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Optimization of four-primary white LEDs based on protective effect and color quality-a solution for museum illumination

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ABSTRACT
A solution was proposed for obtaining white light-emitting-diodes (LEDs) which are suitable for illuminating traditional Chinese paintings painted with inorganic pigments (iop-TCPs) based on the requirements of protective illumination and color quality. The damage laws and degrees of 450nm, 510nm, 583nm, and 650nm monochromatic lights which can construct four-primary white LEDs on the iop-TCPs were obtained through long-term illumination experiment and data analysis by converting color coordinates into CIE DE2000 color difference values. Then we obtained the damage formula of the constructed white LEDs, which can be used to evaluate damage degree. Spectral power distributions (SPDs) of the white LEDs, which can be iterated by brute-force algorithm, were simulated by the Gaussian formula. Constructed SPDs were evaluated by the damage formula and color quality formulas. The color quality eligible white LEDs with higher correlated color temperatures (CCTs) damage less to iop-TCPs. And the lowest damage SPDs satisfying color quality requirements in CCT ranges from 2700K to 4000K were obtained. Achievements can provide the theory and application basis for manufacturing white LEDs suitable for illuminating iop-TCPs; and the method can be further used in preparing white LEDs applicable to other cultural relics.

KEYWORDS
Inorganic pigments; protective illumination; color quality; white LEDs; spectral optimization.

INTRODUCTION
Numerous traditional Chinese paintings (TCPs) in museum suffer irreversible damage in various degrees. Among all the influencing factors, illumination cannot be eliminated for the need of visual effect (Dang et al. 2013). And the TCPs were classified as high responsivity to light by a technical report (CIE, 2004) and code (CNSA, 2009). Thus, the protective effect must be considered in museum illumination. Meanwhile, color quality is also an important element because exhibit paintings is a crucial function of the museum. Accordingly, it is urgent to develop museum light sources meeting both the need of the protective illumination and visual effect. The existing traditional Chinese paintings painted with inorganic pigments (iop-TCPs) are old and delicate. Therefore, we aim at solving the museum illumination problems for iop-TCPs which mainly contain natural mineral material made and easy fading, discoloration, color vanishing pigments-ancient graphite, clam shell powder, azurite, cinnabar, and orpiment-based on protective effect and color quality (Wu, 2011).

White LEDs which feature spectrum adjustable (Schubert and Kim, 2005), no infrared and ultraviolet radiation have the potential to form the desired light sources in museum. First, exhibits suffer seriously damage by infrared and ultraviolet radiation. Second, by adjusting the SPDs of the white LEDs, different wishes are made realizable to accomplish optimization

(Lin et al. 2017). At present, SPDs of the white LEDs satisfying the prerequisites of color quality mostly contain primary of red, yellow, green, and blue (Oh et al. 2012, 2014), namely red/yellow/green/blue (RYGB) four-primary white LEDs. Thus, we choose 450nm, 510nm, 583nm, 650nm waveband monochromatic lights as the deputies of the blue, green, yellow, and red monochromatic lights to construct the desired light sources by framing and evaluating the corresponding SPDs. Some researches explored for the influence of visible radiation on paintings, silks and so on (Farke et al. 2016). However, for our purpose to appraise the damage degree of the RYGB type white LEDs, it is indispensable to quantify the various influence of the corresponding monochromatic lights on the iop-TCPs.

It has been a prevalence to simulate SPDs by Gaussian distribution and iterate SPDs for evaluating figures of merit like the color quality, visual performance, circadian effect by algorithms (Wu et al. 2016). Among them, brute-force method which can cycle all the conditions in given ranges and steps provides accurate iterative results (Robinson et al. 2018).

Herein, we conducted a long-term experiment illuminating specimens of the iop-TCPs by the four monochromatic lights, test color parameters of specimens periodically, and calculated CIE DE2000 color differences; then we obtained relative color damage values of the monochromatic lights through data analysis, and based on which we deduced the relative color damage formula of the corresponding four-primary white LEDs to the iop-TCPs. In addition, we optimized the SPDs of the white LEDs by evaluating simulated spectra based on the obtained damage formula and the formulas about color quality parameters-color rendering index Ra and R_9 (CIE,1995; Hayashida et al. 2017), correlated color temperature (CCT), the distance from the Planckian locus (Duv) (Ohno, 2013).

METHODS

Models of specimens and experimental light sources

One of four groups of the iop-TCPs specimens (Dang et al. 2017), is shown in Figure 1a. And four monochromatic lights with the peak wavelengths of 450nm, 510nm, 583nm, and 650nm were produced by museum tungsten halogen lamp cooperating with infrared cut-off filters and 20 nm narrow band-pass filters. The irradiance of each light source was kept the same and constant during the long-term experiment, spectra are illustrated in Figure 1b.

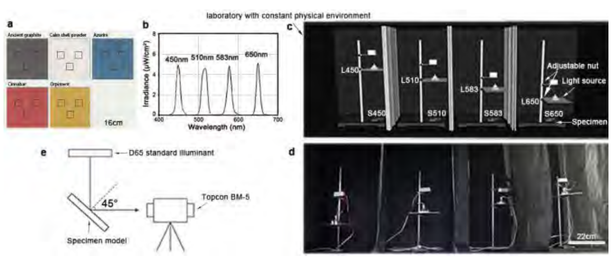

Figure 1. (a) One of four specimen illuminated by light sources. (b) Irradiance distribution of four monochromatic lights on the surface of the specimens. (c) Model of the experimental device, L represents the monochromatic light source, S represents specimen. (d) The realistic experimental device. (e) Diagrammatic sketch of the test environment.

Experimental methodology

The long-term illumination experiment was conducted in the Optical Laboratory. Detail has been depicted by Dang (2017). The experimental scheme is illustrated in Figure 1c-d.

Test of the parameters

After each cycle of illumination, the specimens were moved under the D65 standard light source; and color parameters of the specimens were measured by the standard color test method of CIE (1999), method shows as Figure 1e. The CIE LAB chromaticity coordinates (a*, b*) and metric brightness value L* of four specimens were measured before and each cycle after the illumination, at test points marked in Figure 1b, achieved by Luminance Colorimeter. Color parameters of one pigment in one specimen were determined by the average value of the three test points to minimize the measurement error. Color differences of the five pigments were calculated using the CIE DE2000 formula (Farke et al. 2016).

RESULTS

Changing curves of CIE DE2000 color differences

The damage law and the influence degree of different light sources can be seen in figure 2. We conclude from the figure that monochromatic lights with various peak wavelength impact at different degrees on pigments with distinct colors. It also implies that the monochromatic lights differently affect the iop-TCPs.

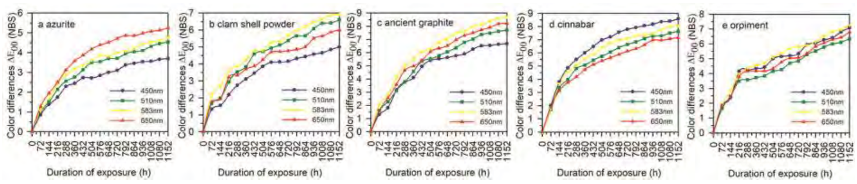

Figure 2. The changing curve of CIE DE2000 color differences of pigments (a) Azurite, (b) Clam shell powder, (c) Ancient graphite, (d) Cinnabar, and (e) Orpiment.

Relative damage values of the monochromatic lights

To express the relative damage of different monochromatic lights to the iop-TCPs whose color can be basically represented by the five pigments, the average damage value of the 450nm light to the five pigments is defined as 1.00, to which other values are normalized, detail is given in Table 1. Accordingly, relative damage values (D) of the monochromatic lights to the iop-TCPs is D(450): D(510): D(583): D(650)=1.00: 1.03: 1.14: 1.06.

Table 1. Relative damage values of monochromatic lights on inorganic pigments.

	450nm	510nm	583nm	650nm
Ancient graphite	1.08	1.19	1.38	1.29
Calm shell powder	0.79	1.02	1.10	0.93
Azurite	0.60	0.71	0.76	0.87
Orpiment	1.09	0.97	1.13	1.03
Cinnabar	1.45	1.25	1.34	1.17
Average	1.00	1.03	1.14	1.06

Damage formula of RYGB four-primary white LEDs

The damage degree to the exposed object is determined by the power of the incident light, the relative spectral responsivity of materials to incident radiation, and the illumination hours (CIE, 2004). The relative damage values we obtain can represent the relative responsivity of the iop-TCPs to the incident radiations; and for one white LED, the four monochromatic light sources constructing it share the same illumination hours; as for the power of the incident light, it is determined by the addition of the spectral power of every wavelength in the waveband. E.g. the power of the 450nm monochromatic light is expressed by Equation 1, and the power of 510nm, 583nm, and 650nm can be calculated in the same way.

$$W(450) = \int_{450-\Delta\lambda_{1l}}^{450+\Delta\lambda_{1r}} S_{450}(\lambda)\cdot d\lambda \tag{1}$$

Where $\Delta\lambda_{1l}$ and $\Delta\lambda_{1r}$ represent left and right half spectral width of the spectrum, respectively; S_{450} is the SPD of the 450 nm monochromatic light.

After confirming the damage factors of the light sources, the relative damage formula for the RYGB four-primary white LED is deduced according to Equation 1, where, the total power of the white LED is divided for eliminating the influence of various energy input:

$$D^*(\lambda) = \frac{1.00W(450) + 1.03W(510) + 1.14W(583) + 1.06W(650)}{W(450) + W(510) + W(583) + W(650)} \tag{2}$$

DISCUSSIONS

Spectral simulation and construction

All of the figures of merit which we want to optimize for the white LEDs-Ra, R_9, CCT, Duv, D^*-are determined by the SPDs. And the SPDs of the white LEDs, which are the determinant factor can be theoretically constructed by the addition of monochromatic lights (Ohno, 2005) as the Figure 3e shows, before practical production to avoid waste and unnecessary preparation. And the monochromatic lights can be simulated by the Gaussian distribution, the model of which we select is an accurate modified Gaussian model (Ohno, 2005). Accordingly, the monochromatic spectra are determined by the main parameters of the Gaussian distribution-peak wavelength λ, relative intensities of the peak wavelength V, and full width at half maximum $\Delta\lambda$ (FWHM)-depicted in Figure. 3a-d. Peak wavelengths of the constructing lights are confirmed to be 450nm, 510nm, 583nm, and 650nm. While, the other two parameters need iterating to form various spectra for further research and optimization.

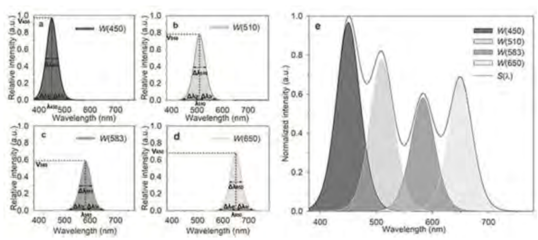

Figure 3. The S-model simulated spectral of monochromatic lights with peak wavelength of (a) 450 nm, (b) 510 nm, (c) 583 nm, and (d) 650 nm, W means the spectral power of the light. (e) spectral diagram of RYGB four-primary WLED, here, S represents the SPD of the WLED.

For overall scanning of the possible spectra, brute-force method is used. For circulation, relative intensities of the four monochromatic lights are set from zero to one with a step of 0.01 and the FWHM cycled from thirty to fifty with a step of five. After obtaining the spectra, values of figures of merit are calculated for further research.

Results of optimization

A total of 9150625 pieces of spectra are simulated. Eliminating unsatisfied spectra according to the color quality requirements for light sources illuminating op-TCPs-Ra≥90, R_9≥90, |Duv|≤0.005, 2700K≤CCT≤4000K (CNSA, 2009; ANSI, 2015)-6742 pieces remain.

Then we analyze the relative damage values $D^*(\lambda)_1$-$D^*(\lambda)_{6742}$ of the satisfied SPDs, which were normalized to the range 0-100 for better comparison. The relationship among $D^*(\lambda)$

values, the amount of the satisfied SPDs, and the relative average damage values in different ranges of CCTs (the ranges of CCTs are divided by the interval of 100, e.g., 2650 K-2750 K represents the range of 2700 K) is displayed in Figure 4.

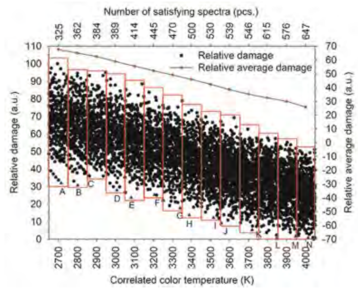

Figure 4. A diagram of D*(λ) values, the amount of satisfied SPDs, and the relative average damage in different ranges of CCT, the points of SPD with the same CCT range are enclosed by the red rectangle. The lowest damage points in the CCT ranges are marked with triangle.

We can see from the Figure 4 that: First, with the increase of the CCTs, relative average damage values in 2700K-4000K ranges appear an overall decrease trend (the black line), mains damage less to the iop-TCPs; second, the amount of SPDs satisfying requirements of color quality increases with the rise of CCTs (shown in the upper axis of Figure 4). e.g., the amount of qualified SPDs in the range of 2700 K is 325, while 647 for the 4000 K; third, when producing white LEDs, from the consideration of cultural relics protection, SPDs in high CCT ranges should be selected preferentially for lower damage, that means SPDs in the range of 4000 K are preferable. For further selection in the selected range, choosing SPDs with the damaged order of low to high in the selected range of CCTs, e.g., for 647 SPDs in the range of 4000 K, the SPD of point N in Figure 4 is firstly developed, but, if the SPD of the point N cannot be manufactured due to technical restrictions, other points in the range of 4000 K will be developed from low to high of the damage degree; fourth, if low CCT light sources are indispensable for reasons like the need of exhibition effect or some others which need further researching, the development should choose SPDs from the low damage to high damage in the target range.

CONCLUSIONS

Different monochromatic lights influence variously on different color pigments. Among all the painting types, the iop-TCPs suffer the damage of 450nm, 510nm, 583nm, and 650nm monochromatic lights by the damage proportion of 1.00: 1.03: 1.14: 1.06, by which a damage formula for the corresponding white LEDs is developed. The specific influence law is illustrated in Figure 2. Then the corresponding RYGB four-primary white LEDs can be evaluated protection effect by our damage formula.

By further analyzing the parameters of the constructed RYGB white LEDs, we conclude that the damage of the RYGB white LEDs to iop-TCPs decrease with the CCT ranges increase. When satisfying the requirements of color quality, the “CCTs,” “spectra amount in different ranges of CCTs,” and “relative damage of each spectrum to iop-TCPs” of the four-primary white LEDs have clear relationships, demonstrated in Figure 4. And in the realistic production of new type white LEDs, method for choosing SPDs is introduced.

The method flow of the illumination experiment, the data analysis, and the optimization of the spectra can be extended to develop and evaluate spectra of white LEDs using for other high-responsivity cultural relics like lacquerwares, frescos, folding screens, dyed silks and so on. In addition, the white LED spectra we obtain by the method flow, which are applicable for different kinds of cultural relics, can be manufactured by the lighting systems due to the tunable characteristics of white LEDs, for which fundamentally solved the problem of protective illumination for cultural relics in museums.

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