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PHYSICAL PRINCIPLES ON THE ILLUMINATION OF DISPLAYED MUSEUM OBJECTS

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ABSTRACT

The illumination of displayed museum objects must fulfil basic requirements such as the established conservation rules, aesthetic values and the visitors' viewing expectations. Therefore, choosing the right intensity and spectral colours of those objects' illumination is a very demanding task to curators, light designers and engineers. For a correct decision, the basic principles of white light composition, the light interaction with the materials, the measurement of the intensity and colours, and the human visual perception must necessarily be considered.

The spectral analysis and synthesis of white light are particularly relevant to understand the objects' physical colours. The use of a particular spectral composition may be constrained by the object conservation restrictions and the public aesthetic and visual expectations and therefore alternative choices must be considered to overcome those possible incompatibilities.

Radiometric and colorimetric measurements must be made to characterize the illumination conditions and establish the best set-up. The physical observation conditions must be evaluated through the knowledge of the reflection, transmittance, absorption and scattering phenomena, affecting colours and intensities. Finally, the physiological effects of a particular illumination on the human vision have to be evaluated through the principles of photometry and human vision physiology.

KEYWORDS Lighting; Illumination; Colour; Radiometry; Photometry

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1. Introduction

For the illumination of displayed museum objects, we must take in consideration the requirements and constrains associated to the object and the observer. Lighting with a suitable light spectral composition and correct levels of illuminance must satisfy the object preservation limits and fulfil objective and subjective viewing conditions, such as colour rendering (fidelity) and the observer’s comfort.

To preserve the object integrity, the illumination must have a spectral composition not to induce photochemical reactions, photo-degradation, colour fading, degradation, or heating which may cause the expansion, cracking and detachment of the object materials.

The concept of colour temperature (CT) is used to spectrally characterize incandescent lamps, since their spectra throughout the visible region can be very closely approximate to that of a blackbody. Blackbody or Planckian locus is the line path, in the CIE chromaticity diagram, that represents the colour of a blackbody at different temperatures. Therefore, the colour temperature of an incandescent lamp can be read on that line (FIG. 1). For other lamps producing white light that don’t have chromaticity coordinates that fall exactly on the Planckian locus but lie near it, the correlated colour temperature (CCT) must be used instead to characterize their temperatures.

The CCT of a light source, expressed in Kelvins (K), is therefore defined as the temperature of a blackbody, which is closest to the chromaticity of that source. It is an essential measuring parameter in the general lighting to specify the perceived colour of an artificial non-incandescent lamp.

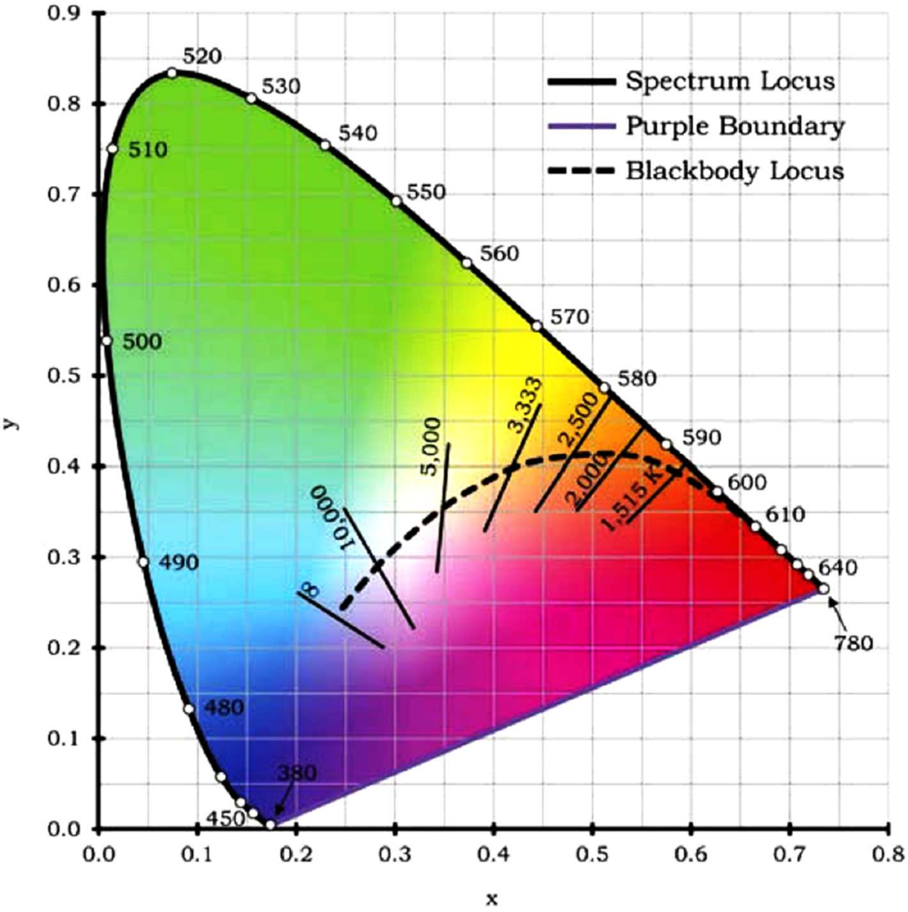

FIG. 1 - Planckian or black body locus: curve in the CIE 1931 diagram covering colour temperatures from 1515K up to infinite. The temperature straight lines are the locus of CCT. Their interceptions with the black body curve are the colour temperatures (Houser et al., 2016).

By international conventions regulated by the CIE (Commission Internationale de l'Éclairage), the illuminants are defined as ideal light sources with specific spectra, providing a basis for comparing images and colours under different lighting. Real light sources try to approach those standards (Malacara, 2011, pp.33-35). By conscious or subconscious comparison, the colour appearance of an object illuminated with a particular lamp may be different of that illuminated with a reference illuminant. The colour-rendering index (CRI) is a quantitative measure of the ability of a light source to reveal faithfully the colours of various objects, in comparison with an ideal or natural light source (Houser et al., 2016). The method of measuring and specifying colour-rendering properties of light sources is established by the CIE norm 13.3-1995, under specific protocol and well-defined parameters (Schanda, 2007). The CIE has specified a series of colour-rendering groups of light sources. In museums and art galleries, it is recommended that all lamps should be within group 1A, which is restricted to CRI values not less than 90 in a scale range from 0 to 100. It must be noted, however, that a high CRI does not imply necessarily a good colour rendition, since the reference source itself may have an imbalance colour. On the other hand, LED systems usually have a CRI rather low, regardless of showing a good colour appearance and a pleasant visual appeal. In face of this, some proposals are being published to establish in future a better colour-rendering criterion (Wendy et. al., 2005; Malacara, 2011, p.38).

The deteriorating effects of light on the material objects depend on the quality and amount of the light energy, measured by the spectral composition and the levels of illumination and exposure. The amount of heating due to light absorption increases with illuminance and exposure and therefore their values should be sufficiently low, without compromising the minimum viewing conditions. As a general approach and reference, the following parameters are used: correlated colour temperature, $3000 \leq CCT \leq 3500K$; wavelength, $420 < \lambda < 750$ nm; illuminance, $50 < E_v < 200$ lux; exposure accumulated during a year $15000 < E_v t < 150000$ lux.h. The use of flash photography by the museum visitors should therefore be restricted according to the responsiveness of the exhibited materials, but it should be noted that its effect is cumulative.

At the observer's point of view, a good illumination must have the potential to show all the visual attributes of the object. Therefore, the illumination must create the conditions for the most accurate viewing, discriminating detail and colour and providing bright and clear impressions of the object. These requirements can be evaluated by a *discrimination factor*. Other observer's subjective conditions, as pleasure, attractiveness, preference and stimulation, can be assessed by a *quality evaluation factor* (Cutte, 2007, p.29).

Some incompatibility may arise from opposing requirements concerning the object and the observer. If this is the case, a decision must be taken to favour the object conservation. For example, the level of illuminance needed for object preservation and the best viewing conditions at vision photopic regime (luminance > 3 cd/m^2, exitance >10 lm/m^2) can be inconsistent. Lower lighting may lead the observer to mesopic (luminance 0.001 to 3 cd/m^2, exitance 0.003 to 10 lm/m^2) or even scotopic (luminance < 0.001 cd/m^2, exitance < 0.003 lm/m^2) viewing regimes. Those regimes correspond to different physiological visual conditions and sensations. The cones are operative in photopic regime allowing suitable colour vision; both rods and cones are operative in mesopic regime; and only the rods, that are nor sensitive to colours, operate in the scotopic regime. The observer´s adaptation from photopic to scotopic regimes may take about ten minutes, which can be very inconvenient if the observer moves between displays illuminated at different lighting levels.

2. The basics of radiometry and photometry

Radiometry deals with the physical quantities associated with light energy. All radiometric quantities are qualified as *radiant*. For example, the radiant flux Φ_e is defined as the time rate of flow of radiant energy of a source.

On the other hand, photometry deals with the visual sensation or brightness caused by the light energy on the eye (Williams et al., 1972, pp.23-47). The respective quantities are qualified as *luminous*. For example, the luminous flux Φ_v is the light power of a source as perceived by the human eye.

The relation between radiant flux and the luminous flux for photopic vision is given by $\Phi_v = V(\lambda)\,\Phi_e$, where $V(\lambda)$ is the luminous efficacy curve for photopic vision. From this relationship, we may easily calculate that the amount of 1 W of radiant flux corresponds to 683 lm of luminous flux, at $\nu_0 = 540 \times 10^{12}\text{Hz}$ or $\lambda_0 = \frac{30}{54}\,\mu\text{m} = 555{,}55\ \text{nm}$ where $V(\lambda)$ has its maximum. In the case of scotopic vision regime, it should be used the luminous efficacy curve $V'(\lambda)$, with its maximum at 505 nm.

Both $V(\lambda)$ and $V'(\lambda)$ are defined in a norm of the CIE. These functions, available in graphical or numerical formats, measure the ability of a light source to produce a visual response from its radiant power in photopic ($V(\lambda)$) and scotopic ($V'(\lambda)$) vision regimes. From those curves, we may conclude that the brightness of a light source depends on its radiant power but also on its spectral composition. For instance, at the wavelength of the helium-neon laser (λ = 632,8 nm) the sensitivity of the eye is only 23.5% of what it is at the peak, leading to 160 lm/W. The green Nd:Yag lasers (λ = 532 nm) present a 88.5% sensitivity, or 604 lm/W. A blackbody at the temperature of the Sun (5800 K) results in a luminous efficacy of 93 lm/W.

TABLE I presents the most important quantities, units and formulas used in radiometry and photometry. While illuminance indicates the level of brightness of light incident at a surface, the exitance indicates the level of brightness leaving a surface. It should be noted that the lux unit is used only for incident light. Exitance is the product of the illuminance and the object reflectance and is expressed in lumens per square meter (lm/m^2); it represents a measure of surface density of reflected light that is available to the observer.

Radiometry		
Quantity name	**Symbol** (unit)	**Formula**
Radiant energy	Q_e (J)	
Radiant energy density	W_e (J/m^3)	$W_e = dQ_e/dV$
Radiant flux/power	Φ_e (W)	$\Phi_e = dQ_e/dt$
Radiant emittance/exitance	M_e (W/m^2)	$M_e = d\Phi_e/dA$
Irradiance	E_e (W/m^2)	$E_e = dQ_e/dA$
Radiant intensity	I_e (W/sr)	$I_e = d\Phi_e/d\omega$
Radiance	L_e (W/sr m^2)	$L_e = dI_e/dA\ cos\theta$

Photometry		
Quantity name	**Symbol** (unit)	**Formula**
Luminous energy	Q_v (lm.s)	
Luminous energy density	W_v (lm.s/m^3)	$W_v = dQ_v/dV$
Luminous flux	Φ_v (lm)	$\Phi_v = dQ_v/dt$
Luminous emittance/exitance	M_v (lm/m^2)	$M_v = d\Phi_v/dA$
Illuminance	E_v (lm/m^2 or lux)	$E_v = dQ_v/dA$
Luminous intensity	I_v (lm/sr or cd)	$I_v = d\Phi_v/d\omega$
Luminance	L_v (cd/m^2)	$L_v = dI_v/dA\ cos\theta$

TABLE I - Most important quantities, units and formulas used in radiometry and photometry.

The basic photometric units are *candela*, *lumen* and *lux*. The *candela*, the unit of luminous intensity, is defined as *the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.* The *lumen*, the unit of luminous flux, is *the luminous flux of light produced by a light source that emits one candela of luminous intensity over a solid angle of one steradian*. The *lux*, the unit of illuminance, equals one lumen per square meter. The levels of natural illumination vary by several orders of magnitude. Full moon clear sky corresponds to 1 lux; direct sunlight light corresponds to 100 000 lux.

3. Light sources — spectral composition and performance

Since Newton’s time, it is known that white light is composed of different colours, the so-called white light spectrum (Fig. 2). A higher resolution image would indicate the presence of black spectral lines that correspond to the absorption of specific wavelengths by chemical elements in the solar and terrestrial atmospheres.

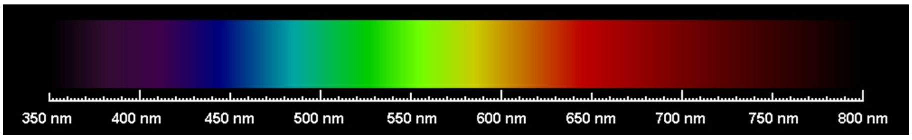

Fig. 2 - Solar spectrum.

The colour perception of a light source depends on its light spectrum and the colour-perception characteristics of the observer (Malacara, 2011). Well-defined colours correspond to a specific spectral bandwidth as indicated in Table II.

Colour	**Wavelength interval** (nm)	**Frequency interval** (THz)
Violet	~ 430 to 380	~ 700 to 790
Blue	~ 500 to 430	~ 600 to 700
Cyan	~ 520 to 500	~ 580 to 600
Green	~ 565 to 520	~ 530 to 580
Yellow	~ 590 to 565	~ 510 to 530
Orange	~ 625 to 590	~ 480 to 510
Red	~ 740 to 625	~ 405 to 480

Table II - Well-defined colours and its correspondence to specific spectral bandwidth.

Different types of light sources, characterized by different spectra, have been used in museum lighting. Incandescent lamps were the preference but nowadays their use is declining and other types are taken the lead. They have the advantage of excellent colour- rendering and a wide range of colour temperatures. However, they show some disadvantages: lifetime is around 1-2000 hours, efficiency is only around 4-5% and IR spectral content is very high.

White light can be synthesized by light of different colours and therefore can be produced by light sources or lamps of different types including those with discontinuous spectra with well-defined bands, large and narrow, such as those of gas discharge and fluorescence lamps or LEDs (Malacara, 2011, pp.55-157). The colour-rendering index of these lamps is however smaller compared with continuous spectrum lamps. The low-pressure sodium lamp emitting at $\lambda =$589 nm has CRI=0 and therefore it is not appropriate for colour reproduction.

The colour constancy indicates the human visual system is insensitive to some variation on the whiteness of the light. Somehow the human visual system knows the spectrum of the light source and it takes that into account when determining the chromatic reflectance properties of a surface. Metameric lights have different spectra although they look of same colour. If they illuminate coloured objects, the colours will look different. In these cases, characterized by low CRI, trial and critical observation is the only way to be sure that the colour reproduction is satisfactory.

LED lamps are becoming a reference lamp for many applications including museum lighting. The spectral flexibility and the consequent variability in colour temperature and colour rendering of these lamps are advantages in addition to their high energy-efficiency (85%) and sustainability. Compared with classical tungsten incandescent lamps, the modern LED lamps can be 10-15 times more efficient in energy consumption, and their lifetime can be 30-40 times longer. Nowadays, there are two main processes for generating white light with LEDs: phosphor conversion (PC) and colour mixing with three or more bands. Compared with a tungsten lamp, the LED mixtures are capable of providing not only high efficacies but also very satisfactory colour rendering, as already proved by experience in many museums wide world.

4. Basic phenomena of light interaction with materials

Light interacts with matter at microscopic or macroscopic levels. This interaction is manifested in different macroscopic phenomena: chromatic selective absorption and reflection, chromatic selective transmission, interference and diffraction, between others.

Some incident photons are absorbed by the molecules, but others may undergo multiple reflections before emerging from the surface. Some photons of different energies will be reflected from the first layers before being absorbed and show therefore the wide spectrum of the illumination light (specular reflection); others emerge after reaching deep layers without being absorbed and show their respective colours (diffuse reflection). Selective absorption/reflection explains the colour of common objects such as paintings. Only part of the spectrum of the illuminating white light will be reflected. For example, a red portion of an object absorbs all the spectral components of the incident white light except the red one, which is reflected and then enters the observer's eye.

Selective transmission is a phenomenon observed with colour filters, which are sometimes used to control the incident light spectrum by eliminating or reducing specific bands. Interference is the phenomenon that separates the colours of white light illuminating a soap ball, and diffraction splits the white light incident on colour hologram, for example.

Light interaction with materials may cause the appearance of permanent marks in the objects, such as colour degradation, a well-understood physical phenomenon occurring in organic and inorganic materials, which is caused, particularly, by UV radiation. Structure degradation, deformation, cracking, detachment may also arise in the illuminated objects due mainly to IR light. Degradation of museum objects must be prevented by any means and therefore some limits have to be imposed to the illumination category and lighting level. Choosing the safe illumination and the right levels, according to the exhibition conditions, is essential for the protection of the objects and the viewing quality. TABLE III summarizes the principal factors relating to the ambient and display lighting systems in the exhibition spaces, according to the material responsiveness (Cutte, 2007, p.268).

Material responsiveness	Non responsive	Slightly responsive	Moderately responsive	Highly responsive
Lighting category	Uncontrolled daylight	Controlled daylight	Restricted exposure	Minimal exposure
Daylight admission	Yes		No	
Sunlight admission	Yes	No		
Illuminance limit (lux)	No limit	200	50	
Exposure limit (lux h/y)	No limit	600 000	150 000	15 000
Colour rendering Index (CRI)	CRI≥85			
Correlated colour temperature (CCT)	2900K<CCT<4200K			
UV control	No	Yes		
IR control	No		Yes	

TABLE III - Principal factors relating to the ambient and display lighting systems in the exhibition spaces, according to the material responsiveness (Cutte, 2007, p.268).

The 50 lux limit results from both the minimum required value of exitance for photopic vision (10 lm/m^2) and the reflectance value of a mid-grey surface that is typically equal to 0.2, meaning that 80% of incident light is absorbed. Dividing 10 lm/m^2 by 0.2 we get 50 lux. This is the illuminance value that is widely recommended as the maximum level for displaying moderately and highly light-responsive museum objects. Below this value, visual discrimination ability is likely to suffer if the object surfaces have a mid-grey appearance. The 50 lux standard should really be qualified as being “50 lux of incandescent illumination;” 50 lux of any other light sources can have a completely different potential damage profile. For each case a solution must be studied according to the specific conditions of the object and the illumination. Values of illuminance up to 200 lux increase significantly visual discrimination but above this value that increasing is less significant. For non-responsive or slightly responsive materials, 200 lux is in general an appropriate value for the illuminance of a mid-grey surface.

The ultraviolet control is particularly important for light-responsive materials independently of the level of their response. The radiation of wavelength less than 400 nm should be completely eliminated in a museum. The same should happen to the IR radiation for moderately and highly responsive materials.

Researchers in Berlin have exposed a range of moderately responsive museum materials under controlled conditions, and have monitored resulting colour changes over time. They got the so-called “Berlin function” which represents the relative damage potential as wavelength changes. This function is a monotonic exponential-type decreasing curve with unitary value at 300 nm and negligible values after 750 nm (FIG. 3).

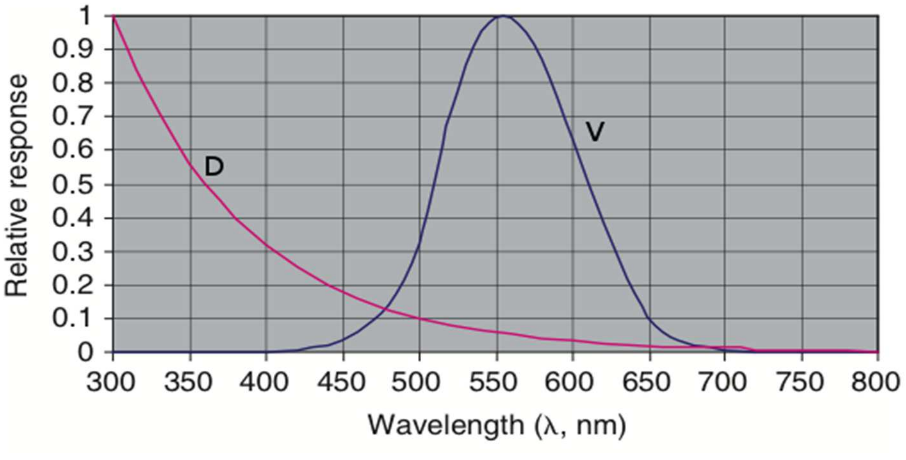

FIG. 3 - The “Berlin function” D compared with the luminous efficacy curve for photopic vision V (Cutte, 2007, p.42).

Comparing it with the luminous efficacy curves we conclude the relative damage response of materials is very different from the human relative visual response. This means that illuminance is not a reliable indicator of exposure rate. The CIE established the international norm CIE 157 2004 for the control of damage to museum objects by optical radiation.

5. Final remarks

For the appropriate lighting of museum objects several aspects must be taken into consideration: the luminous and chromatic characteristics of the light sources; the specific interaction between light and objects; the physical and optical characteristics of the objects; the human visual sensitivity; the limitations imposed by the objects conservation requirements. The chosen solution must not compromise the integrity of the exhibited object even if the appropriate viewing conditions are not completely satisfied. In the most incompatible situations it is always possible to reproduce the objects through photography or 3-D printing, combined with other technologies, and exhibit a model. In the presence of a realistic model, the observer can appreciate the visual characteristics of the original object and thank for the care that is taken to preserve a valuable piece.

Due to degrading effects caused by light in moderately or highly responsive materials of the displayed objects, an especial protection against UV radiation should be taken throughout museum spaces. The readily observed physical effects of light exposure, as the loss of colour and strength will then be minimized. IR radiation, temperature and humidity should also be controlled. Cracking, breaking down of glued joints in wooden objects, and separation of varnishes or painting from substrates will be minimized therefore.

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