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Original article

Spectral damage model for lighted museum paintings: Oil, acrylic and gouache

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ABSTRACT

A spectral aging test was developed to estimate the photochemical damage of oil, acrylic and gouache paints exposed to permanent lighting. The paints were irradiated at seven different wavelengths in the optical range to control and evaluate their spectral behaviour. To reach this objective, boxes with isolated aging cells were made. In each of box, one *LED* of a different wavelength and one photodiode were installed. Inside the boxes, the temperature of an exhibit area was recreated through a thermocouple sensor that controlled the temperature using a fan. The heat produced by the *LED* was dissipated by a thermal radiator. Moreover, to evaluate the exposure time dependence of the irradiation level, the test was performed using two different irradiation levels in ten exposure series. After each series, the spectral reflectance was measured, and the data collected for each paint and wavelength were used to develop a model of damage produced by the interaction between the spectral radiant exposure and the paint.

1. Research aims

A spectral aging test for visible radiation was developed for oil, acrylic and gouache paints. The study was conducted at high and low levels of radiation, and the results were consistent at both levels. To conduct the test, boxes of accelerated aging using *LED*s as a light source were manufactured and characterized. Considering the absorbed radiation for each sample, a theoretical spectral aging model for each type of paint was developed, showing that the damage relation produced at different wavelengths varies with different aging conditions. A theoretical model was developed for each type of paint. A further model integrating the spectral component with the temporal component was also created.

The temporal component has a significant influence in the process. If only certain some areas of a painting were restored, their aging time is different than that of the areas that were not restored. The colour shifts are higher when the paint is new. As a consequence, after some time, the colour of the restored areas will be different than the original colour. The proposed model could be applied to the development of optimized illuminants used in artworks painted with materials similar to those analysed in the present study.

2. Introduction

Care, preservation and exhibition of cultural heritage strongly depend on the museum environmental conditions [1,2]. Lighting, one of the most important parameters, can also cause photochemical degradation [3,4] if not properly monitored and controlled. Indeed, most organic and many inorganic substances change with time and with light action, as can be appreciated in processes in nature. Both artificial and natural light can produce undesirable effects in exposed materials in museums [5,6]. Colour change is usually the most obvious indication of light-induced damage to cultural heritage.

Cultural heritage can be affected and damaged through photochemical effects due to at least four main factors [4]: the irradiance, the exposure time, the spectral distribution of the light and the spectral response of the exposed material.

The latter factor is difficult to determine due to the complex nature of the cultural heritage goods. Because museums have to address many different materials in different conservation statuses, the current research proposes several strategies to address this situation [4,7–10].

For instance, Cuttle developed a model applied to the damage produced by light in several materials [7] and the CIE 157 defined

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a model to evaluate damage due to optical radiation [3,4]. CIE 157 (model of Berlin) defines the damage suffered by an object exposed to light *DM* as a function of the spectral irradiance of the light source E_{dm}, the relative spectral responsivity of each exposed material $s(\lambda)$ and the exposure time t,

$$\mathrm{DM} = \mathrm{f}\left(\mathrm{E_{dm}}, \mathrm{s}\left(\lambda\right), \mathrm{t}\right). \tag{1}$$

According to this model, $s(\lambda)$ can be expressed as,

$$\mathrm{s}\left(\lambda\right) = \exp\left[-\mathrm{b}\left(\lambda - 300\right)\right] \tag{2}$$

where λ is the wavelength in nm, and the parameter b is specific for each material expressed in standard CIE 157-2004. This function is normalized at a wavelength of 300 nm.

Most of the time, the spectral responsivity of the materials does not give much practical information to optimize the light spectrum in museums because cultural goods are analysed as a whole. Currently, multispectral analysis of each specimen is becoming a common technique. These measurements are also more accurate and require less time [11–13].

Spectral reflectance is an important parameter to evaluate the conservation status in cultural heritage, especially in the case of paintings. Indeed, the spectral data can provide relevant information to curators about the artwork they have to restore. For example, spectral data are useful for pigment identification [14], especially when a database of frequently used pigments is available [15]. These data are then used for physical characterization, forensic work, lighting purposes [16] and others [17,18]. The spectral reflectance associated with other techniques can also provide information about subsurface microstructures [19]. Even in areas where colours appear similar to the naked eye, the spectral curves can show differences because metameric effects can occur [20].

Spectral reflectance is also a very important tool to evaluate the results of a retouching restoration process [21], where the only way to evaluate is the metamerism with changes of illumination [22].

Furthermore, the painting damage can be calculated by measuring different physical and chemical parameters. One of the most useful parameters is the colour shift, which is symptomatic of chemical changes inside the material. When radiation falls onto the painted surface, only the absorbed radiation can produce a change in the material; therefore, the damage evaluation in this work was performed using this absorbed radiation.

In principle, the absorbed energy is a function of the reflected energy. Given a light source with a spectral irradiance distribution E_λ, falling onto a material with a spectral reflectance ρ_λ, the effective radiant exposure H_{dm} can be expressed as follows:

$$\mathrm{H_{dm}} = \iint_{\mathrm{t},\lambda} \mathrm{E}_\lambda \quad \mathrm{s}(\lambda) \quad \alpha(\lambda) \qquad \mathrm{dt} \quad \mathrm{d}\lambda \tag{3}$$

where $\alpha\left(\lambda\right) = \left(1 - \left[\rho\left(\lambda\right) + \tau\left(\lambda\right)\right]\right)$ is the spectral absorbance, i.e., the energy absorbed by the paints. In the case of this study, the transmittance $\tau(\lambda)$ is assumed equal to zero.

An evaluation of the photochemical effect that takes into account absorbed energy implies a more sophisticated and time consuming analysis because it requires knowing the spectral reflectance factor of each cultural good, but the process would be more accurate and the results will be much better than when only irradiance of the surface is used.

The purpose of this work is to develop a model for the spectral photochemical damage produced in three common materials found in museum objects, namely, oil, acrylic and gouache. These materials are often used to retouch old paintings; therefore, the exhibition curators should be able to compare future changes in restored areas with areas where the aging is due to natural effects.

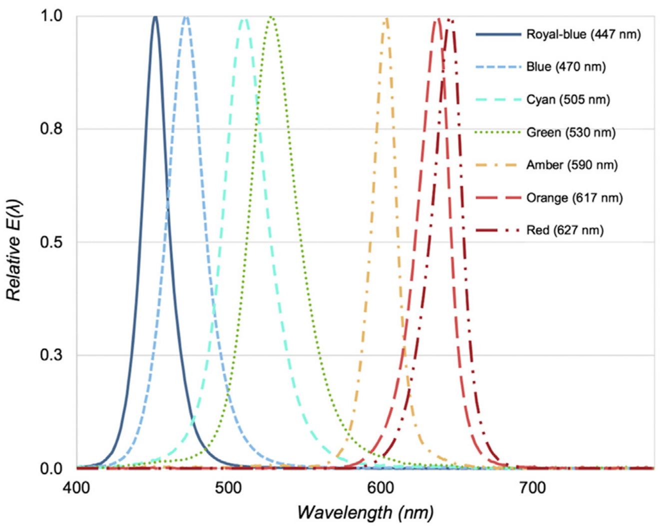

Fig. 1. Normalized spectral distribution of the 7 LED sources installed inside the aging boxes.

3. Methodology and experimental setup

Thirty-nine paints were exposed to light to test the photochemical degradation process. The paints were selected by the curators of the Reina Sofía and Thyssen Museums of Madrid according to practical criteria, based on their experience. The paint samples comprised 23 oil, 9 acrylic and 7 gouache paints. The characteristics of the paints used in this work are presented in Supplementary data, Table A.1.

Paint samples were prepared by application of a thin layer of paint onto glass plates of 250 × 4 × 2 mm (*L*, *W*, *T*) through a standard paint extender with constant thickness 120 μm [23]. Paint samples were then placed in a dark room in the laboratory at an average temperature of 25 °C for a drying process of 9 months before starting the aging test. Paint samples were put inside 11 aging boxes, each box containing 4 samples and 8 isolated areas (individual cells). Seven of these areas were irradiated and the last area was not irradiated but was used as a control zone. To increase the luminous uniformity, these cells had diffused white walls. As a radiation source for the aging process, seven *LEDs* with central wavelengths of 447, 470, 505, 530, 590, 617 and 627 nm were used in the different isolated cells (Fig. 1). Current new lighting systems based on *LED* sources permit spectral distributions optimized to the requirements of museum exhibition and conservation and also offer other important advantages, such as low energy consumption and longer life times [24].

This configuration assured a specific irradiation level for each cell according to the *LED* characteristics, and the variation was taken into account by measuring the spectral power distribution of 77 *LEDs* (11 aging boxes, seven *LEDs* in each aging boxes) using a *Stellarnet EPP2000* spectrophotometer.

The aging process was tested at two different irradiation levels over the paint samples, in 10 sessions: 6 sessions at low irradiation level (*LIL*) and 4 sessions at high irradiation level (*HIL*). During the aging process, the spectral reflectance of each area was measured.

To detect and to monitor possible breakdowns or an output radiation flux decrease from the *LEDs*, a photodiode was installed in each isolated cell of each box. Because it was not possible to assure an identical output flux for all *LEDs* at the same wavelength, the output flux of each *LED* in each cell was measured during the whole aging test over the paint samples plane and inside each cell using a *Thorlabs PM*100 *USB* power meter. Measurements were made at the paint samples centres of each cell (area of 0.5 mm radii). Table 1

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