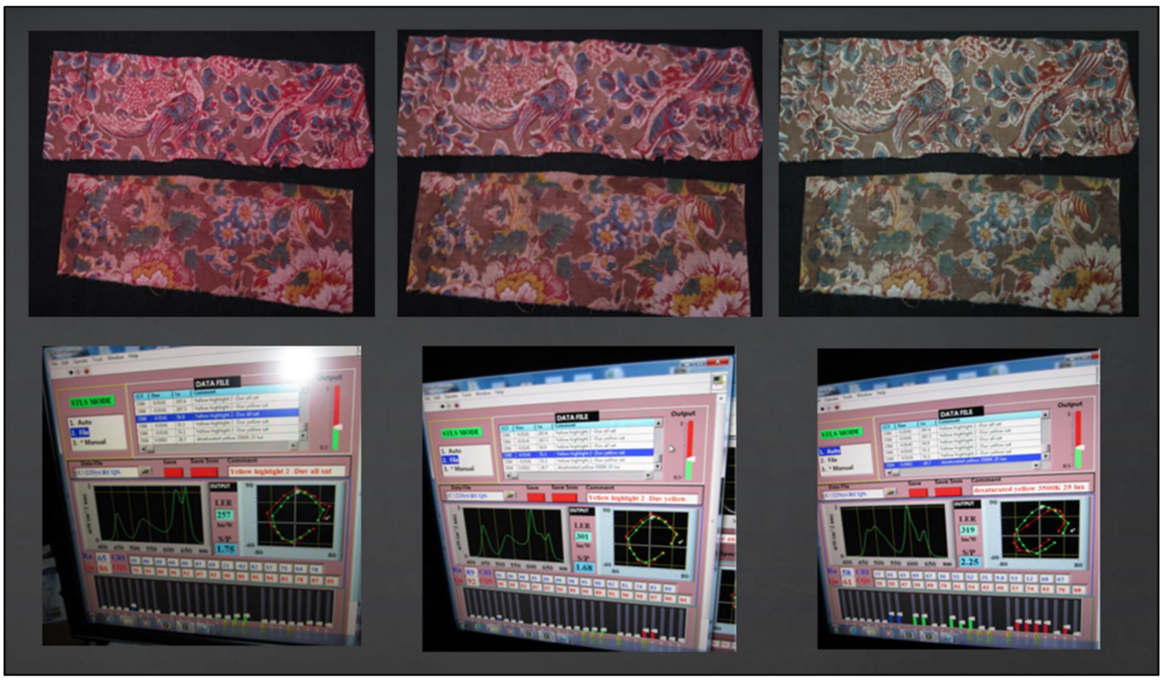

Fig. 17. The three top images show the same two textiles under different lights with different saturations but the same CCT and lux values. The first image is of the textile with all colors saturated; the second image is of the textile with only the yellows saturated; and the third image is of the textile with all colors desaturated. The computer from the STLS with the SPD of the light source and the CIELAB results are shown below. Sample donated by Cora Ginsburg, Inc., New York City. [24]

The TCS-CQS Excel program allows the user to look at the samples under all of the light sources (including theoretical sources that are not found in real life lamps).[22]

The evaluation of a light source, like CIE's F8 (Source #41), using both CRI and CQS-textiles upon the Crookes swatch values (CQS-Textiles) is shown below (Figure 17). The mid-chroma values using CRI provides a score of 96; the Crookes samples result in a CQS score of 98. The discrepancies in color rendering, ΔE_{ab}^* between this lamp and the original reference source (D

6500 daylight) are listed below each visual representation of that color difference. For the present project a portable HunterLab visible spectrometer (Miniscan XE Plus with diffuse/8° sphere geometry and with a small viewing area (8 mm) was employed using the Easy Match QC program 4.50. Scans at 10 nanometer intervals from 400 to 700nm were taken of each fabric were taken in the warp direction, the weft direction, and on the bias; these were averaged for each color. The program also provides simultaneous compilations in CIE L*a*b* and other functions. After some practice, the protocols included a black mask for stripes (in order to only measure the dyed portion desired) and multiple readings to account for surface geometry (n=6). Ultimately, thirty-six samples were used and their spectra entered into the Excel digital simulator program created by NIST (Fig. 18). Of the 124 light sources included in the simulator program, 28 sources had the best fidelity as seen by the ΔE_{ab} of the samples. Of these, two lamps with CQS of 96 and 95 were selected where the ΔE_{ab} values were low indeed. Ideally, a spectrophotometer with lower intervals might be preferable.

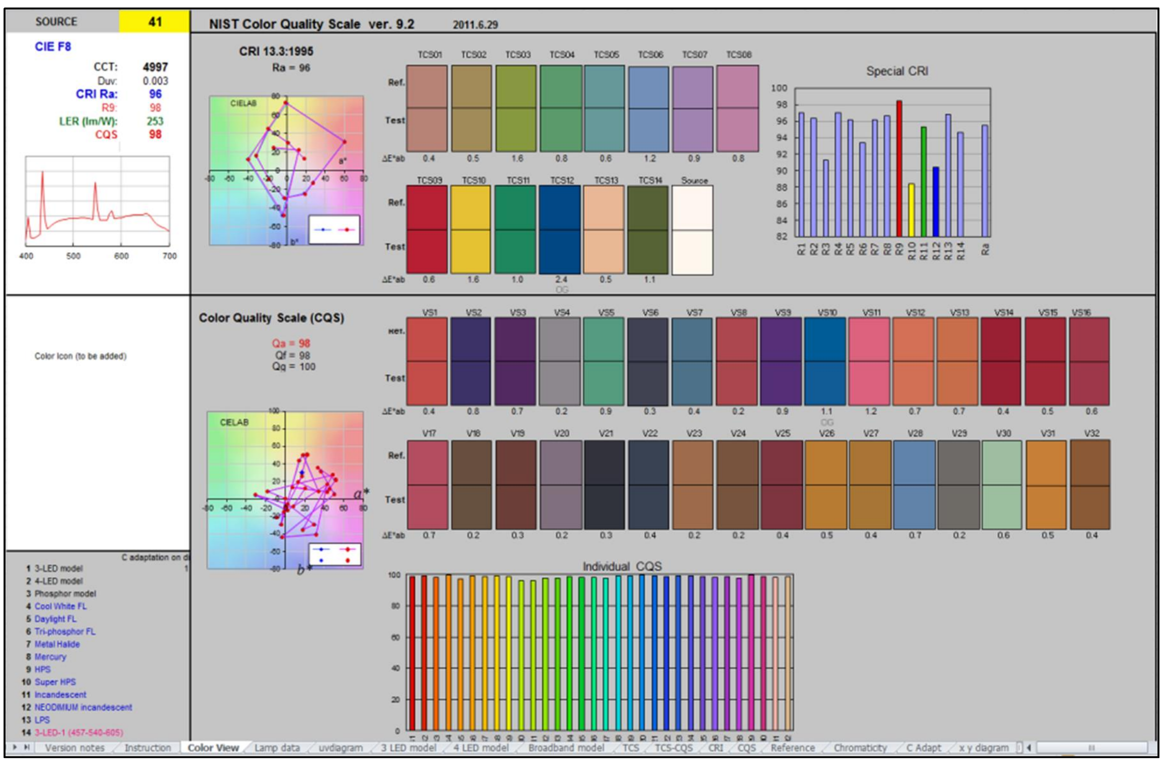

Fig. 18. An abbreviated version of the CQS Excel sheet with the samples from Crookes's book added for experiment. For each of the swatches, the reflectance values from the spectrometer are incorporated into the program. The patch of color below it indicates the color that would be shown were the particular 'test' lamp to be used. [24,23,14]

Discussion

CRI has never worked well to characterize discontinuous SPD sources like fluorescent, high intensity discharge (metal halide) or light emitting diode lamps. There are distinct advantages of the CQS for textile chemists and colorists, for designers and manufacturers, for textile conservators. The formula and its application are congruent to the fundamental rationales for the ongoing textile uses of the CIELAB: the system allows the reviewer to decide whether a particular gamut is appropriate, in the same manner that dyestuff maps have for the past several decades (Fig. 19). A high chroma color outside the perimeter cannot be achieved. Paler (fainter) shades will be suitably noted if the original high chroma references can be defined within the gamut perimeter. [25]

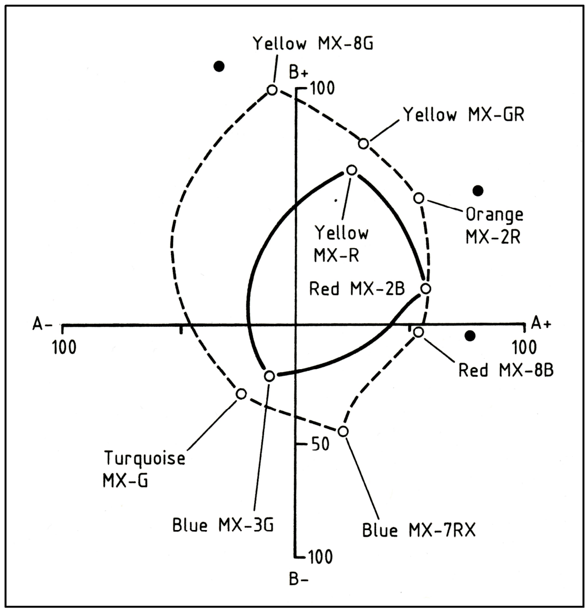

Fig. 19. Gamut of ICI's Procion Reactive Dyes available in 1956 (solid line) and in 1976 (dashed line). Three unidentified black spots representing high chroma colors will not be matched with these dyes because they fall outside the ranges of the 1956 and 1976 dye sets [25]

The CQS also permits its reviewer to consider the role of the light source in the movement of the λ_{max} of the dye (Fig. 20), a purview more often associated with color chemistry and dye synthesis. Although the CQS does not and cannot resolve basic difficulties inherent to visible light and human perception, the CQS captures their interaction. As seen by examples in this paper (Fig. 11 and 13, Table III), wherever the color absorbed seems to be a blend of 2 wave peaks, there is a stronger potential for color distortion. [26] This is caught using CQS.

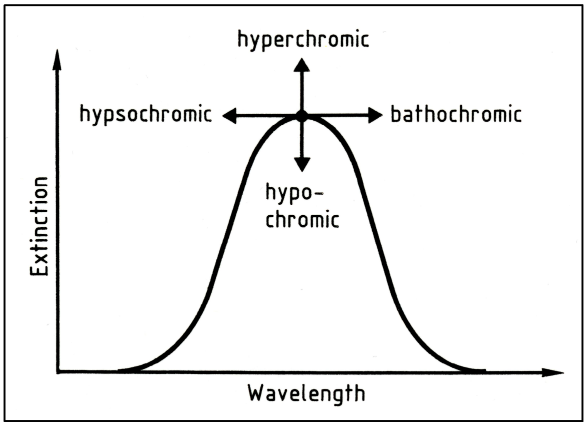

Fig. 20. Terminology for changes of wavelength shifts with changes of extinction of absorption bands [25]

Table III. Relationship of Colors Seen to Wavelengths of Light Absorbed [26]		
Light absorbed		**Complementary Color Seen**
Wavelength (nm)	**Color**	
400-435	Violet	Green-Yellow
435-480	Blue	Yellow
480-490	*Green-Blue*	Orange
490-500	*Blue-Green*	Red
500-560	Green	Purple
560-580	*Yellow-Green*	Violet
580-595	Yellow	Blue
595-605	Orange	Green-Blue
605-750	Red	Blue-Green

Max Saltzman wrote "You can't Judge a Dye by Its Color" to describe how two different natural dyes might be mistaken for one another on the basis of their spectral reflectance. [27] Madder and indigo produced a cheaper purple than Tyrian Purple as do madder and Aniline Black. Paintings conservators and conservation scientists have found similar issues with blue pigments. [28, 29] with that limitation in mind, it is prudent to confirm that the palette of relevant reflectance curves is indeed composed of the dyes that they purport to be—and not substitutions or repairs, particularly for deep chroma and for sensitive hues like orange, red, or violet. [23,24, Appendix A] Once a painting or textile is moved from the museum conservation laboratory to a gallery space with a different SPD, any disparities in the reflectance curves between original and repair may be enhanced. CQS is more likely than CRI to catch discrepancies in tonalities with changes of extinction of absorption bands. [Fig. 20]

A limitation of the CQS is that both real and theoretical LED light sources are described. There are slots in the NIST CQS simulation spreadsheet to add SPD of new lights as they enter the market should a manufacturer or lighting designer wish to do so. This paper has not reviewed the manufacturing components and systems of the LEDs themselves—the heat sink, microchip, driver, the types of Solid State Lighting (SSL). The Cree "LRP38" LED substitute for the 60W Halogen PAR38 in Table I is no longer manufactured—a scant four years later [30]. Standards and products are shifting, still being defined, and refined: new products may appear on the market with additional or different SPDs.

The CQS does not cost out the value of the light source; a LED with 4 or 6 broad peaks may not be quite as efficient, last quite as long, as one of the less expensive lighting sources. Indeed, some LEDs may vary slightly from batch to batch, or from manufacturer to manufacturer, and some shift SPD over time. The CQS is not designed to characterize changes in LEDs technology nor all the variables associated with manufacture.

Conclusions

While the advent of a new technology for indoor lighting is at hand but incomplete, there *is* a means for those caring for textiles in museums to create a specification system that is relevant to the palette of dyes and colorants used in their collection and to the lighting designer. Using CQS allows the textile conservator or curator to define the SPD most suitable for the textiles in an exhibition while the gallery space is being planned before the expenditure on a particular gallery lighting system is executed.

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APPENDIX A: EFFECT OF NIST LED SIMULATIONS ON CROOKES SAMPLES

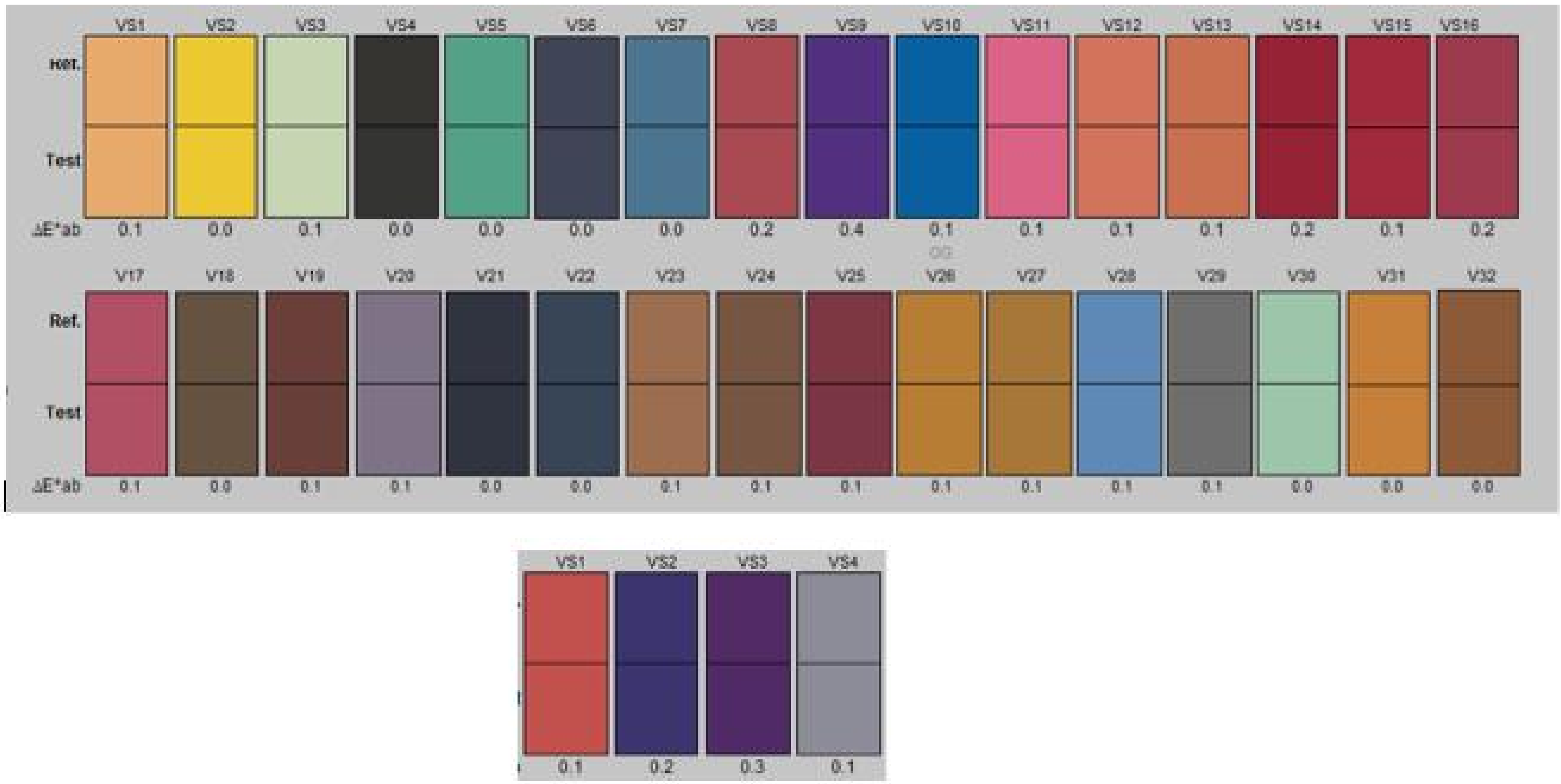

Fig. 1. Crookes Samples inserted into the CQS program, available with instructions from the internet as NIST CQS simulation 7.4xls (Yoshi Ohno and Wendy Davis 5/5/08). Here the Crookes fabric swatches are the Reference and the Test is as viewed with D65 light.

The following list provides dye information for the dyes used in the experiment. The list corresponds to Fig. 1 of Appendix A.

VS1. Iron buff Iron buff   [Nankeen, Nankin, Hydrated Ferric Oxide ($FeO(OH)\cdot nH2O$ Mineral Dye]

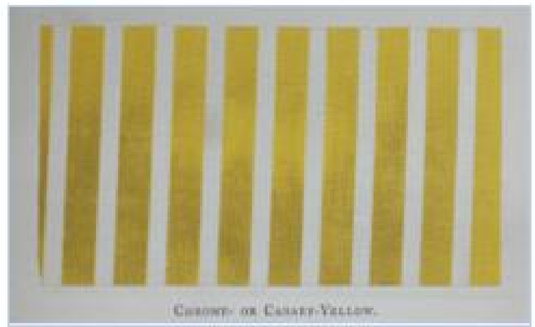

Fig. 2a. Iron Buff printed on cotton, Crookes, p. 155. Sample is discolored.
Fig. 2b. Canary/chrome yellow on cotton, Crookes, p. 155. Sample is also discolored.

VS2. Canary/chrome yellow [Koechlin, 1821 PbCrO4; C.I. Pigment Yellow 24, C.I. 77603 Mineral Dye]

VS3. Arsenical green [Sheele's green, 1778 $CuHAsO_3$ Mineral Dye]

Fig. 3. Wilner, an Arsenical Green, Crookes, p.157

VS4. Aniline black [Lightfoot, 1863, C.I. Pigment Black 1, C.I. 50440]

VS5. Chrome green(s) Chrome oxide (Cr_2O_3), C.I. Pigment Green 17,   CI 77288; Chrome hydroxide ($Cr_2O_3\cdot 2H_2O$), CI Pigment Green 18, C.I. 77289; Chromium Arsenite Cr_xAsO_3; Mineral Dyes

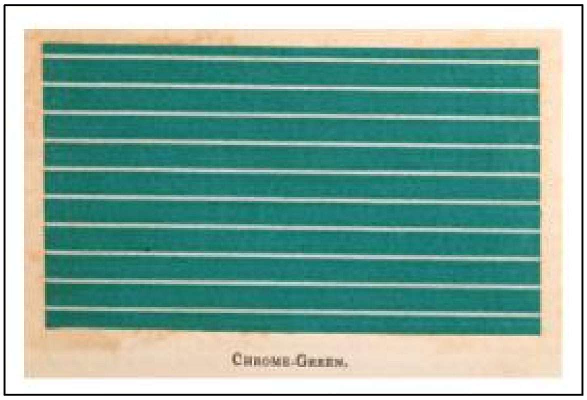

Fig. 4. Chrome green printed on cotton, Crookes, p. 157

VS6. Dark blue Prussian Blue, Royal blue [Prussian blue [Diesbach 1704, Macquer, 1749 Napoleon's Blue, Turnbull's Blue, Royal Blue), a stannous & potassium ferric ferrocyanide $K[Fe_4[Fe(CN)_6]_3]$; C.I. Pigment Blue 27, Mineral Dye].

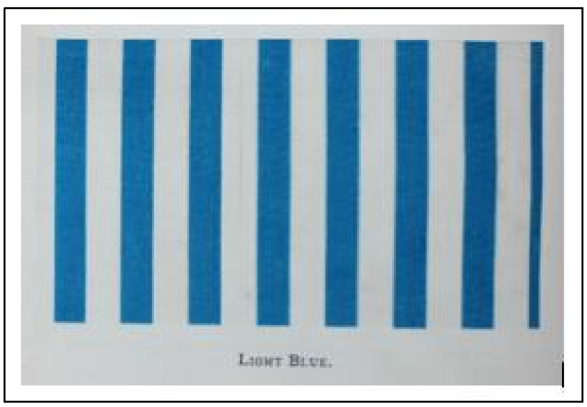

Fig. 5. Prussian Blue on cotton, Crookes, p. 164

VS7. Light blue Prussian blue [Diesbach 1704, Macquer, 1749 Napoleon's Blue, Turnbull's Blue, Royal Blue), potassium ferric ferrocyanide $K[Fe_4[Fe(CN)_6]_3]$; C.I. Pigment Blue 27, Mineral Dye].

VS8. Ponceau [on wool, proprietary trade name from Brooke, Simpson, and Spiller]

VS9. Hofmann's Violet B [A.W.Hoffman & Geyger, 1863, C.I. 42530]

VS10. Nicholson's Blue 4B [sic] [Girard & deLaire, 1861; Nicholson 1862, C.I. Solvent Blue 3 formerly used as a basic dye , C.I. 42770 or Nicholson, 1862, C.I. Acid Blue 48/C.I. Pigment Blue 18, C.I.427705]

VS11. Saffranine pink [Greville Williams, 1859; C.I. Basic Red 2, C.I. 50240 Safranine T]

VS12. Coralline yellow [Persoz, 1859 Sodium salt of Aurine, C.I.43800]

VS13. Aurine orange [Runge, 1834; C.I.43800 rosolic acid]

VS14. Madder red [C.I. Natural Red 8, C.I. 75330]

VS15. Artificial alizarin [Graebe & Liebermann, 1868/1869/1871, C.I. Mordant Red 11, C.I. 58000]

VS16. Madder red (dark pink)[C.I. Natural Red 8, C.I. 75330, C.I. 75340, C.I. 75350, C.I. 75410, C.I. 45420]

VS17. Madder pink as above

VS18. Madder style as above

VS19. Garacin [Robiquet & Colin, 1828, madder treated with sulfuric acid, C.I. Natural Red 10, C.I. 75330]

Fig. 6. Garacin on cotton, Crookes, p. 579

VS20. Madder and aniline black

VS21. Dark indigo [C.I. Natural Blue 1, C.I. Vat Blue 1, C.I. 73000]

VS22. Light indigo [C.I. Natural Blue 1, C.I. Vat Blue 1, C.I. 73000]

VS23. Standard light brown [Catechu or Cutch, C.I. Natural Brown 3]

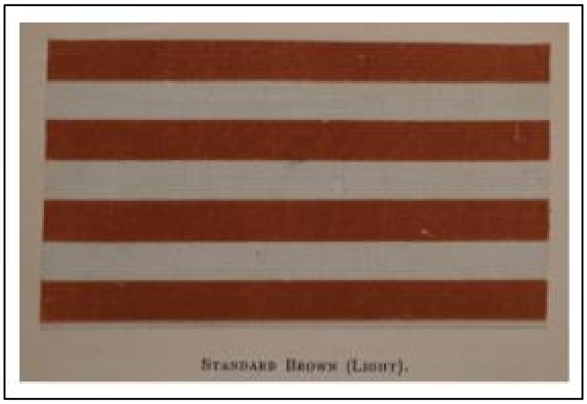

Fig. 7. Standard light brown (Catechu or Cutch), Crookes p. 604

VS24. Standard dark brown [Catechu or Cutch, C.I. Natural Brown 3]

VS25. Cochineal [C.I. Natural Red 4, C.I. 75460]

Fig.8. Cochineal Pink, Crookes, p. 609

VS26. Dark yellow with Persian berries [Dyers Buckthorn, C.I. Natural Yellow 13]

VS27. Pale yellow with Persian berries [Dyers Buckthorn, C.I. Natural Yellow 13]

VS28. Ultramarine [Synthetic Ultramarine 1828, $Na_{8-10}Al_6Si_6O_{24}S_{2-4}$ C.I. Pigment Blue 29, C.I.77007].

VS29. Carbonaceous gray [C.I. Pigment Black 6 or 7, C.I. 772666]

VS30. Padded green [a Chrome Green]

VS 31. Light chrome orange Chrome orange $PbCrO_4 \cdot Pb(OH)_2$; C.I. Pigment Orange 21, CI 76601 *Mineral Dye*

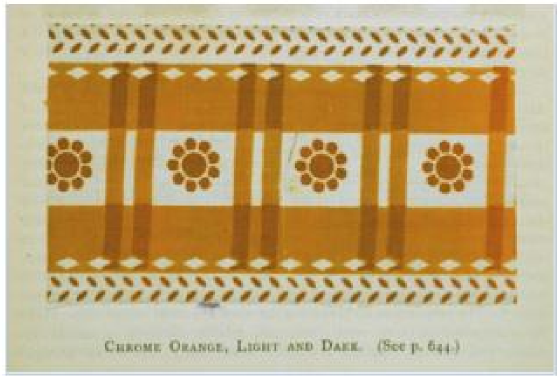

Fig. 9. Chrome orange printed on cotton, Crookes, p. 645

VS32. Dark chrome orange $PbCrO_4 \cdot Pb(OH)_2$; C.I. Pigment Orange 21 CI 76601 *Mineral Dye*

VS1. Vermillion Mercury Sulfide (HgS); C.I .Pigment Red 106 Pigment

Fig. 9. Vermillion fixed with albumen, printed on cotton, Crookes, p. 153

VS2.Spiller's purple [a Violet of a very blue shade, courtesy of "Brooke, Simpson, & Spiller"]

VS3. Hofmann's violet RRR [A.W.Hofmann and Geyger, 1863, C.I. 42530 Basic dye, a mixture of rosaniline C.I. 42510 and C.I.42500 pararolsaniline]

VS4. Aniline gray (Castelhaz, a precipitate of mauveine paste and concentrated H_2SO_4 treated with aldehyde)

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