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ASSESSING LED LIGHTS FOR VISUAL CHANGES IN TEXTILE COLORS

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Increasingly, museums are installing energy-saving light sources, such as LED (light emitting diode) lamps. LEDs represent an evolving technology; there are concerns about the effects of light spectra on artifacts, including textiles. Many LED models do not possess the same color rendering properties that observers are accustomed to, and it is important to understand the effects that spectra can play on dyed textiles. This research focuses on the visual effects of different light spectra, including those of LEDs, on textile colorants in order to gauge the range of color differences produced. Nine early synthetic dyes and one commercial fading standard were utilized. This paper summarizes our findings to date: that LED spectra with the same color temperature can render very different observable colors, especially with saturated colors. Saturated purples were found to be extremely hard to render accurately with LEDs. Other hues may also be compromised. Experimental work indicates that color temperature, illuminance level, and the commercial Color Rendering Index (CRI) are insufficient specifications for exhibitions LED light sources. An instrumental method for assessing LEDs before exhibition installation is suggested.

KEYWORDS: *Light emitting diode, LED, dyes, color rendering index, CRI, color quality scale, CQS, spectral power distribution, SPD, colorants, textiles*

I. INTRODUCTION

Color and lighting of historic textiles is a critical factor in the visitor's experience. Museum patrons want adequate light to perceive color well, while museums want to minimize light on artifacts to reduce actinic damage. Traditional artificial lighting sources used in museums are incandescent, including halogen, and occasionally fluorescent. However, light emitting diode (LED) lighting is quickly gaining popularity as an energy-saving option because manufacturers are now able to offer better quality assurance and color uniformity. The spectral power distribution (SPD) of LEDs is, however, dissimilar to other artificial lighting sources and can significantly alter the appearance of artifacts. In order for museums to use these options safely a better understanding of light spectra and their effect on dye colorants is needed. To do this, spectrally sensitive dyes were observed and assessed under different LED technologies.

The Energy Independence and Security Act of 2007 introduced energy efficiency regulations for lighting that have effectively banned (after 2014) the production of incandescent lamps, excluding specialty bulbs ([US Statutes 2007](#)). With incandescent lighting obsolete, the lighting industry is producing innovative lighting options, including LEDs. LEDs are manufactured to

work by using inorganic semiconductors engineered for performance with phosphor materials. This creates an effect called electroluminescence, where light is emitted in response to an electrical current or strong electric field. The first patent for applicable LED technology was issued in 1966 ([Biard and Pittman 1966](#)) using gallium arsenide as the semiconductor. Over the last half century, semiconductors have become an important material used in many different industries, and the market demand is driving research in the electronics and lighting industry. While gallium arsenide remains a popular semiconductor, indium gallium nitride is more common in current cost-effective LEDs on the market. Indium gallium nitride's emitted wavelength ranges from 390 to 440 nm depending on the material's band gap (controlled by the ratio of GaN/InN) ([Assessment 2013](#)). As museums implement and install LEDs, it becomes increasingly important to understand how the spectra of these technologies affect the color rendering of historic dyed textiles.

The market for LEDs is expanding into fields where color rendering is critical. The Department of Energy (DOE) has funded the Solid-State Lighting GATEWAY Demonstrations to showcase high-performance LEDs in different applications, including museum gallery lighting. GATEWAY museum

demonstrations include projects with the Smithsonian American Art Museum, J. Paul Getty Museum, Jordan Schnitzer Museum of Art, and the Field Museum of Natural History. These reports focus on energy savings and feasibility of installing lamps in detail, and examine appearance of artifacts displayed under LEDs (Myer et al. 2010; Miller 2011; Miller et al. 2012a, 2012b; Perrin et al. 2014). However, they did not study the effects of LEDs on fidelity in color perception of textiles. The international color organization, Commission Internationale de L'Eclairage (CIE), has released a draft of terms and definitions for lighting with inorganic semiconductors that will later be developed into a standard (Commission Internationale de L'Eclairage 2013) and a report that examines the suitability of existing lighting quality measures for interior LED lighting (Dikel et al., 2013). With increasing interest in LEDs' ability to render color, there is a need to explore and collect information about the effects of LEDs used in museums to light galleries with historic dyed textiles.

The elements that make up an LED's semiconductor material determine the color of light emitted in a manner similar to neon lighting; there is a good deal of variability between lamp models. The majority of LEDs use a semiconductor that emits a peak of blue-green light and a phosphor that luminesces a broader band of orange-yellow, which together create a white light (fig. 1E). The white light produced in this manner by LEDs is not a true white light, meaning a white light made up of nearly equal quantities of all colors of light in the visible spectrum. While LED technology does have the capacity to create a full spectrum light source, doing so increases the cost of producing the lamp and also sacrifices energy efficiency; LEDs are gaining interest for their energy-saving properties and color rendering is not critical in many applications (Assessment 2013). Yet it is important to understand the effects that spectra can have on the perception of dyed textiles, since many LED models may not possess the same color rendering properties within the tradition of incandescent lamps.

In this research three questions were asked: Does LED lighting change color rendering uniformly by affecting all colors equally or does it change color rendering by groups of color? Uniformly changing the colors would affect the tonality but not their harmony. However, if different hues at different chroma are not equally affected, the color rendering of the textile may be skewed, depending upon the particular colorway. Are existing descriptors used to differentiate or grade LEDs adequate for purposes of dyed textiles? The color rendering index (CRI) measures the ability of light sources to illuminate objects faithfully in comparison to an ideal or natural light source. Another descriptor often used is Correlated Color Temperature (CCT) for the apparent color of a source

warmer or cooler in color tone, meaning closer to incandescent light or to daylight respectively. Finally, can the SPD as described by its manufacturer be used to predict color rendering? Nanometer by nanometer across the 400–700 nm visible spectrum, the LEDs can be engineered to have specific levels of energy. The SPD of LEDs can vary from other artificial lighting sources and could significantly alter the appearance of artifacts (Ohno, 2005).

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 MATERIALS

Cotton and silk selected for dyeing were bleached desized cotton (style 400) and silk broadcloth (style 607) from Testfabrics, Inc. They possess similar fabric and weave structure, which reduces the possibility of textural variation in the color readings (Table 1; AATCC EP 6-2008).

Dyes selected for the study included eight early synthetic dyes (Table 2) from Dr. Helmut Schweppe's selection of 67 popular dyes used for high value textiles like tapestries, carpets, and silk fashions (Schweppe 1987). These dyes were selected for their known poor light fastness, for their particular hue and chroma, and for their levelness when dyed under laboratory conditions. Of particular interest were colorants with hues that reflected in two regions of the visible spectrum, such as orange-red or violet (fig. 2). Colorants known for their high chroma — intense brightness or saturation — that might react differently to the small differences in the distribution of radiant energy peaks, were chosen.

2.2 SAMPLE PREPARATION

Cotton and silk fabrics were cut into samples that weighed approximately 20 grams each and the weight, to four decimal places, was recorded. Each of the synthetic dyes was dissolved in deionized water at 1% by weight (e.g., 1 gram of dyestuff per 100 mL of deionized water). Each sample was separately dyed with the appropriate auxiliaries (Schweppe 1987) using a 1:50 dye bath liquor ratio.

2.3 VISUAL EXAMINATION

Ten unique SPDs with different attributes were created using the spectrally tunable lighting source (STLS) facility at the National Institute of Standards and Technology (NIST) with the assistance of Dr. Yoshi Ohno (fig. 1). The 22 color channels of LEDs covering the 440–640 nm region of visible light used in the system simulate potential SSL (solid-state lighting) sources, of which LEDs are the current commercialized products, and traditional light sources with a white light spectrum of 2500–10,000K. SPDs represented

TABLE 1 FABRICS USED IN STUDY

Fiber	Testfabrics, Inc. style #	Fabric weight (g/m ²)	Weave construction	Yarn count (cm)		Fiber density (g/cm ³)
				Warp	Weft	
Cotton	400	100	Plain	34.5	30	1.55
Silk	607	105	Plain	36	27.5	1.30

TABLE 2 DYES USED IN STUDY

Dyestuff	C.I. Name	C.I.#	Substrate(s)
Chrysoidine	Basic orange 2	11270	Cotton, silk
Congo red	Direct red 28	22120	Cotton, silk
Magenta	Basic violet 14	42510	Cotton
Rhodamine 6G	Basic red 1	45160	Cotton, silk
Naphthol yellow	Acid yellow 1	10316	Silk, silk*
Auramine	Basic yellow 2	41000	Cotton, silk
Crystal violet	Basic violet 3	42555	Cotton, silk
Diamond green B	Basic green 4	42000	Cotton
AATCC xenon fabric	Disperse dye	–	Dacron polyester

*Two different recipes.

three different types of LED models: RGB, RGB-A, and broadband. The SPDs were mostly 3000K and viewed at 100 lux (fig. 3).

2.4 VISUAL EVALUATION METHODS

Each sample was measured for color rendering changes under different spectra using the STLS facility at NIST where it is possible to switch rapidly between spectra using a viewing geometry of 0°/45° Option B/ preferred; (AATCC EP 9-2011).

A Canon PowerShot ELPH-150 12 megapixel digital camera was used to record color changes (or their lack) by photograph and by videos of the samples with the existing (changing) light sources. These photographs and videos give a general idea of the color change seen, but may not be completely accurate in portraying the change seen in person.

2.5 INSTRUMENTAL EXAMINATION

The CRI metric was originally designated to characterize the color differences between a fluorescent light source and a designated natural light (CIE 1965). Its applicability to discern color quality for LEDs and SSL has been criticized thoroughly elsewhere (Žukauskas et al. 2009). Of the various methods suggested to replace the CRI, the color quality scale (CQS)

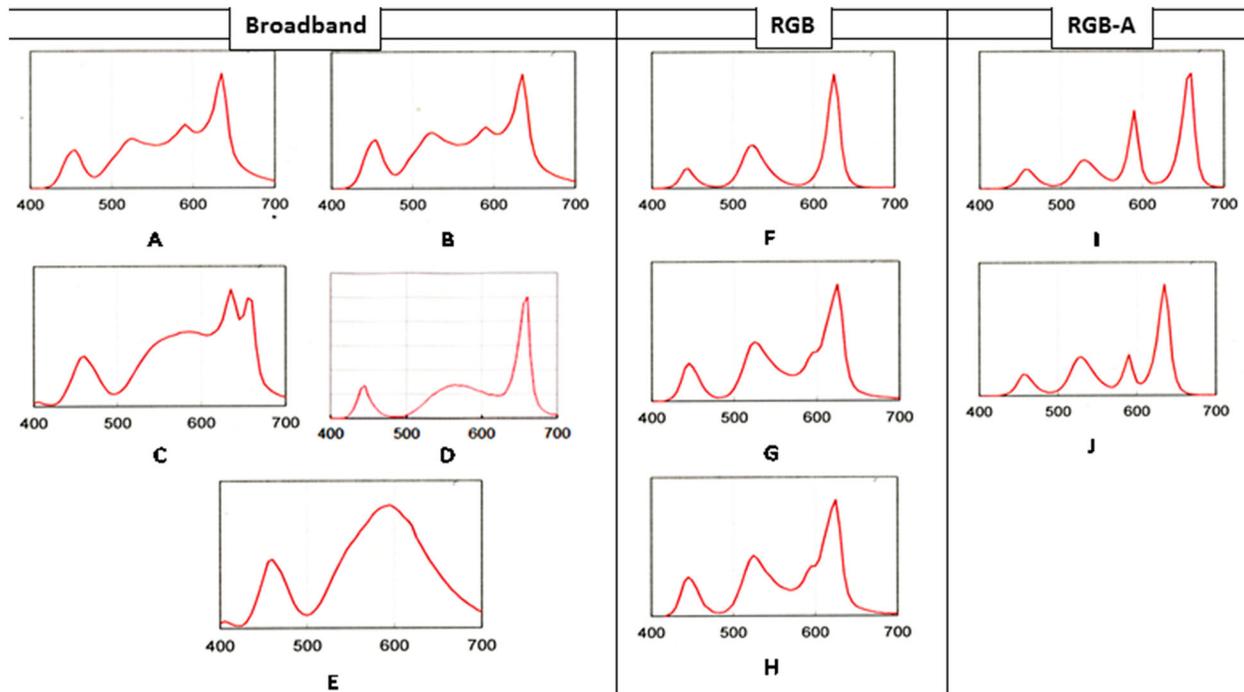
program developed by NIST (Davis and Ohno 2010) conveniently maintains the CRI valuations for comparison. As a government service to the public, the CQS from NIST is available free of charge (search the internet for CQS spreadsheet). Substitution of the CQS test colors is possible.

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 700 nm were taken of each fabric in the warp direction, the weft direction, and on the bias; these were averaged for each color (fig. 2). HunterLab's Easy Match QC® program also provides simultaneous compilations in CIE L*a*b* and other functions (AATCC EP 6-2008; AATCC EP7-2009).

Textile colorists, chemists, and conservators routinely employ tristimulus colorimetry to evaluate color differences between two fabrics or between two dye lots, or between 'before cleaning/treatment' and 'after cleaning/treatment' based on the CIE L*a*b* formula

$$\Delta E_{ab}^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (1)$$

and its geometry, the Pythagorean theorem. In those instances, the light source is kept constant, and the difference between two samples is instrumentally measured for acceptability to observers. Some



A m-CB_3000K broadband LED with peaks at 455nm
B m-CB_3500K broadband LED with peaks at 455nm
C m-CB_3000K blue phosphor_CRI 85
D m-CB_YAG white 3000K, 100 lux
E m-CB_3000K blue RGB_CRI 67
F m-CB_3 Peak_RGB_CRI 37
G m-CB_3 Peak_RGB_CRI 85
H m-CB_3 Peak_RGB_CRI 85, 40 lux
I m-CB_4 Peak_3000K, 100 lux B
J m-CB_4 Peak_3000K, 100 lux A

FIG. 1 SPDs of some LED spectra used in the NIST CQS calculator. The visible spectrum is measured in nanometers (abscissa) and the energy present at each nanometer (ordinate) is relative.

formulations of small color differences take into consideration the gradations of visual acuity for tans, pinks, reds, etc.; others took differences in chroma to produce acceptable ellipsoid cross sections (Harold 1987; Kuehni 1987; McDonald and Smith 1995; Berns, 2000; AATCC TM 173-2009).

The CIE $L^*a^*b^*$ formula is also used in the NIST CQS with modifications. The NIST CQS keeps the color sample constant and notes the difference in the spectral reflectance between two light sources instrumentally measured for acceptability to observers. 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 adjusted to correspond to the CCT. To compensate or adapt the chromatic values, the values for color reference samples are modeled using the Color Measurement Committee's chromatic adaptation transform and the CIE's adaptation transform (Davis and Ohno 2010).

Such adaptations are used in formulations when measurements of small, perceptible color differences are critical (AATCC TM 173-2009). The chroma (C^*) value was also determined.

The goal of the NIST CQS 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

$$\Delta C_{ab}^* = C_{ab\ test}^* - C_{ab\ ref}^* \quad (2)$$

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:'

$$\Delta E_{ab}^* = [(\Delta E_{ab}^*)^2 - (\Delta C_{ab}^*)^2]^{1/2} \quad (3)$$

The NIST CQS provides a means to estimate the color fidelity of a dyed textile in the presence of an LED light

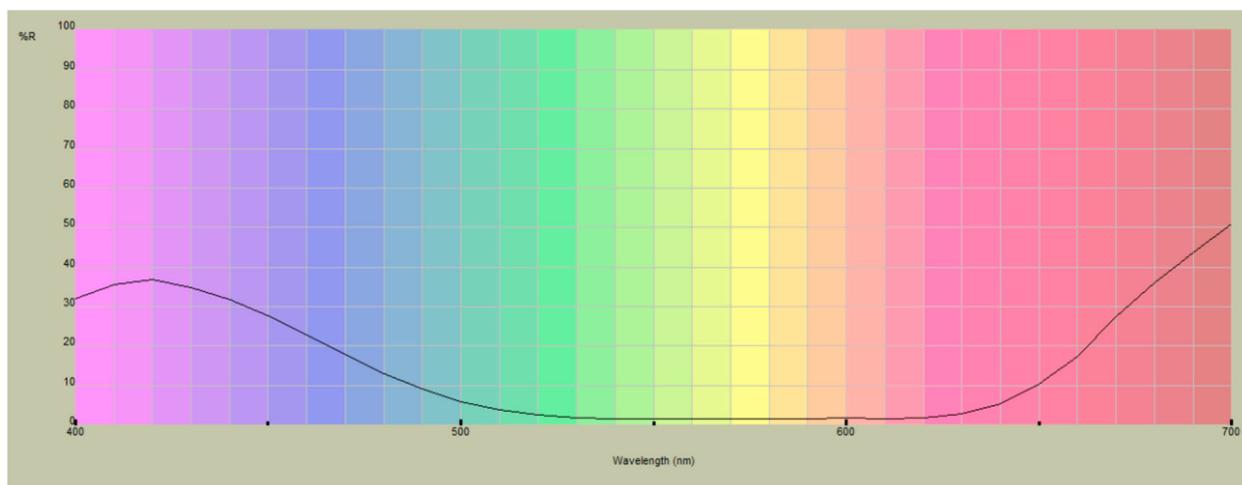


FIG. 2 Reflectance data for crystal violet on silk. The background colors of the chart depict radiant energy as *emitted* at that wavelength. The black curve of the chart represents the reflectance of the sample, where peaks indicate those wavelengths of light *not* absorbed.

source if the SPD of the LED has been ascertained and reflectance spectrum of the dyed sample has been taken (Davis and Ohno, 2010).

2.6 INSTRUMENTAL METHOD WITH TEXTILE COLOR SIMULATION

Instrumental evaluations were made using the NIST CQS with its Textile Color Simulation (TCS). The reflectance measurements of the textile colorants from the conventional visible spectrophotometer were inserted into the NIST CQS to substitute for the NIST chroma chips.

The TCS-CQS Excel program allows the user to look at the samples under all of the light sources (including the ones that do not represent existing lamps). It is set on cool white florescent or Source #4 as an example (fig. 4). To view a different light source, the user goes to the “Color View” tab in the Excel program and changes the number in row 1 column C—a bright yellow block—to the number

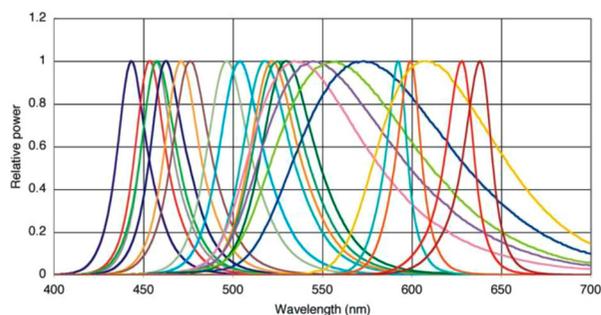


FIG. 3 Spectral distributions of the 22 color channels of LEDs used in the STLS facility at the NIST.

that corresponds to the desired lamp (found in rows 49-183 in column A).

The level of color fidelity is summarized using the CRI and the CQS textiles using the dyed textiles produced at the Museum Conservation Institute (MCI) for this project. The discrepancies in color rendering, ΔE_{ab}^* , are listed below each visual representation of the color difference. The intense textile colorants in shades of red, brown, and purple present larger differences than the more muted tones of the standard pigment shades.

3. VISUAL RESULTS

In this research 10 unique SPDs were examined to approximate the effect of different LED lights on color rendering of 11 dyes on two textile fabrics. For example, the same crystal violet sample (reflectance data for this sample was collected with a Hunter MiniScan EZ and is shown in (fig. 2)) was examined under two LED lights with the same color temperature, but different SPDs (fig. 5). The first LED has a peak around 660 nm (red region) making the sample appear redder, while the second LED does not have any strong red peaks making the sample appear bluer. Purple is unique in reflecting high energy (blue) and low energy (red) visible light, and, therefore, is difficult to render accurately under LEDs. Subsequent research has shown that multiple purple spectra including those of Tyrian (royal) purple (C.I. Natural Violet 1), Mauveine (Basic Dye, C.I. 50245), and Prussian blue (C.I. Pigment Blue 27), are all subject to discrepancies under different light spectra (Bolin and Ballard 2014).

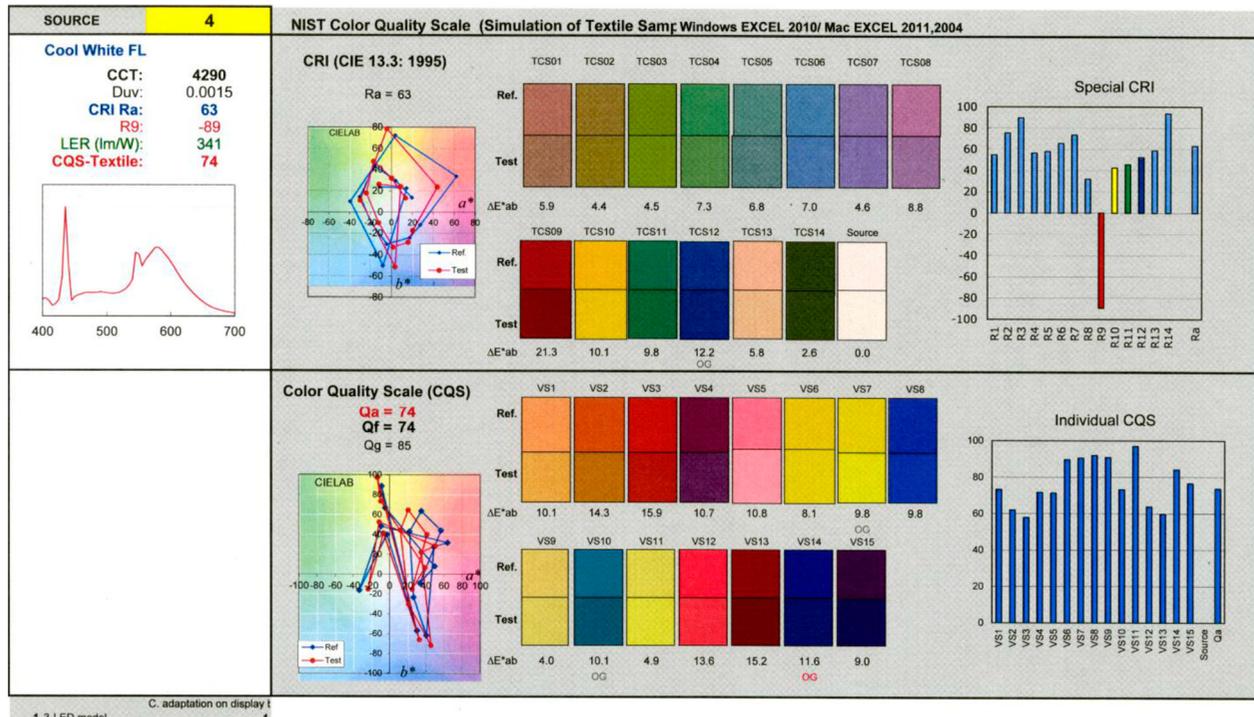


FIG. 4 The NIST CQS results for cool white fluorescent light with dyed test samples inserted into the CQS program.

During visual assessment, it was found that using a lamp with a low CRI value, measuring the ability of light sources to render colors faithfully in comparison to an ideal or natural light source (usually incandescent), did not always prove to be a poor choice. Deviation from incandescent properties could be beneficial to museums by increasing color saturation under low levels of light while still maintaining a neutral background. For example, a silk sample dyed with Congo

Red (fig. 6) 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 and creates a stronger red, a more saturated appearance of the Congo Red sample. Normally this would not be desirable — the color could become over-saturated.

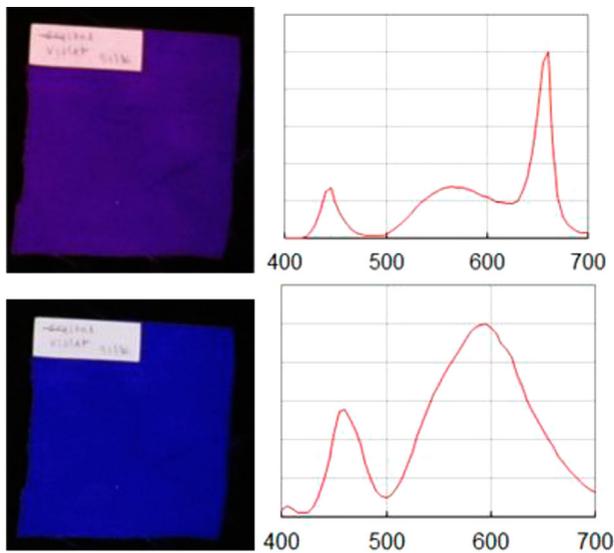


FIG. 5 Crystal violet on silk shown under two 3000 K LEDs.

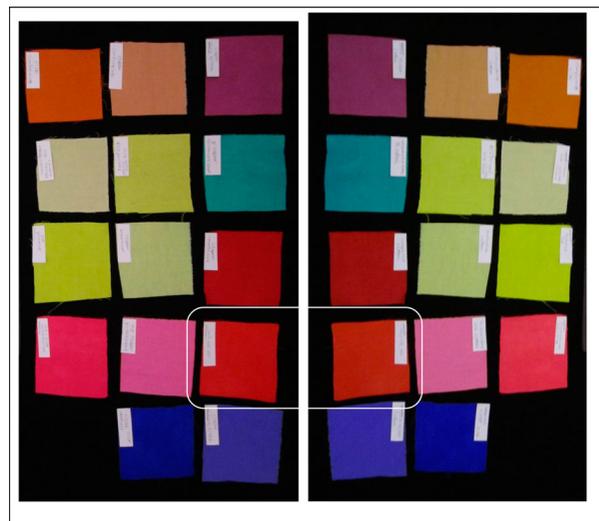


FIG. 6 Two sets of samples on the left, shown under a three peak RGB fig. 1(F) and Table 3 with a CRI value of 40 and, on the right illuminated under another three peak RGB with a CRI value of 85 fig. 1(G) and Table 3. Congo red on silk is outlined in white.

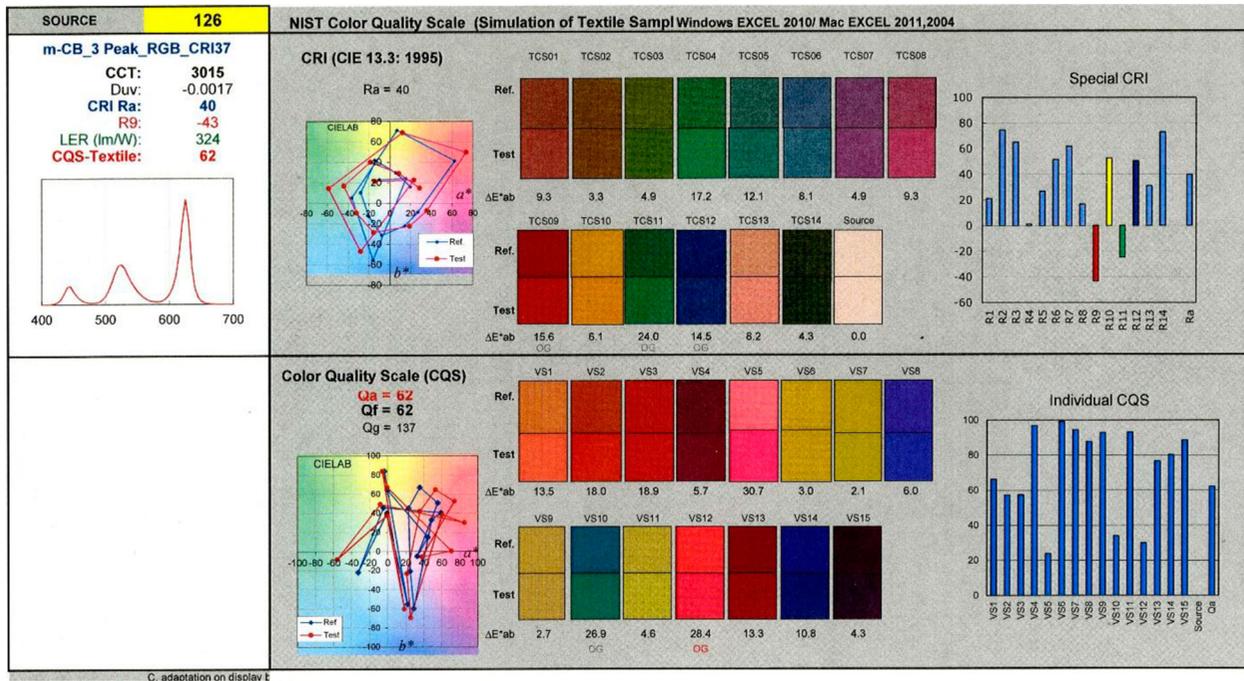


Fig. 7 Color view of the NIST simulator program for a three peak LED with a CCT of 3015K. Both the CRI (upper) and CQS (lower) results are shown, by percentage charts and by an a^*b^* location in the CIE $L^*a^*b^*$ system.

Yet, with faded objects the color would look more vibrant to viewers even at low illuminance levels (less than 50 lux). This phenomenon might prove beneficial when it is desired to intensify the color seen with low levels of light.

4. INSTRUMENTAL RESULTS

The NIST CQS program displays both the CRI graphic ΔE^*_{ab} and its CQS counterpart along with the chips or swatches and their individual ΔE^*_{ab} (fig. 7). With the conventional textile evaluations, an instrumental ΔE^*_{ab} between 0.4 and 1.25 is considered a first perceptible color change (AATCC EP7-2009). Of particular interest are the chromaticity maps showing the reference chip or swatch in blue and the effect on the test colorant in red. Here the position of the colorant's individual ΔE^*_{ab} value is seen to increase or decrease chroma: if the reference value is larger — further out — than that of the test value, the color has become less saturated, paler; if the test value lies beyond, outside that of its original reference placement, the test sample is now brighter (Ohno and Davis, 2010).

At the present time there are 137 different light sources in the MCI TCS-CQS textile program. A tabulation of the CQS program results for the textile swatches against some of these light sources (their SPD's are found in fig. 1) is seen in Table 3. Large differences in ΔE^*_{ab} are marked in bold. True color fidelity would show no change or very minor change, as seen with incandescent light and D65 daylight. The

CCT's around 3000K are given blue fields. All of the LEDs have some emboldened numerical values. All show deviation in violet tones, some in orange-red or green-blue. The three-peak RGB LED (F) and the Blue Phosphor LED (E) have pronounced differences. When the CQS values are reviewed in detail, the three-peak RGB (F) and the blue Phosphor LED (E) share color deviations to different degrees and in different hues—pink for (F) and yellow for (E).

5. DISCUSSION

Conventional textile color differences compare two textile samples both present physically and visually. Visual assessment relies on the eye to correlate the difference between samples into a gray scale valuation between five (no change) and one (great change) by half-step (AATCC EP 1-2012). Here, visual differentiation of the same swatch under changing light sources can be hard to define, especially with a palette of colors to compare. Which is a perceptible four grade level, comparable to a ΔE^*_{ab} of about 1.7, and which a substantial 3, with a ΔE^*_{ab} of 3.4 or more? Photodocumentation or videotaping can help, but the color differences are redefined by the criteria of the recording mechanism, not the eye itself.

In this respect, the NIST CQS program provides a purpose-built means that adapts color instrumentation using a polychromatic spectroradiometer to record the SPD of the light source and a spectrophotometer to measure the initial reflectance values of a colored

TABLE 3 DIFFERENCE BETWEEN COLOR OF INSTRUMENTAL VALUE OF REFERENCE SAMPLE WITH STANDARD LIGHTING AND AS TESTED WITH DIFFERENT LIGHT SOURCES USING THE NIST CQS EXCEL PROGRAM. BOLD NUMERICAL VALUES INDICATE A COLOR DIFFERENCE, ΔE^*_{AB} , GREATER THAN 2.0 UNITS. THOSE DYES FOR WHICH THE TEST LIGHT SOURCES ALWAYS SHOW A PERCEPTIBLE COLOR DIFFERENCE ARE EMPHASIZED IN PALE ORANGE. LIGHT SOURCES WITH APPROXIMATE CCT OF 3000 KELVIN LIE IN A BLUE BOX.

Light Source: see Figure 1 ¹		INC ²	D65 ³	CWF ⁴	A	B	C	E	F	G	H	I	J
CCT (K) ⁵		2812	6504	4290	3205	3541	2945	3023	3015	3157	3153	3089	3022
LER, lm/W ⁶		153	248	341	330	325	308	346	324	357	365	276	322
CRI-Ra ⁷		100	100	63	97	96	88	69	40	86	85	90	69
Average CQS for textile set ⁸		100	100	74	93	94	89	77	62	85	86	90	87
Average ΔE^*_{ab} of dyes CQS ⁹		0.1	0.1	8.7	2.0	1.7	3.6	8.1	10.6	4.7	4.7	3.2	4.1
ΔE^*_{ab} each dye by CQS ¹⁰ :		ΔE^*_{ab}											
Sample #	Sample Dye Name and Fiber												
VS 1	Chrysodine on Cotton	0.1	0.0	10.1	0.8	1.0	4.9	8.8	13.5	2.4	2.3	2.5	6.0
VS 2	Chrysodine on Silk	0.1	0.0	14.3	0.4	1.1	6.0	11.7	18.0	3.0	2.7	2.4	8.9
VS 3	Congo Red on Silk	0.1	0.1	15.9	0.4	1.1	3.2	11.3	18.9	3.4	3.1	5.5	9.7
VS 4	Magenta on Cotton	0.1	0.2	10.7	2.4	1.6	2.3	8.7	5.7	4.0	4.2	1.2	3.9
VS 5	Rhodamine 6G on Cotton	0.1	0.0	10.8	2.0	2.8	3.5	9.6	30.7	12.1	11.9	3.7	12.9
VS 6	Naphthol Yellow on Silk	0.1	0.0	8.1	2.7	2.3	8.4	9.3	3.0	7.1	7.5	4.6	3.0
VS 7	Auramine on Silk	0.1	0.0	9.8	2.5	2.2	13.6	14.9	2.1	7.0	7.5	5.7	4.0
VS 8	Crystal Violet on Cotton	0.1	0.2	9.8	4.3	3.4	3.7	7.2	6.0	8.5	8.8	4.6	1.6
VS 9	Naphthol Yellow on Silk #2	0.0	0.0	4.0	1.0	0.9	4.8	5.5	2.7	1.8	1.8	2.5	1.7
VS 10	Diamond Green B on Cotton	0.1	0.1	10.1	3.2	3.7	5.7	11.2	26.9	11.3	11.2	2.9	9.6
VS 11	Auramine on Cotton	0.0	0.0	4.9	2.8	2.6	6.4	6.7	4.6	6.4	6.7	4.4	3.9
VS 12	Rhodamine 6G on Silk	0.1	0.0	13.6	1.2	1.8	3.5	10.8	28.4	9.6	9.2	9.2	10.6
S 13	Congo Red on Cotton	0.1	0.1	15.2	1.0	0.6	2.2	10.5	13.3	0.8	0.8	3.4	8.2
VS 14	Crystal Violet on Silk	0.1	0.3	11.6	6.4	5.2	4.6	8.1	10.8	11.4	11.6	4.5	6.0
VS 15	AATCC Xenon Fabric on pollyester ¹¹	0.1	0.3	9.0	5.3	4.4	3.6	9.1	4.3	8.1	8.4	2.6	1.9
Average ΔE^*_{ab} for the entire textile set using CQS		0.1	0.1	10.5	2.4	2.3	5.1	9.5	12.6	6.5	6.5	4.0	6.1

¹Light Source: Letter refers to the Spectral Power Distributions appearing in Figure 1 of this paper

²Incandescent

³Daylight, using a xenon power source filtered to match 6500 Kelvin

⁴Cool White Fluorescent

⁵Correlated Color Temperature

⁶Luminous Efficacy of Radiation in Lumens/Watt (LER, lm/W) measures effective brightness per watt of energy

⁷Average Color Rendering Index (CRI-Ra)

⁸Average for Color Quality Scale (CQS) for textile set

⁹Average ΔE^*_{ab} (saturated) for the entire textile set using CQS

¹⁰Individual Differences between the Color of the Instrumental Value of the Reference Textile Sample with Standard Lighting (D65) and as tested with the Light Sources (ΔE^*_{ab}) Using the CQS

¹¹Not a commercial dye; produced in-house by DuPont: 1.8% 2,4-dinitro 6 bromo 2 amino-4(N,N-diethylamino)azobenzene at 129 °C (265F) for 1 hour and then heat set at 179 °C (335F) for 30 seconds. As of 2014, Xenon Reference Fabric is no longer produced for AATCC.

swatch. The CQS program is designed to capture color deviations from the reference standards. While it includes the CRI system in its “Color View” (fig. 4) for each light source, the free-download NIST CQS program permits substitution of one’s own color palette as reference colorants. Additional SPDs of new lighting products can also be added.

The ΔE^*_{ab} values in the CRI may be positive or negative. Thus, the weighted average and final CRI Ra may be brought down by the negative of a single or few samples. In the CQS system, the ΔE^*_{ab} values are always positive whether or not the deviation enhances or detracts from the saturation of the swatch (fig. 7). Visually, it is easy to see the difference between the reference and test swatch, the skew of the a^* and b^* placements. It is also possible to read the detailed data sheets to ascertain the actual ΔC^*_{ab} for any test sample. Note that while the 3Peak LED does lead to tremendous color deviations as with VS₅ (Rhodamine 6G on cotton) and VS₁₂ (Rhodamine 6G on silk), these may be advantageous for faded samples — to brighten them up in the viewer’s eye.

With the SPDs of the LEDs sampled, the particular difference from fundamental color fidelity for each dyed sample is clear. Using the NIST CQS program, it was also determined that LEDs with specially formulated SPDs may offer many possibilities to museums. The lamps are very energy-efficient and can be designed to offer options minimizing absorbed light and increasing the color saturation seen by observers. Since there are many available materials for LEDs, manufacturers can create unique spectra, either very unlike those of more traditional light sources, or at slightly greater expense, very much like traditional sources. In the past, illuminance level (lux or foot-candles) and color temperature may have been used to communicate lighting variants with incandescent sources; with LEDs, additional specifications will be necessary.

6. CONCLUSIONS

By comparing human perception and digital color prediction simulations, it was possible to gauge how useful the simulator program was in estimating the difference in color rendering. It was determined that the program’s digital rendering was accurate for predicting the suitability of a source to be used with textiles for color rendering purposes.

LED lighting can affect the color appearance of dyed historic textiles and the color distortion can be hue-specific. Overall, the present study indicates that the SPD is required to communicate an LED’s color rendering characteristics and to predict a lamp’s suitability for use on a case-to-case basis. The SPD, often provided by LED manufacturers, may be useful in predicting color

distortion issues and specifying lights for exhibits. The study also confirms that current metrics used to communicate lamp specifications (e.g., CRI, CCT, illuminance) are neither adequate nor informative when communicating precise specifications for LEDs to be used in exhibits of dyed historic textiles, especially those with bright chroma, multiple color-ways, or interplays of hue. The CRI and the CCT were not suitable criteria for predicting this distortion and should not be used to specify lighting for their exhibits; SPD information is required.

Purple colors seem particularly vulnerable to distortion by indiscriminant lighting with LEDs. While the authors used known dyes for this study, textile conservators and conservation scientists might be able to use the NIST program to predict the effect of an LED with a known SPD on any colorant where reflectance spectra are available. Knowing the identity of the dye is not necessary. The reflectance curves of dominant colors—with known or unknown dyes—of textile objects can be entered into the NIST program to predict the color distortion. By fine tuning the interaction of the LED’s particular SPD with the reflectance data of the dominant or more important colors or tones, conservators, lighting designers, and conservation scientists eventually may be able to enhance the colors, even purple reds, of a historic textile with lower overall illuminance values (lux or foot-candles).

To assess LED lights for visual changes to textile colorants or to colorants of other objects:

- (1) Collect visible spectra of the palette (major colorants, greatest chroma) to be exhibited.
- (2) Enter these into the CQS program downloaded from the NIST website.
- (3) Input the SPD of the proposed LED.
- (4) Ascertain which LED provides the lowest ΔE^*_{ab} for the palette group and for the individual colorants.

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REFERENCES

- AATCC (American Association of Textile Chemists and Colorists). 2015. Evaluation procedure I-2012. Gray scale for color change. *AATCC Technical Manual* 90: 415–6.

- AATCC (American Association of Textile Chemists and Colorists). 2015. Evaluation procedure 6-2008. Instrumental color measurement. *AATCC Technical Manual* 90: 423–8.
- AATCC (American Association of Textile Chemists and Colorists). 2015. Evaluation procedure 7-2009. Instrumental assessment of change in color of a test specimen. *AATCC Technical Manual* 90: 429–30.
- AATCC (American Association of Textile Chemists and Colorists). 2015. Evaluation procedure 9-2011. Visual assessment of color difference of textiles. *AATCC Technical Manual* 90: 433–5.
- AATCC (American Association of Textile Chemists and Colorists). 2015. Test method 173-2009. CMC: Calculation of small color differences for acceptability. *AATCC Technical Manual* 90: 324–6.
- Assessment of Advanced Solid State Lighting*. 2013. Washington, D.C. The National Academies Press. <http://www.nap.edu/catalog/18279/assessment-of-advanced-solid-state-lighting> (accessed 12/31/14).
- Berns, R. 2000. *Billmeyer and Saltzman's Principles of color technology*, 3rd ed. New York: Wiley.
- Biard, J. R., and G. E. Pittman. 1966. Semiconductor radiant diode. US Patent 3293513, filed August 8, 1962, and issued December 20, 1966.
- Bolin, C. A., and M. Ballard. 2014. Assessing lights for textile colorants. In *Textile specialty group postprints American institute for conservation 42nd annual meeting, San Francisco*. Washington, DC: AIC. 24:85–95.
- CIE (Commission Internationale de L'Eclairage). 1965. Method of measuring and specifying colour rendering properties of light sources. Pub. CIE 13.
- CIE (Commission Internationale de L'Eclairage). 2013. Draft international standard. Light emitting diodes (LEDs) and LED assemblies — terms and definitions. CIE DIS 024/E: 2013.
- Davis, W., and Y. Ohno. 2010. Color quality scale. *Optical Engineering* 49 (3): 033602-1-16.
- Dikel, E., L. Dokuzer Öztürk, M. Knoop, N. Miller, E. Mochizuki, A. Némethné Vidovszky, J. Schanda, and P. Thorns. 2013. Review of lighting quality measures for interior lighting with LED lighting systems. Technical Report No. CIE 205: 2013. Vienna, Austria: Commission Internationale de L'Eclairage.
- Harold, R. H. 1987. Objective instrumental shade sorting. In *Color technology in the textile industry*, ed. G. Celikiz and R. G. Kuehni. Research Triangle Park, NC: Association of American Textile Chemists and Colorists. 155–61.
- Kuehni, R. G. 1987. Objective color difference in the textile industry. In *Color technology in the textile industry*, ed. G. Celikiz, and R. G. Kuehni. Research Triangle Park, NC: Association of American Textile Chemists and Colorists. 123–7.
- McDonald, R., and K. J. Smith. 1995. CIE94 — A new colour difference formula. *Journal of the Society of Dyers and Colourists* 111 (12): 376.
- Miller, M. 2011. Demonstration of LED retrofit lamps at the Jordan Schnitzer Museum of Art, Eugene, Oregon. Report of the US Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Building Technologies Office, Solid-state Lighting Technology Demonstration GATEWAY Program. https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/2011_gateway_schnitzer.pdf.
- Miller, N. J., and J. R. Druzik. 2012a. Demonstration assessment of light-emitting diode (LED) retrofit Lamps at the J. Paul Getty Museum, Malibu, California. Report of the US Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Building Technologies Office, Solid-state Lighting Technology Demonstration GATEWAY Program. https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/getty_museum_gateway_final.pdf.
- Miller, N. J., and S. M. Rosenfeld. 2012b. Demonstration of LED retrofit lamps at the Smithsonian American Art Museum, Washington, DC. Report of the US Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Building Technologies Office, Solid-state Lighting Technology Demonstration GATEWAY Program. <https://energy.gov/eere/ssl/gateway-demonstration-indoor-projects>.
- Myer, M. A., and B. R. Kinzey. 2010. Demonstration assessment of light-emitting diode (LED) accent lighting at the Field Museum, Chicago, Illinois. Report of the US Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Building Technologies Office, Solid-state Lighting Technology Demonstration GATEWAY Program. <https://energy.gov/eere/ssl/gateway-demonstration-museum-reports>.
- Ohno, Y. 2005. Spectral design considerations for white LED color rendering. *Optical Engineering* 44 (11): 111302-1–111302-8.
- Ohno, Y., and W. Davis. 2010. Rationale of color quality scale, archived presentation given at DOE solid-state lighting workshop/conference. June 8, 2010. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/cqs_rationale_06-10.pdf.
- Perrin, T. E., J. R. Druzik, and N. J. Miller. 2014. SSL adoption by museum: Survey results, analysis, and recommendations. Report of the U S Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Building Technologies Office, Solid-state Lighting Technology Demonstration GATEWAY Program. <https://energy.gov/eere/ssl/gateway-demonstration-museum-reports>.
- Schweppe, H. 1987. *Practical hints on dyeing with early synthetic dyes*. Smithsonian Institution: Conservation Analytical Laboratory (now Museum Conservation Institute). http://www.si.edu/mci/english/learn_more/publications/articles.html.
- US Statutes. 2007. Energy Independence and Security Act of 2007, Sections 321-325. Public Law 110-140 — Dec. 19, 2007:121 STAT. 1573-121 STAT. 1596.
- Žukauskas, A., R. Vaicėkauskas, F. Ivanauskas, H. Vaitkevičius, P. Vitta, and M. S. Shur. 2009. Statistical Approach to Color Quality of Solid State Lamps. *IEEE Journal of Selected Topics I Quantum Electronics* 15 (4): 1189–98.

SOURCES OF MATERIALS

Dyes were obtained as commercial samples (in powder form) from a variety of companies in preparation for the short courses on dyeing and dye analysis taught by Dr. Helmut Schweppe at MCI between 1987 and 1991 and kept sealed in dark storage since that time. Several of these companies, including International Dyestuffs Corp. of Clifton, New Jersey; Carolina Color and Chemical Corp. of Charlotte, North Carolina, and Passaic Color and Chemical Co. of Patterson, New Jersey, are no longer in business; an alternate supplier is co-listed. Dyes are often considered eye irritants and some early synthetic dyes are potential carcinogens. Please consult safety literature including data found on Important Early Synthetic Dyes on the MCI website.

Bleached desized cotton (style 400), silk broadcloth (style 607)
 Testfabrics
 415 Delaware Avenue
 PO Box 26
 West Pittston, PA 18643
 Tel: 570-603-0432

Fax: 570-603-0433
www.testfabrics.com

Miniscan XE Plus, Portable visible spectrometer
 Hunter Associates Laboratory, Inc.
 11491 Sunset Hills Road
 Reston, VA 20190
 Tel: 703-471-6870
 Fax: 703-471-4237
www.hunterlab.com

Dyestuff, except Magenta
 Sigma-Aldrich, Inc.
 3050 Spruce Street
 St. Louis, MO 63103
 Tel: 800-521-8956
www.sigmaaldrich.com

Magenta dyestuff
 Organic Dyestuffs Corporation ("Orco").
 65 Valley Street
 East Providence, RI 02914
 Tel: (401) 434-3300
 Fax: (401) 438-8136
<http://organicdye-px.rtrk.com/>

Résumé - Les musées installent de plus en plus des sources lumineuses à économie d'énergie, telles que les lampes DEL (diodes électroluminescentes). Les DEL sont une technologie en pleine évolution, mais soulèvent des inquiétudes quant aux effets du spectre lumineux sur les objets culturels, notamment les textiles. De nombreux modèles de DEL ne possèdent pas les propriétés de rendu des couleurs auxquelles les utilisateurs sont habitués, et il est important de comprendre les effets que le spectre lumineux peut avoir sur les textiles teints. Cette recherche s'intéresse aux effets visuels de différents spectres lumineux, notamment ceux de DEL, sur les teintures textiles afin d'évaluer les différences de couleur générées. Neuf teintures disponibles depuis le début de la production de teintures synthétiques et un standard commercial de résistance à la lumière ont été utilisés. Cet article présente un résumé des découvertes faites à ce jour, dont le fait que certaines DEL de même température de couleur peuvent rendre des couleurs observées très différentes, particulièrement pour les couleurs saturées. Les violets saturés se sont révélés extrêmement difficiles à rendre avec des DEL. D'autres teintes pourraient également être visuellement modifiées. Ce travail d'expérimentation indique que la température des couleurs, le niveau d'éclairage et l'Indice de Rendu de Couleur (IRC) commercial ne sont pas des caractéristiques suffisantes pour départager les sources lumineuses DEL pour des espaces d'exposition. Une évaluation des DEL par mesure instrumentale est recommandée avant l'installation dans une exposition.

Resumo - Cada vez mais frequentemente os museus estão instalando fontes de luz que economizam energia, tais como as lâmpadas de LED (diodos emissores de luz). Os LEDs representam uma tecnologia em evolução. Há preocupação sobre os efeitos dos espectros de luz sobre os artefatos, incluindo os artigos têxteis. Muitos modelos de LED não possuem as mesmas propriedades de reprodução de cor com as quais os observadores estão acostumados, e é importante entender os efeitos que os espectros podem desempenhar nos tecidos tingidos. Esta pesquisa está centrada nos efeitos visuais de diferentes espectros de luz, incluindo os de LEDs, sobre corantes têxteis para medir a gama de diferenças de cor produzida. Utilizaram-se nove corantes sintéticos iniciais e um padrão de desvanecimento comercial. Este trabalho resume nossas descobertas até a data atual: que os espectros de LED com a mesma temperatura de cor podem fazer com que a reprodução das cores observadas seja muito diferente, especialmente com cores saturadas. Percebeu-se que com a iluminação de LED é extremamente difícil reproduzir com precisão as cores púrpuras saturadas. Outros tons também podem ser comprometidos. Os trabalhos experimentais indicam que a

temperatura da cor, o nível de iluminação e o Índice de Reprodução de Cor (CRI) comercial são especificações insuficientes para as exposições. Sugere-se um método instrumental para avaliar os LEDs antes da instalação da exposição.

Resumen - Cada vez más frecuentemente, los museos están instalando fuentes de luz ahorradoras de energía, tales como las lámparas LED (diodos emisores de luz). Los LED representan una tecnología en evolución. Hay preocupación sobre los efectos de los espectros de luz sobre los artefactos, incluyendo los textiles. Muchos modelos de LED no poseen las mismas propiedades de reproducción de color a las que los observadores están acostumbrados, y es importante entender los efectos que los espectros pueden jugar en los textiles teñidos. Esta investigación se centra en los efectos visuales de diferentes espectros de luz, incluyendo los de LEDs, sobre colorantes textiles para medir la gama de diferencias de color producida. Se utilizaron nueve colorantes sintéticos tempranos y un estándar de desvanecimiento comercial. Este trabajo resume nuestros hallazgos hasta la fecha: que los espectros de LED con la misma temperatura de color pueden hacer que la reproducción de los colores observados sea muy diferente, especialmente con colores saturados. Se encontró que es extremadamente difícil reproducir con precisión los púrpuras saturados con iluminación LED. Otros tonos también pueden verse alterados. Los trabajos experimentales indican que la temperatura del color, el nivel de iluminación y el Índice comercial de Reproducción de Color (CRI) son insuficientes como especificación para las exposiciones. Se sugiere un método instrumental para evaluar los LED antes de la instalación de la exposición.

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