Light damage to selected organic materials in display cases: A study of different light sources

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The protection of works of art and cultural assets against light-induced aging is vital when planning exhibitions. Newly developed lighting systems render the selection of suitable light sources more difficult, not least in the context of energy–economical systems. This study accordingly examines different lighting systems (fluorescent tubes, halogen lamps, low-voltage metal halide lamps, and LED lamps) in terms of the damage potential they hold for the materials concerned. The changes in color were evaluated using the CIEDE2000 color-difference formula. This study focuses on selected organic materials and shows that changes in color already occur after only a brief exposure time. The color changes induced by the fluorescent tubes were consistently more intense than those induced by the other light sources. The results obtained with the remaining lamps show that the color changes depend more on the material under investigation than on the source used. The changes determined after a relatively short exposure period (five months) vividly demonstrate that exposing sensitive materials to light for longer terms (as is the case during a permanent exhibition) is most definitely a non-viable option.

Keywords: Lighting, Light damage, Visible spectroscopy, Preventive conservation

Introduction

The purpose of museum cases or exhibitions in general is the optimal display of works of art and cultural assets in combination with the maximum protection from damage. With the development of preventive conservation over the last generation, the definition of damage has broadened beyond mechanical damage to include the effects of the surrounding conditions: e.g. ambient air and light. Protection against light-induced aging is especially a prerequisite when planning exhibitions. The use of appropriate light sources is of primary importance for preventive conservation. The guidelines in CIE 157 (CIE, 2004), published 10 years ago, suggested that the new light-emitting diode (LED) sources should be the least harmful in comparison to other more traditional illumination systems. This study was designed to evaluate this suggestion and to offer a tool assisting conservators in their choice of appropriate lighting systems.

Historical development of lighting in museums

At the end of the nineteenth century, the nature of light was at the center of a deep controversy. The situation was such that light was studied ‘according to the wave theory on Mondays, Wednesdays, and Fridays, but was seen as streams of flying energy quanta or corpuscles on Tuesdays, Thursdays, and Saturdays’ (Bragg, 1921). The particle theory of light expounded by Newton (1706) described light as a substance not amenable to weighing, with its particles emitted by the light source. This theory, now superseded, has been incorporated in the quantum theory of electromagnetic waves where the interaction of light with matter takes place through elemental units called photons. It is remarkable that the Newtonian theory could correctly interpret part of the interaction of light with matter: in this respect some of its insights have retained their validity to this very day.

For example, at the end of the nineteenth century it was described how, when the radiation of a light source is being absorbed by the coloring agent’s particles, this will entail not only a rise in temperature, but may also lead to a chemical change (Hilbert,
2002). The interrelationship between the duration and intensity of such radiation was likewise examined in this context. Russell and Abney (1988) stated: ‘If a certain hue is exposed to a radiation intensity of 100 and then fades within one hour, an identical hue – when exposed to an intensity of 1 – will exhibit the same fading effect only after 100 hours.” (Brommelle, 1964) During their investigations, they observed that the most striking changes were caused by the blue and violet components of white light. When assessing natural light, they drew a distinction between a clear sky and a cloudy one, and concluded that these wavelengths were present only to a smaller extent in artificial light.

**Incandescent lamps**
The findings highlighted above are hardly surprising if one recalls how major museums were lit in the later nineteenth century. Illumination by daylight was predominant, with the increasing proportion of artificial light being mostly provided by gas lighting or the new electric incandescent lamps. In the latter group, an electric current flows through a wire filament, thus heating it up. At very high temperatures, the heated filament will emit radiation in the visible spectrum as light. For human beings, given their naturally evolved perception of color (fire, hearth fire, oil lamps, and candlelight) and the continuous spectrum involved, this radiation, and the visible light it produces, has an optimum quality of color reproduction. The light emitted by incandescent lamps possesses this property to a high degree, even though it exhibits a certain shift towards the red range of the radiation spectrum. It is the incandescent lamp’s inclination towards the red range (with its radiation maximum lying in the infrared range of the spectrum while decreasing toward the blue wavelengths) that results in its comparatively low potential for damage. Typical incandescent bulbs (no longer sold in the EU), for example, possess hardly any radiation component in the UV range, which accounted for their huge popularity and wide dissemination in museums.

**Fluorescent tubes**
The use of coated fluorescent tubes (gas discharge lamps) in a variety of versions in the more recent past has meant that the preservation advantages of incandescent lamps were abandoned in favor of a significantly more economical technology. The physical principle on which all discharge lamps are based is rooted in the capability of some gases to briefly absorb energy and then release it as light during discharge (Schmits, 2001). In the case of the technical discharge lamp, the excited state is induced by feeding in electrical energy. At a relatively low discharge pressure, mercury vapor exhibits hardly any radiation in the visible range, but mainly in the UV range. This UV irradiation may trigger fluorescence in some substances that convert the UV radiation into visible light. The fluorescent tubes are built on this principle. Besides the incandescent lamp, the fluorescent tube is the source of artificial light that has the most manifestations in terms of size, color of light, and reproduction of color, while in contrast to the former, it generates a light output that is four to eight times higher than that of an incandescent lamp with the same wattage. These benefits have to be offset against the technological disadvantages involved. For example, the spectrum is not continuous (only some special variants of the fluorescent tube achieve a very high quality of color reproduction), and their design means that they are not suitable for creating clear-cut shadows. Furthermore, the fluorescent tubes’ spectrum contains UV components to a greater or lesser degree. This is why, when tubes of this kind are to be used in a museum, suitable UV screening measures will invariably be necessary.

This is also and most especially true for the metal halide lamps, which have recently been a popular choice for sophisticated spotlighting effects in the exhibition. When it comes to generating daylight artificial light, in particular, this type of lamp has been unsurpassable for simulating directional daylight right up to the most recent past (Schmits, 2001).

**LEDs**
Unlike the conventional light sources (incandescent lamps, gas discharge lamps, or fluorescent tubes), LEDs are semi-conductor devices that use electroluminescence to convert electrical energy directly into light, without the need of a filament or an incandescent mantle. Quite like microchips, LEDs also consist of semi-conductor crystals and are built up layer by layer on appropriate production lines (ERCO, 2013). White LED light does not contain any UV or IR components, and is therefore basically well suited for illuminating sensitive museum materials.

**Light screening as a conservation approach**
In the period after the Second World War, the problems of light screening for sensitive cultural assets were the subject of investigations worldwide. In the USA in particular, the parchments of the Declaration of Independence and of the Constitution Document were to be given the best-possible protection. This task was assigned to the National Bureau of Standards (NBS), which systematically examined light with a variety of wavelengths, and scrutinized different protection options. However, each of the trials involved was performed not with parchment, but with low-grade paper. During the course of these tests, the ‘Relative Damage Factor ($D_r$)’ was defined for the first time.
(Feller, 1994). Note that this factor arbitrarily assigns the numerical value of 1 to the damage experienced by the paper at a wavelength (\(\lambda\)) of 546 nm. For shorter wavelengths, correspondingly more severe effects are obtained as multiples. The report drawn up by the NBS contains the relevant scale, which is by extrapolation extended to the wavelength range from 360 to 720 nm.

Similar studies were also conducted in Germany where, as an example, in 1961 Kühn examined the option of filtering UV radiation out of the daylight. As part of this project, the suitability of fluorescent tubes used in museums and the filtering of their UV components were also examined.

In the following decades, further scientific studies were carried out. A summary of vital points gathered from a variety of publications is given below (Michalski, 1987; Saunders & Kirby, 2001; Cuttle, 2007).

- Higher moisture content will accelerate the fading of natural coloring agents.
- Color changes do not exhibit a constant progress in terms of speed; they are more marked with unexposed material than with material that has already suffered light-induced damage.
- Depending on the temperature involved, paper can exhibit both yellowing and fading phenomena.

On the basis of these studies, a variety of insights have since then been taken on board in museums, and incorporated into direct instructions for action and exhibition recommendations. For example, Thomson's (1978) suggestion of specifying the limit values governing illuminance for paintings at 150–200 lux and for graphical objects at 50 lux has been accepted all over the world. Moreover, as a general rule, objects that are light-sensitive should only be illuminated as long as the actual opening times of an exhibition require. Preventive conservators should focus more on an object's annual exposure to light, in particular, and less on illuminance (Hilbert, 2002).

As from the mid-1970s, there were also quite a few studies (some of them very extensive in scope), addressing the issue of the deleterious effects exerted by fluorescent lamps on museum objects. On behalf of the Institute for Museology, the most important question of changes in color observed in materials illuminated with fluorescent tubes was examined in 1983 at the Institute of Lighting Technology of the University of Applied Sciences in Berlin (Krochmann, 1988). One of the results reached during these examinations was that the damage factor likewise used initially (similar to the 'Relative Damage Factor' mentioned above) was not optimally conducive to achieving the study's goals. While the study was ongoing, the term 'relative spectral sensitivity' (s(\(\lambda\))dm,rel') was introduced, and has retained its validity to the present day. This term has enabled the multiplicity of insights gained from the artificial exposure studies to be meaningfully interpreted. Also, while these extensive studies were progressing, the categorisation of museum-typical material on the basis of the "useful lifetime" gained wider acceptance and replaced the practice of assessing the light-sensitivity of objects in a museum by simple comparison with international standards for lightfastness like the ISO Blue Wool Standards.

Within the overall framework of the project described below, an irradiation system was used to induce color changes in more than 350 reference materials and a small number of surrogate samples relevant to paper, natural materials on wood, and traditional dyed textiles following two steps, after which the changes found were evaluated.

This information allows conclusions to be drawn on their photochemical degradation. Any object illuminated is continually under exposure to photons. The frequency \(f\) equals the speed of light \(c\) divided by the wavelength \(\lambda\). A photon's energy is thus inversely proportional to the wavelength. This means, the shorter the wavelength, the greater the energy. So with an increasing proportion of energy-rich photons, the probability that illumination will cause molecular processes in a light-sensitive substance will also increase. The operation of any photochemical process is conditional on active absorption. These are first and
foreground degradation processes, with a distinction drawn here between primary and secondary reactions. One primary reaction is photolysis, which will result in a change in the molecular structure of the illuminated material without active involvement of any other substances, whenever the photons’ energy is sufficient for breaking up the intermolecular bonds. Secondary reactions are photo-oxidation and photo-reduction, in which foreign molecules are invariably involved.

Building on these well-known facts, the experiment described below is intended first to verify these studies in a realistic set-up, and second to illustrate the effects of various light sources on the materials being exhibited in a museum. Here special attention is being given to the effects exerted by LED illumination, which is being increasingly used in museums based both on economic considerations and recent CIE recommendations (CIE, 2004).

This study has the objective of investigating the advantages offered by LED sources with respect to more traditional illumination techniques, as far as the lightfastness of exhibits is concerned. For this purpose, light-sensitive samples such as naturally dyed textiles were prepared and tested under different illumination conditions.

Experiment

**Construction of model display cases**

Four identical display cases, each with a different light source, were selected for the experimental set-up. All display cases had the following dimensions: 353 × 707 × 1000 mm³ (Fig. 1). The top was in each case formed by a light box. Each light box housed a different light source, as follows:

- Display Case 1: Fluorescent tubes above a diffusing plate
- Display Case 2: A halogen light source focussed with fibre-optic lenses
- Display Case 3: Low-voltage metal halide lamps
- Display Case 4: LEDs focussed with semi-spherical optical lenses (variable radiation angle between 30° and 60°)

Although all light sources were dimmable, the experiment was conducted using the maximum illumination allowed for each case with the aim of inducing the largest change possible. To simulate realistic exhibition conditions, an intermittent switch was used to provide illumination during six-hour intervals. Illumination cycles of six hours were employed, each one separated by 12 hours of darkness for a total number of illumination hours of 240 hours/month.

The side walls of the display cases were made of 10-mm-thick laminated safety glass panes, and designed as three-way sliding doors, which were sealed by twin-wall silicone profiles. The locking mechanism was integrated in the aluminium frames located on the top and at the bottom of the case. In each case, the light box was inserted into the top frame. The bottom frame was sealed off from the display case’s interior by a glass base, on which the material samples were placed for the duration of the experiment.
experiment. Conditioned air was fed in through appropriate inlets in the glass base. All display cases had constant values of 23°C and 50% for temperature and relative humidity, respectively, achieved by the use of a HAHN RK-2 unit (Glasbau Hahn GmbH, Frankfurt, Germany). These two environmental parameters were maintained constant with the goal of minimizing any secondary reactions due to climatic factors.

Each display case was individually fitted with a lightproof, snugly contoured textile hood from outside, so as to prevent mutual cross illumination of adjacent display cases (see Fig. 1).

Preliminary tests included analysis of the volatile organic components (VOCs) in the air within each display case (Wiegner et al., 2012). A permanent inflow of purified and conditioned air into the display cases’ interior prevented any risk of damage by such contaminants to the reference materials placed inside them. A leak test conducted using tracer gas revealed an air exchange rate of approximately 0.5 d⁻¹. This constitutes an acceptable value, and must be regarded as a good mean value for average museum display cases.

Reference materials
A variety of materials were placed inside the display cases with the goal of testing the influence of light on their aging behavior. Different textiles (silk, cotton, and wool) dyed with a variety of natural coloring agents (saffron, safflower, dyer’s broom, Brazil wood, cochineal and folium) were employed. Each textile was dyed for 30 minutes at 40°C in a bath consisting of alum (0.1 mol/l) and dye (10%) in demineralized water. In addition, softwood was treated with different bonding agents. The range of reference materials was supplemented by three types of paper:

- different bonding agents. The range of references consisting of alum (0.1 mol l⁻¹) and dye (10%) in deminer-
- each material. Four of these were placed in the various display cases, while the fifth was kept in the dark and used as a control set.

Analysis of light source emission spectra
The light emitted by the sources of each display case was sampled with a single strand, multi-mode optical fiber (VIS-NIR, 0.22 NA, Avantes, Apeldoorn, The Netherlands) of 300 μm diameter and 5 m length. The fiber, rolled in a coil of 40 cm diameter to avoid transmission losses, was connected to a UV-Vis spectrometer (USB2000 UV-VIS, Ocean Optics, Dunedin, FL, USA) operating in the 200–850 nm wavelength range. The fiber had SMA-905 connectors at both ends. One end was attached to the spectrometer while the other one was located in front of the light source, at a distance of ca. 100 mm, with its axis perpendicular to the front of the emitted light. The position of the sampling end was manually adjusted to collect the highest signal intensity.

Spectra were normalized to the integral intensity of the light source measured with a handheld light intensity detector (Mini-Lux, Cristoph Waller, Eichstetten, Germany) and was constantly recorded using a HOBO U12 (Onset Computer Corporation, Cape Cod, MA, USA) data logger inside each display case. The handheld Mini-Lux works with a silicon photo sensor with V(λ) and cosine correction, in accordance with DIN 5032 Part 7 Class B. The total error of measurement according to DIN 5032 (1985) is <10%. The HOBO U12 is a four-channel logger with a 12-bit resolution. This instrument can store 64 K of data and can record up to 43 000 measurements or events. The light intensity measured was in the 10–32300 lux range.

Detection of aging with VIS spectroscopy
Investigations conducted on reference materials were meant to be non-invasive, easy to handle, and applicable to museums’ daily routines. Accordingly, the aging processes were evaluated by means of visible reflectance spectroscopy (Johnston-Feller, 2001). The investigations were carried out using a SPM 100 spectrophotometer (Greta-Imaging AG, Regensdorf, Switzerland), which measures visible reflectance in the 380–780 nm range. This device allows measuring a small spot of about 3 mm in diameter. By extending the head, the surface of the sample is illuminated for half a second, using a small 2 W bulb. The instrument was calibrated using a white BaSO₄ standard.

Taking the reflectance spectra as a starting point, the CIE L* a* b* (CIELAB) values of the reference samples are determined before and after exposure to light (Richter, 1981; DIN EN ISO 11664-4, 2007). In the CIELAB system, the three parameters L*, a*, and b* are used to describe each color by means of a three-dimensional coordinate system. While the L* value describes the lightness (from 0 to 100), the a*
value represents the red-green color channel (positive: red component, negative: green component) and the b* value the blue-yellow color channel (positive: yellow component, negative: blue component). Color differences were also evaluated using the CIE DE 2000 formula (CIE, 2001)

\[
\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L}S_L\right)^2 + \left(\frac{\Delta C'}{K_C}S_C\right)^2 + \left(\frac{\Delta H'}{K_H}S_H\right)^2 + R_T \left(\frac{\Delta C'}{K_C}S_C\right)\left(\frac{\Delta H'}{K_H}S_H\right)}
\]

where \(L\) is the lightness, \(C\) is the chroma and \(H\) is the hue. \(K_L\), \(K_C\), and \(K_H\) are weighing factors, depending on the observation conditions. \(S_L\), \(S_C\), and \(S_H\) are compensations for lightness, chroma, and hue, respectively. Moreover, \(R_T\) accounts for the rotation of the ellipses in the blue.

This formula is considerably more complicated than the previous \(\Delta E_{ab}^*\) (CIE, 1988) and \(\Delta E_{94}\) (CIE, 1995), but it solves the issues of perceptual uniformity not accounted for or partly considered in the earlier color systems. Also, it describes small color differences better than the both \(\Delta E_{ab}^*\) and \(\Delta E_{94}\). A code to implement \(\Delta E_{00}\) based on the scheme proposed by Sharma, Wu, and Dalal was written and tested for consistency against the color pairs described earlier by the above mentioned authors (Sharma et al., 2005). A discussion of this formula and its implementation is beyond the scope of this publication. Further details can be found in the work of Sharma et al. (2005) and references therein.

The samples were measured at the beginning of the experiment, and at the end of each month, over a period of five months. This method is not aimed at drawing conclusions in terms of chemical changes experienced by the reference materials but to effectively document and quantify color changes in the artifacts. Its main advantage is that it can be easily integrated into a museum’s daily routine, fulfilling one of the main goals for the present study.

Results

Emission spectra of lighting systems

The emission spectra of the various lighting systems were determined and are shown in Fig. 3. Lighting System 1 (fluorescent tubes) shows a significant band spectrum with clear-cut emission bands at 435, 490, 595, 685, and 610 nm. Lighting Systems 2 and 3 (a halogen light source focussed with fibre-optic lenses and low-voltage metal halide lamps) exhibit a broad, bell-shaped distribution of the emission spectrum with a maximum at 595 nm. Lighting System 4 (LEDs in optical lenses) excels in terms of narrower distribution of the emission spectrum, with two maxima at 550 and 600 nm, and an additional band at 460 nm. Since Lighting System 1 exhibits a significant distribution in the blue range of the visible spectrum, it was safe to assume that extensive damage potential would be revealed by this case (Fig. 3). The spectra for Cases 2 and 3 contain light of wavelength as short as 380 nm and should present a higher damage potential than the source used in Case 4 (CIE, 2004).

The \(\Delta E_{00}\) value

To assess the changes in color, the CIE \(L^*a^*b^*\) (CIELAB) values were always determined at three points of the homogeneous samples, and expressed as a mean value. The standard deviation was on average smaller than one percent, and is therefore ignored in the remarks below. The color difference value \(\Delta E_{00}\) was then determined for each reference material with respect to increasing exposure times of one, two, three, four, and five months.

A control set, kept in the dark during the whole experiment, was used to conduct background measurements. Fig. 4 shows the temporal change in the corresponding \(\Delta E_{00}\) values. These values are distributed in a relatively narrow band, with 80% of the points lower than \(\Delta E_{ab}^* = 1\). It has been assumed that
$\Delta (\Delta E_{ab}) = \pm 0.5$ as measuring error. Some of the reference samples (e.g. Brazilwood/wool and Folium/cotton) show discolorations high above average, indicating a dependence of the lightfastness on the sample’s age. The histograms for $\Delta E_{ab}$, seen in Fig. 4, broaden with time, indicating that the effect of aging on lightfastness is general. If the color difference distribution is independent of time, the histograms measured in different months would show similar shapes. It can be concluded that the reference samples age even when kept in the dark, an effect probably correlated to the fabrication and preparation of the samples. This is probably the reason why a lack of correlation was observed between irradiance and lightfastness in this experiment. (The number of bins was set automatically, based on the standard deviation of the data set.)

Color changes measured for the samples placed inside the four display cases are reported in Table 1. The color variation is calculated as $\Delta E_{ab}$. When the measuring error of $\Delta (\Delta E_{ab}) = \pm 0.5$ is taken into account, the general trend of higher discoloration with longer exposure time is evident. But some samples, like ‘Dyer’s broom’/cotton’ and ‘cochineal/ silk’, show no discoloration at all. Also the sample materials in Display Case 1 seem to have suffered a higher discoloration, as expected given the higher amount of blue light irradiated by this source. Two striking exceptions are the ‘Brazilwood/wool’ and the ‘Parchment/Edding®’ samples. For these two samples, exposure to the LED light in Display Case 4 resulted in the most marked changes. When softwood samples are considered, the general trend of higher discoloration for higher light exposure is confirmed for all of the samples, with the exclusion of ‘softwood/linseed oil.’ It was concluded that, despite the evidence for a general trend of growing discoloration with growing exposure, the results cannot be easily interpreted in terms of a generalized model.

Nevertheless, the data in Table 1 allow for a qualitative classification of the effect of different light sources on the lightfastness of the material. The cases were ranked according to the amount of color change registered in the CIELAB system $\Delta E_{ab}$ ($1 = $highest, $\ldots, 4 = $lowest). The sum of the indexes for each case (cumulative index) is a measure of the effect of each case on the lightfastness of the materials under study and can be used to qualify the different light sources with respect to the set of materials. The cases with the lowest cumulative indexes are the ones causing higher discoloration of their reference materials.

From Table 2, we can conclude that Case 1 (with the fluorescent tubes) resulted in more harm to the objects, while Case 4 (with the LED sources) turned out to be the least harmful, confirming the hypothesis based on

| Table 1 | Color change ($\Delta E_{ab}$) registered by the samples after irradiation with different light sources for 1 through 5 months. 1 month = 240 hours exposure |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Month   | 1st | 2nd | 3rd | 4th | 5th |
| Case 1 (fluorescent tube) | | | | | |
| Saffron/silk | 1.7 | 2.1 | 3.8 | 4.4 | 4.9 |
| Saffron/wool | 2.6 | 3.0 | 4.3 | 4.9 | 5.6 |
| Saffron/cotton | 3.1 | 4.1 | 6.5 | 7.3 | 8.9 |
| Safflower/silk | 4.3 | 5.3 | 7.2 | 8.6 | 8.9 |
| Safflower/wool | 1.7 | 2.3 | 3.7 | 4.0 | 4.8 |
| Safflower/cotton | 3.1 | 3.9 | 6.1 | 6.9 | 8.1 |
| Dyer’s broom/silk | 1.0 | 1.1 | 2.2 | 2.5 | 2.6 |
| Dyer’s broom/wool | 1.6 | 1.6 | 2.4 | 2.8 | 2.7 |
| Dyer’s broom/cotton | 2.2 | 2.3 | 1.7 | 1.7 | 1.5 |
| Brazilwood/ink | 1.3 | 1.0 | 2.1 | 2.2 | 2.6 |
| Brazilwood/wool | 2.1 | 1.7 | 3.1 | 3.0 | 4.7 |
| Brazilwood/cotton | 2.0 | 2.2 | 3.1 | 3.6 | 4.2 |
| Cochineal/silk | 0.6 | 0.4 | 0.4 | 1.0 | 1.1 |
| Cochineal/wool | 4.8 | 5.2 | 5.9 | 6.3 | 6.3 |
| Cochineal/cotton | 4.0 | 4.6 | 5.9 | 6.5 | 7.2 |
| Folium/cotton | 2.0 | 3.6 | 5.6 | 7.0 | 8.6 |
| Softwood/wax | 1.3 | 1.7 | 3.6 | 4.4 | 6.6 |
| Softwood/linseed oil | 3.0 | 2.5 | 3.0 | 3.7 | 5.0 |
| Softwood/shellac | 2.1 | 2.5 | 4.9 | 5.4 | 7.6 |
| Softwood | 0.5 | 0.4 | 2.9 | 3.4 | 5.7 |
| Parchment | 1.6 | 1.6 | 2.0 | 2.2 | 2.2 |
| Archival board | 1.3 | 1.7 | 2.7 | 3.3 | 3.8 |
| Paper I | 1.1 | 1.1 | 1.4 | 1.5 | 1.7 |
| Paper III | 0.4 | 0.4 | 0.6 | 0.7 | 0.7 |
| Parchment/edding | 2.1 | 1.8 | 2.3 | 1.8 | 2.4 |
| Archival board/edding | 0.3 | 0.3 | 0.5 | 0.6 | 0.6 |
| Paper I/edding | 1.3 | 1.4 | 1.5 | 1.3 | 1.6 |
| Paper III/edding | 1.3 | 1.5 | 1.7 | 1.5 | 1.5 |
| Newsprint | 1.5 | 3.0 | 3.5 | 3.5 | 4.5 |
| Case 2 (halogen lamp) | | | | | |
| Saffron/silk | 2.0 | 2.2 | 2.8 | 3.3 | 4.2 |
| Saffron/wool | 2.4 | 2.6 | 3.5 | 3.6 | 4.4 |
| Saffron/cotton | 2.1 | 3.5 | 4.8 | 5.4 | 7.1 |
| Safflower/silk | 3.8 | 4.9 | 5.5 | 5.9 | 7.1 |
| Safflower/wool | 1.2 | 1.2 | 1.8 | 2.0 | 2.5 |
| Safflower/cotton | 2.4 | 3.2 | 4.2 | 4.8 | 6.1 |
| Dyer’s broom/silk | 2.0 | 2.0 | 2.1 | 2.6 | 2.7 |
| Dyer’s broom/wool | 0.8 | 1.0 | 1.3 | 1.5 | 1.7 |
| Dyer’s broom/cotton | 2.4 | 2.5 | 2.4 | 2.7 | 2.6 |
| Brazilwood/ink | 0.8 | 0.8 | 1.0 | 1.1 | 1.4 |
| Brazilwood/wool | 3.1 | 2.9 | 3.4 | 4.0 | 3.7 |
| Brazilwood/cotton | 1.7 | 1.9 | 2.6 | 2.8 | 3.3 |
| Cochineal/silk | 0.7 | 1.4 | 1.3 | 0.8 | 1.1 |
| Cochineal/wool | 1.1 | 1.2 | 0.7 | 0.8 | 0.8 |
| Cochineal/cotton | 0.6 | 1.0 | 1.8 | 2.3 | 3.2 |
| Folium/cotton | 0.5 | 0.9 | 1.6 | 3.0 | 4.1 |
| Softwood/wax | 1.0 | 1.4 | 3.5 | 4.1 | 6.0 |
| Softwood/linseed oil | 3.5 | 2.3 | 1.7 | 2.1 | 4.6 |
| Softwood/shellac | 1.9 | 2.4 | 4.6 | 5.6 | 8.1 |
| Softwood | 1.1 | 0.8 | 1.7 | 2.1 | 4.0 |
| Parchment | 0.7 | 0.8 | 1.1 | 1.2 | 1.2 |

*Continued*
Table 1  Continued

| Month                        | 1st | 2nd | 3rd | 4th | 5th |
|------------------------------|-----|-----|-----|-----|-----|
| Archival board               | 1.7 | 2.1 | 3.0 | 3.4 | 4.0 |
| Paper I                      | 0.6 | 0.6 | 0.6 | 0.7 | 0.9 |
| Paper III                    | 0.4 | 0.4 | 0.5 | 0.6 | 0.6 |
| Parchment/edging             | 1.3 | 1.2 | 1.4 | 2.0 | 1.5 |
| Archival board/edging        | 3.0 | 3.3 | 3.7 | 4.0 | 4.0 |
| Paper I/edging               | 1.9 | 2.2 | 2.1 | 2.2 | 2.0 |
| Paper III/edging             | 1.2 | 1.3 | 1.4 | 1.3 | 1.4 |
| Newsprint                    | 1.5 | 3.1 | 3.6 | 4.5 |     |

*Case 3 (low voltage metal halide)*

| Dye             | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
|-----------------|-----|-----|-----|-----|-----|
| Saffron/silk    | 1.8 | 2.1 | 3.3 | 3.7 | 3.8 |
| Saffron/wool    | 0.7 | 1.5 | 2.6 | 2.9 | 3.4 |
| Saffron/cotton  | 1.7 | 2.8 | 5.2 | 5.9 | 7.0 |
| Safflower/silk  | 3.2 | 3.9 | 6.4 | 7.0 | 7.4 |
| Safflower/wool  | 0.3 | 0.8 | 1.2 | 1.4 | 1.5 |
| Safflower/cotton| 2.2 | 2.7 | 4.8 | 5.5 | 6.4 |
| Dyer’s broom/silk| 2.0 | 1.9 | 2.5 | 2.9 | 2.9 |
| Dyer’s broom/wool| 1.5 | 1.6 | 2.1 | 2.1 | 2.5 |
| Dyer’s broom/cotton| 2.6 | 2.5 | 2.5 | 2.6 | 2.7 |
| Brazilwood/silk  | 1.2 | 1.5 | 1.8 | 2.0 | 2.0 |
| Brazilwood/wool  | 1.2 | 0.9 | 1.8 | 2.0 | 2.5 |
| Brazilwood/cotton| 2.5 | 2.4 | 2.8 | 3.2 | 3.3 |
| Cochineal/silk   | 0.7 | 0.7 | 0.7  | 0.8 | 1.1 |
| Cochineal/wool   | 1.2 | 1.8 | 2.9  | 3.4 | 3.6 |
| Cochineal/cotton | 1.8 | 2.0 | 3.0  | 3.4 | 3.1 |
| Folium/cotton    | 1.4 | 1.1 | 1.2  | 2.0 | 2.5 |
| Softwood/wax     | 1.8 | 2.3 | 3.3  | 3.8 | 5.3 |
| Softwood/linseed oil| 3.1 | 2.0 | 1.3  | 1.4 | 1.5 |
| Softwood/shellac | 3.2 | 3.8 | 4.9  | 6.4 | 7.5 |
| Softwood         | 1.0 | 0.9 | 1.8  | 2.4 | 3.7 |
| Parchment        | 1.5 | 1.3 | 1.3  | 1.7 | 1.6 |
| Archival board   | 1.4 | 1.7 | 2.4  | 2.8 | 3.2 |
| Paper I          | 0.8 | 0.8 | 0.9  | 1.0 | 1.2 |
| Paper III        | 0.3 | 0.3 | 0.3  | 0.5 | 0.5 |
| Parchment/edging | 5.9 | 5.3 | 5.1  | 7.0 | 6.3 |
| Archival board/edging| 2.0 | 3.1 | 2.3  | 1.6 | 2.1 |
| Paper I/edging   | 0.2 | 0.1 | 0.8  | 0.2 | 0.2 |
| Paper III/edging | 1.0 | 1.3 | 1.6  | 1.0 | 1.3 |
| Newsprint        | 1.4 | 3.0 | 3.2  | 4.2 |     |

*Table 1  Continued*

| Dye             | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
|-----------------|-----|-----|------|-----|-----|
| Cochineal/silk  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Cochineal/wool  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Cochineal/cotton| 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Folium/cotton   | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Softwood/wax    | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Softwood/linseed oil| 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Softwood/shellac| 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Softwood        | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Parchment       | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Archival board  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Paper I         | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Paper III       | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Parchment/edging| 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Archival board/edging| 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Paper I/edging  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Paper III/edging| 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |
| Newsprint       | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 |

Continued

the spectral power distribution of the light source employed. The data indicate that different materials and dyes react differently to the different sources (Table 3).

After sorting the results by dye and materials classes, it can be seen that the fluorescent light tube (Case 1) has the most harmful effects. However, the advantage of the LED source (Case 4) with respect
Table 2  Effect of different light sources on the lightfastness of the materials

| Material  | Case 1 | Case 2 | Case 3 | Case 4 | Increased discoloration with exposure time |
|-----------|--------|--------|--------|--------|--------------------------------------------|
| Saffron/silk | 1      | 2      | 3      | 4      | Yes                                        |
| Saffron/wool | 1      | 2      | 3      | 4      | Yes                                        |
| Saffron/cotton | 1      | 3      | 3      | 4      | Strong                                     |
| Safflower/silk | 1      | 2      | 3      | 4      | Yes                                        |
| Safflower/wool | 1      | 3      | 3      | 4      | Strong                                     |
| Safflower/cotton | 1      | 3      | 3      | 4      | Strong                                     |
| Dyer’s broom/silk | 1      | 1      | 1      | 1      | Little                                     |
| Dyer’s broom/wool | 1      | 4      | 1      | 1      | Little                                     |
| Dyer’s broom/cotton | 4      | 1      | 1      | 1      | No                                         |
| Brazilwood/silk | 1      | 4      | 3      | 1      | Little                                     |
| Brazilwood/wool | 2      | 3      | 4      | 1      | Yes                                        |
| Brazilwood/cotton | 1      | 4      | 4      | 2      | Yes                                        |
| Cochineal/silk | 2      | 3      | 2      | 1      | No                                         |
| Cochineal/wool | 1      | 4      | 2      | 3      | Yes                                        |
| Cochineal/cotton | 1      | 2      | 2      | 4      | Yes                                        |
| Folium/cotton | 1      | 2      | 4      | 3      | Yes                                        |
| Softwood | 1      | 3      | 4      | 2      | Strong                                     |
| Softwood | 1      | 2      | 4      | 4      | Strong                                     |
| Softwood/shellac | 3      | 1      | 3      | 4      | Strong                                     |
| Softwood/linseed oil | 1      | 3      | 1      | 4      | Yes                                        |
| Parchment | 1      | 4      | 3      | 2      | Little                                     |
| Archival board | 2      | 4      | 1      | 3      | Strong                                     |
| Paper I | 1      | 2      | 4      | 3      | Little                                     |
| Paper III | 1      | 3      | 2      | 3      | No                                         |
| Parchment/edding | 3      | 2      | 4      | 1      | Little                                     |
| Archival board/edding | 4      | 2      | 1      | 3      | Yes                                        |
| Paper I/edding | 2      | 3      | 1      | 4      | No                                         |
| Paper III/edding | 1      | 1      | 3      | 4      | No                                         |
| Newsprint | 1      | 4      | 1      | 3      | Strong                                     |
| Cumulative index | 43      | 77      | 73      | 82      |                                            |

Table 3  Effect of different light sources on the lightfastness of selected materials, sorted by dye and material classes

| Material  | Case 1 | Case 2 | Case 3 | Case 4 | Increased discoloration with exposure time |
|-----------|--------|--------|--------|--------|--------------------------------------------|
| Saffron/silk | 1      | 2      | 3      | 4      | Yes                                        |
| Saffron/wool | 1      | 2      | 3      | 4      | Yes                                        |
| Saffron/cotton | 1      | 3      | 3      | 4      | Yes                                        |
| Safflower/silk | 1      | 3      | 2      | 4      | Strong                                     |
| Safflower/wool | 1      | 2      | 3      | 4      | Strong                                     |
| Safflower/cotton | 1      | 3      | 2      | 4      | Strong                                     |
| Brazilwood/silk | 1      | 4      | 3      | 1      | Yes                                        |
| Brazilwood/wool | 2      | 3      | 4      | 1      | Yes                                        |
| Brazilwood/cotton | 1      | 4      | 4      | 2      | Yes                                        |
| Softwood | 1      | 3      | 4      | 2      | Yes                                        |
| Softwood/shellac | 3      | 1      | 3      | 4      | Yes                                        |
| Softwood/linseed oil | 1      | 3      | 1      | 4      | Yes                                        |
| Parchment | 1      | 4      | 3      | 2      | Little                                     |
| Archival board | 2      | 4      | 1      | 3      | Strong                                     |
| Paper I | 1      | 2      | 4      | 3      | Yes                                        |
| Paper III | 1      | 3      | 2      | 3      | Yes                                        |
| Newsprint | 1      | 4      | 1      | 3      | Yes                                        |
| Cumulative index | 43      | 77      | 73      | 82      |                                            |

Figure 5  Visible reflectance spectra to safflower on cotton and corresponding first derivative as a function of exposure time.

to the halogen (Case 2) or halide metal (Case 3) is lamp become less obvious. For example, the LEDs mounted in Case 4 have a small effect on samples dyed with saffron and safflower, while the opposite effect was observed for samples dyed with brazilwood.

It has been found that the specific surface treatment of a material can have a deep impact on its resistance to light-induced damage, as shown by the softwood samples. Softwood coloration is very sensitive to all sources of lights used in this experiment. The addition
of wax or shellac increases the sensitivity of those samples to all light sources with the exception of the LED in Case 4.

For paper samples, less discoloration was found for the samples exposed to light from halogen lamps (Case 2).

The results indicate that each material reacts differently depending on the light source employed.

**Reflectance spectra**

In order to calculate the CIE L* a* b* (CIELAB) values, the reflectance curves of the individual colorants were measured. These can be used for characterizing unknown color materials (Fuchs & Oltrogge, 1994; Hahn *et al.*, 2004). Spectra of safflower on cotton exposed in display Case 1 were selected as a representative example (see Fig. 5). The reflectance spectra show a broad band from 450 to 730 nm, including two inflexions at 450 and 550 nm as well as a shoulder band at 500 nm. The first derivatives show two peaks centered at 450 and 550 nm. An increased reflectance is observed with longer exposure times.

It is manifest that the reflectance curves were slightly altered during the aging period. Nonetheless, the reflectance curves’ characteristic features are retained, so that identification of the corresponding colorants is still possible, as expected.

**Conclusion**

The results of this study can be summarized as follows:

- There are incipient color changes very soon after first-time illumination (then still invisible to the human eye).
- Widely varying results were obtained for the watercolor samples. For example, after irradiation for 3120 hours, a sample with gamboge had already changed by as much as 48 CIELAB units. The Raw Sienna sample, in contrast, exhibited a change of only 2 units after 6000 hours.
- Besides gamboge, the most sensitive samples were carmine, madder lake, and alizarin crimson.
- Concurrently conducted chemical tests indicate a clear relationship between the level of reflectance concerned and the substance degradation (Hahn, 2014).

These results illustrate that changes in color already occur shortly after first-time illumination. This is observed at different degrees, and depends not only on the illumination used, i.e. the light source and the illuminance, but also on the material studied and its conservation state. In the category of yellow coloring agents, the changes observed were comparable to those reported by Colombini *et al.* (2007). This is of major significance for any exhibition showcasing sensitive objects.

For this study, the exposure duration was deliberately kept relatively short, as this is customary practice in temporary exhibitions. As far as sensitive materials, exposing them to light for longer periods (as is the case in permanent exhibitions) is most definitely a non-viable option, as cogently demonstrated by this study.

It has also been confirmed that fluorescent tubes cause higher damage to light-sensitive materials. However, investigating the effect of light from low-voltage halogen lamps, metal halide lamps, or LED lamps showed a mixed picture, with no clear-cut advantage for any of the light sources. This is somewhat surprising because an assessment of the damage potential of the different sources according to the guidelines in CIE 157:2004 suggested that the LED source should have been the least harmful. The authors believe that an expansion of the spectral response database for dyes and materials will improve their ability to predict the effect of specific light sources on exhibits.

Finally, it is important to mention that the issue of ‘acceptability levels of light damage’ cannot be addressed through instrumental studies alone, because it involves the interaction between visitor, lighting, and exhibition (Lull, 1995; IESNA, 1996). More specific studies are needed in order to make recommendations in these other areas (Druzik, 2004; Miller, 2011).

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