

MUSEUM LIGHTING AN HOLISTIC APPROACH



SAPIENZA
UNIVERSITÀ DI ROMA

PhD thesis
In Energy and Environment

Faculty of Engineering
Dept of Astronautical Electrical and Energetic Engineering - DIAEE

MUSEUM LIGHTING: An holistic approach
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“To play with light is to play with magic”

*For my parents,
to my daughter*

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Abstract

Keywords: museum lighting, dosage, artificial lighting, holistic, daylight, Climate-Based Daylight Modeling, workflow, visual perception, road lighting, daylight filters

Among the environmental parameters that effect exhibited artifacts, light is the most complex and the only essential for the observer as to appreciate the artifacts, thus being one of the most critical variables of art exposure. Research on strategies for energy saving and the renovation of light destined to Heritage is examined by daylight admission and Light-Emitting Diode (LED) technology.

The extended review of the literature presented below, over museum lighting, evidenced the parallel advance of lighting principles with lighting design, concerning what determines visual quality and perception. Lighting quality is an interdisciplinary field of research affecting human activity and under a requested task, visual performance, while at the same time improving well-being. In this sense, the role of the lighting designer is to match and rank human needs with economic and environmental aspects as to architectural principles and to translate the results into a feasible design and an efficient installation.

Quality factors for art exposure, involving color fidelity and damage, along with visual perception necessitate of useful metrics through established criteria. The challenge for the museum for a holistic design of natural and artificial light is still missing of substantial metrics, even though recent findings provide some insight on the workflow to establish.

Luminance-based design metrics and contrast criteria are used in this study as key strategies for museum lighting, combining comfort and viewing fine arts through advanced computer rendering. The exploration of the transition inside a daylight gal-

lery where moving in the museum environment offers an experience for a series of adaptation changes through photopic, mesopic and dark-adapted scotopic function, along with change on the sensitivity of the spectrum.

The luminance appearance and the transition adaptation in the museum field lack of research examination; the relationship of prescriptive requirements and luminance-based design has been explored initially in the field of road lighting, where the relative visual performance has been evidenced to be in the center of the CIE standard for tunnel lighting. Daylight simulation via climate-based modeling, introducing daylight filters as solar shading devices, has been proposed as the object of experimental research, connecting light “filtering” with luminance; this workflow could be applied in several fields of research considering museum environment and give responses in the preservation of artwork involving daylight.

The subject of this thesis is the proposal of a ‘trama’ surface installed on windows to reduce and control daylight, studying how energy and conservation targets can be achieved. New light sources and smart control systems will integrate to a holistic approach for museum lighting design.

Introduction

Symbiosis between art, science and the strings connecting nature's geometry matrix with architectural design, has been the inspiration for the research on the field of lighting as physical and aesthetical phenomenon; lighting conditions and luminous quality are not analyzed as targets, by means of recommendation standards, but as results of both methodological and sensitive approach.

The symbiotic state of art and science above the major multidisciplinary fields considering architecture issues has been broadly accepted as a crucial node of modern research and design, while recently, in the field of lighting design, gained a unique ally utilizing lighting simulations engines. Computer processing has made possible what used to be the result of difficult calculations or applied rules of thumbs, by rendering images of new spaces, now predicting illumination, lighting distribution and daylight control systems by modeling.

In this thesis the field of lighting design that has been chosen is the museum lighting, representing an environment with significant complexity of real needs and prescriptive specification; minimize light damage by minimizing the energy absorbed by artifacts, to guaranty at the same time architectural integration, viewing, and circulation.

The lighting industry has been subjected to an unprecedented era of change, driven by changes in legislation and advances in lighting technology since Solid-state lighting won much acceptance for energy saving issues while improving and re-elaborating the majority of LED's quality characteristics. Both of these factors offer attractive advantages for museums and galleries, in particular, the potential for consumption and maintenance costs.

The demands created by CIE 157:2004 publication of non-visible effects of exposure [1] shifted the focus of the illumination of artworks from illumination levels to total exposure over time, and reassessed energy use and reduction in museums as

a critical factor. Targets are expressed as recommended maximum annual lighting dosages, correlating display time with the expected life of light-sensitive materials and are quoted in lux hours of exposure. Widening adoption of dosage, as the primary target for lighting conservation, provided both opportunities and challenges for curators, designers, and lighting specialists.

As far as exposure from artificial lighting, which in any terms can be easily controlled, dosages can be predicted or measured in an ongoing installation; a far more difficult task is related with daylight, which, up to this “holistic” evaluation, most museums ignore as earlier techniques did not permit it. Overpassing Gary Thomson’s preventive conservation recommendations on low levels of Daylight Factor [2], today’s targets to maximize building’s passive performance allows architects to introduce daylight again in the building envelope design, accomplishing prescription criteria for both energy and standards for museum environmental control.

Introduced by John Mardaljevic in CIBSE National Conference 2006 Climate-Based Daylight Modeling (CBDM) is a computer-based analysis of daylight in interiors that uses realistic sky and sun conditions to simulate the amount and distribution of light accurately. This type of modeling is founded on standardized climate files and is location specific. It enables the prediction of absolute values of illuminance and luminance and permits the calculation of cumulative periods of daylight levels to exceed or does not achieve user determined targets. Recent studies on damage limitation of light-sensitive materials in galleries through climate-based simulations show that a daylight exposure strategy could be undertaken. A similar workflow will be therefore analyzed as the basis for a techno-scientific approach that consists of the mathematical path of the current project.

Standard compliance of lighting an art gallery remains though part of a more complicated task that includes visual quality and non-objective sensations; curators often propose a museum route, telling a story, enhancing sentiments, creating contrasts and unexpected hierarchies. Lighting is mentioned as the key to viewing scenes and general visitor’s visual perception. Luminance and contrast are rarely considered from the designers and are poorly mentioned on guidelines. In this perspective, the research of luminance-based design metrics and contrast criteria as key strategies for museum lighting will be therefore analyzed as parameters

connected with comfort related to the viewing of fine arts. Advanced computer rendering provides the opportunity to an investigation of luminance distribution not neglecting daylight contribution; this permits a preliminary hypothesis of the relationship among background luminance and target contrast requirements for the perceived visual performance of a museum collection.

The relationship of prescriptive requirements and luminance-based design has been investigated in the field of road lighting where the relative visual performance has been evidenced to be in the center of the CIE standard for tunnel lighting. Daylight simulation via climate-based modeling has been explored, introducing daylight filters as solar shading devices, and has been the object of innovative research connecting light “filtering” with luminance. This workflow could be applied in several fields of research considering museum environment and give responses to the preservation of artwork involving daylight.

State of the Art

Historical development of museum lighting

The environmental parameters that effect exhibited artifacts considered as a unique physical system that interacts and evolves through time have been objects of scientific research in the different fields of applied physics in the last centuries, defining and monitoring the "museum micro-climate." Among them, light exposure is arguably the most complex and the only one that is essential to the observer as to appreciate the cultural heritage making lighting one of the most critical variables of art exposure.

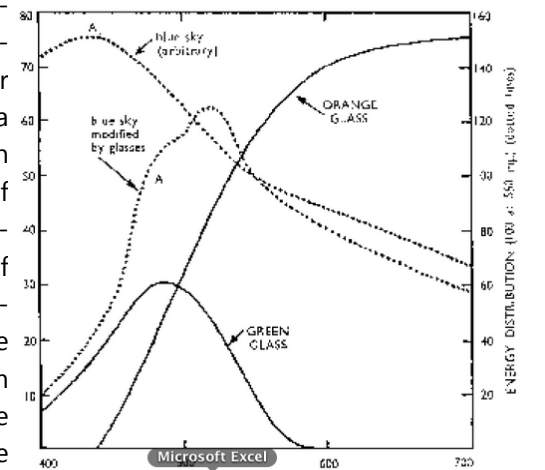
Color fading is probably the most common indication of light-induced damage to cultural heritage by photochemical effects and is due to at least four main factors: the irradiance, the exposure time, the spectral distribution of the light and the spectral response of the exposed material. Depending on the nature of the exhibit the latter factor and is by far the most difficult to determine [3]. Quantification of fading rates and recommended techniques to slow deterioration historically evolved into controlling illumination levels; discussion though has been raised recently in different fields of lighting design as lux recommendation maybe be limited for the complex task of visual performance as a holistic approach.

the lux laws

The first modern scientific study of light damage is considered a series of experiments on the influence of light on watercolors published by Russell and Abney in 1888. Samples were exposed on Whatman Paper to mixed sunlight and equivalent daylight, simulating 480 years of exposure. They used the spectrophotometric description of change stating the reciprocity law in its modern form meanwhile effects of light filtration have been reported [4]. In their investigations concluded that damage of exposure of blue and near violet bands of light is the most definitive; the exposure to various other parameters such as dry air, wet air, hydrogen, under vacuum, under colored glass, has been examined noting that fading presence of humidity and oxygen is, in general, essential for fading.

Bunsen and Roscoe previously introduced the concept of the proposed exposure reciprocity law for photochemical reactions in 1923; a property is directly dependent on its exposure dose, as the product of the irradiation intensity and exposure time, though independent of its individual values of the. Deterioration factor in photography where the blackening of photographic film is only dependent on the exposure dose established the concept of the law.

Figure 1 plot of the transmission of daylight under the colored glasses of the roof



The application took place in many different fields since that time where incident radiation is used to generate a response; the law assumes that light intensity is proportional to the rate of the overall photochemically process and uniquely depend on the dose. While this is true for most primary photochemical processes (e.g., absorption) at reasonable light intensities, subsequent processes are not generally described by the same relationship. [5].

The law is expressed as:

$$H = \int_t E_e dt \quad (Wh / m^2)$$

Where E_e is irradiance incident on the surface and t is time in hours (h)

For artificial light where E_e is constant the equation is $H = E_e t$

Based on the report of Russell and Abney, a worth to mention experiment took place in one of the top-lighted galleries in South Kensington Museum with the encouragement of Captain Abney. With the aim of modifying the light to render it harmless to watercolors, while still enabling them to be seen, the roof has been modified and in 1894 Raphael Cartoon Gallery was moved there, see Figure 18. The roof consisted of an equal number of alternate strips of green and orange glasses of the same size and below this composite, a lay light of colorless diffusing Milanese glass. The transmission curves of the glasses and the quality of the light modified by the combined effect of them has been calculated for blue skylight and as shown in Figure 1 the modification brings a progressive reduction in transmission below 500 nm which without any doubts has been a useful insight for preservation meanwhile flux was reduced by about 80% [6]. However, Abney's conviction that the public did not notice the yellowish color of light was not real, raising critics and finally in 1923 the Cartoons were removed to a space of the museum in lack of daylight.

Daylight illumination in the museums in the later nineteenth century was predom-

¹Capt. W. de W. Abney was attached to the Science and Art Department of South Kensington and an important figure in all matters treating on photography and its kindred sciences; for several years occupied the chair of the Physical Section of the British Association.

inant, with the increasing need for artificial light being mostly provided by gas lighting and later by electric incandescent lamps; in the latter case, light radiation is emitted by heating at very high temperature when electric current flows through a wire filament. The naturally evolved perception of color in human beings and the continuous spectrum of the visible light by incandescent lamp have an optimum quality of color reproduction though it exhibits a shift towards the red range of the radiation spectrum. This inclination, with its maximum radiation lying in the infra-red range of the spectrum while decreasing toward the blue wavelengths, makes typical incandescent bulbs comparatively as low potential for damage, hardly possessing any radiation component in the UV range, a fact that accounted for their vast popularity and wide dissemination in museums [7].

The first recommendations for museum light intensity appeared in the July 1930 issue of Burlington Magazine; Robert L. Feller presented thirteen sets of recommendations for low, medium and high illumination levels in average 57, 142 and 258 lux, respectively. His laboratory focused on building up the foundations of preventive conservation science using a clear research base in the paint and textile industries, which continued for several years and Unesco published a complete volume of his work in 1964. An extensive review of recent literature of photochemical deterioration was included and among his recommendations, the concept of total annual exposure for the first time appeared as seen Figure 2 as a consequence of the Bunsen-Roscoe law.

Close to Feller's recommendations for illuminance levels, Garry Thomson publishes *The Museum Environment*, perhaps the first complete guide to preventive conservation, presenting in detail lighting recommendations. His suggestion of specifying the limit values governing illuminance for paintings at 150–200 lux and for graphical objects at 50 lux has been globally accepted. Moreover, objects that are light sensitive should only be illuminated as long as the actual opening times of an exhibition requires [8].

During the 1970s, preservation advantages of incandescence have been slowly abandoned in favor of the coated fluorescent tubes with a significant economic benefit. Meantime, the effects of UV radiation on fugitive and permanent colors were determined, and industrial fading-standards became widely accepted in exposure studies in the paint industry and were later adopted in conservation research. Already in 1956 ICOM publication has investigated the deleterious effects of the discharge lamps that emit mainly in UV range but enriched of fluorescent substances convert radiation into visible light. The plurality of choices as for size,

color of light, and color reproduction, and the four to eight times higher output than that of an incandescent lamp with the same wattage have established their use against the technological disadvantages involved [7]; discontinuous spectrum instead to special products, not suitable to create clear-cut shadows, UV component and as result screening measures to reduce it.

In the following decades the scientific studies continued and a summary of vital points gathered from a variety of publications is given below [7] [9]:

- high moisture rate accelerates fading of natural coloring agents;
- color changes are not constant concerning speed; they are more marked with unexposed material than with material that has already suffered light-induced

TABLE II. Levels of intensity recommended and used for the illumination of pictures in museums^a

Lux			Footcandles			Reference
Low	Medium	High	Low	Medium	High	
50			5			<i>Burlington Mag.</i> , 57 (July 1930), p. 31.
40	180		4	18		<i>Museum</i> , 27-28 (1934), p. 193.
30	100		3	10		<i>ibid.</i> , 33-34 (1936), p. 185.
60	100		6	10		<i>ibid.</i> , 33-34 (1936), p. 191.
	110			11		<i>Museum</i> , 5 (1952), p. 28.
	120	300		12	30	L. S. Harrison [23].
	180			18		J. J. Balder [2].
80		250	8		25	<i>Lichttechnik</i> , 9 (1957), p. 547.
70		200	7		20	<i>Couleurs</i> , no. 20 (1957), p. 15.
80	150	300	8	15	30	<i>Museum News</i> , 38, no. 4 (1959), p. 26.
	180			18		<i>Museum Journal</i> , 59 (1959), p. 66.
50	150	300	5	15	30	G. Thomson [49].
	150	200		15	20	<i>Museum Journal</i> , 61 (1962), p. 259.

Figure 2 Recommended light levels and annual exposure [11]

a. For convenience, 10 lux is taken to equal 1 footcandle (1 lumen/square foot).

TABLE III. Approximate total annual exposure of objects, calculated in terms of a 10-hour day

Intensity		Approximate exposure	
Footcandles	Lux	Footcandle-hours/year	Lux-hours/year
5	53.5	18,300	195,000
15	160.5	55,000	585,000
30	321.0	110,000	1,170,000
59 ^a	631.3	215,000	2,304,000

a. Average annual value estimated for "galleries with sun louvres properly operated", L. S. Harrison [23].

damage;

- the yellowing and fading of the paper are both possible phenomena, depending on the temperature involved.

Since these insights, actions have been taken on board in museums with instructions for exhibition recommendations. The research of both Feller and Thomson led to the prescription of rules or "lux laws" and prohibitions on ultraviolet and infrared radiation. Concepts of risk management will only appear later parallel to a more in-depth investigation of the parameters of preventive conservation and the control of the museum environment as a unique system.

damage of exposure

Light is radiant energy, and exposure to both artificial and natural light gradually causes permanent damage to many museum objects. Indeed, most organic and many inorganic substances change with time and with light action, as can be appreciated in processes in nature. The absorbed energy of the exposed material can promote two distinctly different processes; radiant heating and photochemical reaction. In the first case, temperature rises at the surface of the exposed material as a consequence the surface of the object expands relatively to the body, causing surface cracking, lifting of surface layers, and loss of color. The symptoms of photochemical action can be similar, but the process is entirely different and often more severe: chemical change occurs when a molecule irreversibly changes its structure, this may include fading or darkening of colors, yellowing, loss of strength, fraying of fabrics, and even dramatic color changes of some pigments [10].

Photochemical reaction is triggered by photons traveling as steam by the radiant flux which includes ultraviolet (UV), visible and infrared (IR) wavebands. Their energy level is directly proportional to frequency and expressed as:

$$E = h\nu \quad (\text{Joule})$$

where h is Planck's number $h = 6,626 \times 10^{-34} \text{ Js}$, a number that relates units of frequency to energy and ν is frequency (hz) which is inversely proportional to wavelength λ so the equation could be expressed:

$$E = (h c) / \lambda$$

where c is the velocity of light in vacuum, showing that short wavelength luminous flux, i.e., blue light has higher photon energy making ultraviolet radiation, wavelengths under 400 nm, responsible for the reaction.

After the Second World War, the concerns of screening light destined to sensitive cultural assets were the subject of extensive investigations: in the USA the National Bureau of Standards (NBS), examined systematically light in a variety of wavelengths and scrutinized protection methodology. During the course of these tests, the *Relative Damage Factor* ($D\lambda$) was defined for the first time based on Harrison's computational method [11] with the intent to compare damage potential of alternative light sources and filter combinations. The factor could thereby be used to determine a Damage Index DI for incident radiation:

$$DI = F_{(dm,rel)} / F_{(v,rel)}$$

The relative damage flux is given by:

$$F_{dm,rel} = \int_{\lambda} \Phi(\lambda) T(\lambda) D(\lambda) d(\lambda)$$

where $\Phi(\lambda)$ is the spectral radiant power, $T(\lambda)$ spectral transmittance of the filter, $D(\lambda)$ is damage function and λ the wavelength and the relative luminous flux:

$$F_{v,rel} = \int_{\lambda} \Phi(\lambda) T(\lambda) V(\lambda) d(\lambda)$$

where $V(\lambda)$ is the spectral luminous efficiency of photopic vision.

Although Harrison's observations were interesting and other authors recognized the effectiveness of the index [8] [11], his proposal failed to gain the scientists' community acceptance. Later will be evidence that the index is a simple logarithmic function with a slope of -1,25 log $D(\lambda)$ units per 100 nm of wavelength [12].

Changes in color observed in materials illuminated by fluorescent tubes was examined in 1983 at the University of Applied Sciences in Berlin by the Institute of Lighting Technology. During the study the term 'relative spectral sensitivity' $s(\lambda)_{dm,rel}$ was introduced to define the response of a material to monochromatic light as a function of wavelength and made meaningfully interpreted the many insights gained from the study of artificial exposure [7] expressed by:

$$s(\lambda)_{dm,rel} = a(\lambda) \frac{1}{\lambda} f(\lambda)$$

where $a(\lambda)$ is the spectral absorptance and $f(\lambda)$ a function determined by the receiving material.

The principle of this model is that firstly energy has to be absorbed to cause damage; secondly, the photochemical response is related to the photon energy level which is proportional to the reciprocal of wavelength; and lastly, a function of wave-

length will be determined by the inherent properties of the material. For a given wavelength absorptance is described by:

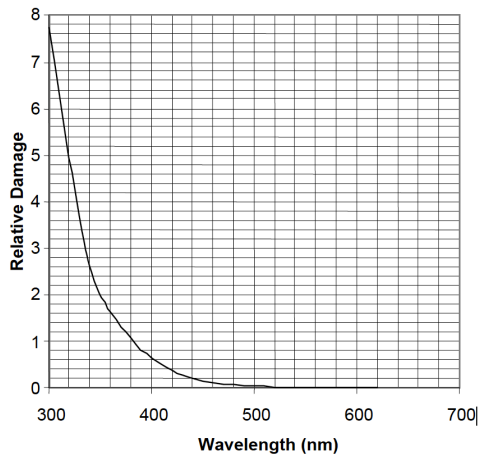
$$\alpha(\lambda) = 1 - [\rho(\lambda) + \tau(\lambda)]$$

where $\rho(\lambda)$ and $\tau(\lambda)$ are spectral reflectance and transmittance, respectively.

The deterioration studies of Feller [11] also involved the radiant heating effect when surface temperature rises above environment temperature due to absorption of incident radiant flux putting in evidence that the maximum attainable temperature of an irradiated object is defined as:

$$T_{max} = T_a + \frac{kAE_e}{h_c}$$

where T_a is ambient temperature, k is a proportionality constant A is the absorptance of the object E_e is irradiance in (W/m²) and h_c a coefficient of convention heat loss.



As described the rise of temperature on the surface of an object above ambient temperature is proportional to irradiance and independent of an object's thermal capacity, density or thickness. The effects may be of smaller evidence that those of photochemical damage but still relevant to dimension change and deformation with particular stress when materials of different coefficients of expansion are in contact. Moreover, relative humidity variations cause the migration of moisture. The result of heating cause hardening, discoloration,

and cracking. Damage is particularly likely in materials that are hygroscopic such as organic materials or where the surface clusters layers of dissimilar materials, such as varnish over pigment, or pigment over a substrate. IR radiant flux is apparently associated with incandescent lamps, even if their UV content is lower than for most other types of lighting.

Given the three distinct bands of radiation, light, ultraviolet, and infrared the signif-

Figure 3 Harrison's damage function $D(\lambda)$

icant general deterioration could be organized as follows [13]:

- Light fades: colors that fade can disappear even in some hours of direct daylight, or just a few years under low level of museum lighting. Among the materials that do not fade, some may last centuries in direct sunshine like Minoan frescoes. All colored objects fall somewhere between these two extremes.
- Ultraviolet causes yellowing, chalking, weakening, as also disintegration of materials. Chalking of paint media is often mistaken for pigment fading.
- Infrared heats the surface of objects, and thus becomes a form of incorrect temperature, with all the damage possibilities outlined.

Nonetheless, relating light exposure to damage led museum professionals to define reliable measures of damage and this way prevent deterioration.

metrics

Recommendations to reduce light damage of color fading by Ultraviolet (UV) radiation and potentially reduce or introduce daylight in galleries have been described in Blue Wool Scale that measures and calibrates the permanence of coloring dyes. Initially, Blue Wool cards were used by the textile industry and later adopted by the printing industry as a comparison to “lightfastness” quality of ink colorants. Described as lightfastness the chemical stability of the pigment or dye under prolonged exposure to light is primarily used today also in the polymer industry for measurement of pigment and color stability. The comparison takes place with two identical dye or pigment samples where one is placed in the dark, and the other is exposed to sunlight, or equivalent, for three months. The by comparison to the original color and the amount of fading is measured, and a rating between 0 and 8 is awarded. A score of eight #8 is supposed not to have been altered from the original and thus credited as being lightfast while zero #0 denotes extremely poor colorfastness.

<i>ASTM</i>	<i>Description</i>
<i>I</i>	<i>Excellent lightfastness. Blue wool #7-#8, unchanged pigment for more than 100 years</i>
<i>II</i>	<i>Very good lightfastness. Blue wool# 6, unchanged pigment for 50 to 100 years</i>
<i>III</i>	<i>Fair lightfastness (Impermanent). Blue wool #4-#5, unchanged pigment for 15 to 50 years</i>
<i>IV</i>	<i>Poor lightfastness (Fugitive). Blue wool #2-#3, the pigment begins to fade in 2 to 15 years</i>
<i>V</i>	<i>Very poor lightfastness (Fugitive). Blue wool #1, the pigment begins to fade in 2 years or less</i>

Table 1 ASTM lightfastness categories as described by Colby [14]

Described by Colby K. [14] for Montreal Museum of Fine Arts in 1991 a policy for fine arts that associates Blue Wool scale to fastness levels, from #1_fugitive to #8_extremely lightfast, designating the amount of light exposure required to produce a color change at each level and the approximate match between the eight blue wool and five ASTM lightfastness categories shown in Table 1. This table is a guide for the selection of artist paints though the relationship with exposure hours is a primarily accepted applied rule. Exposure to average indirect indoor lighting - 120 to 180 lux- for an average of 12 hours a day equals from 0.53 to 0.79 megalux hours each year.

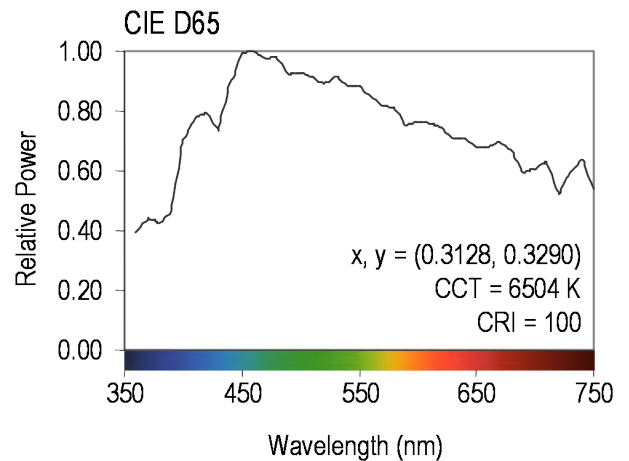
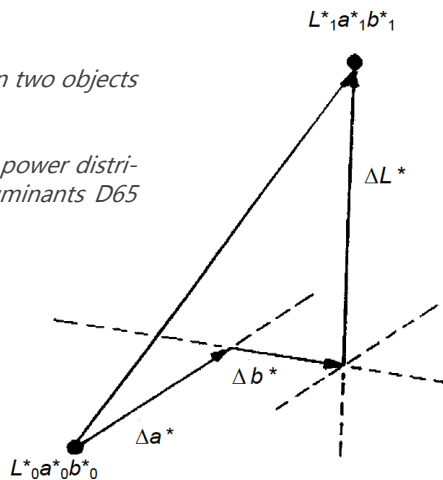
Another approach to convert Blue Wool rating scales into an estimated time of light exposure that will cause just noticeable fading is provided by the Canadian Conservation Institute - CCI, based on Michalski's report of 1987 [9] and shown in Table 2.

The exposure is considered for a daily period of eight hours, and the year for 3,000 hours. By this means "just noticeable fade" is given as a range based on the doses for the range of ISO Blue Wools in the same sensitivity category. The "almost total fade" is based on a conservative estimate of 30 per the "just noticeable fade," although fading often slows down, so that an estimate of 100 per, the just noticeable fade, is probable for many colors.

ISO Blue Wool numbers are the main route into the literature on colorant sensitivity; in museum lighting, though the categorization of typical materials by the "useful lifetime" gained wider acceptance and replaced the practice of assessing the light-sensitivity of objects by simple comparison to them.

Figure 4 Distance between two objects in CIELAB color space

Figure 5 Relative spectral power distributions (SPDs) of CIE illuminants D65 from 380 nm to 780 nm



Some materials still don't fade but show yellowing or become darker or change the hue. As to record these changes, modern testing uses color measurement instruments, such as colorimeters and spectrophotometers, that can detect differences indiscernible to the human eye and then instantly display these differences in numerical terms. With the definition, color difference is described the numerical comparison of a sample's color to the standard that indicates the differences in absolute color coordinates and is referred to as Delta (Δ). The color differences between sample and standard color are calculated using the resulting colorimetric values expressed by L*a*b* CIELAB values the most common color space color applied in cultural heritage according to CIE 15:2004 Colorimetry Report. It has been modeled over a color-opponent theory which stated that two colors could not be simultaneously red and green or yellow and blue.

The system defines a three-dimensional color space within which color characteristics of a material are specified concerning lightness dimension L*, and two chromatic dimensions a* is the red/green coordinate, and b* is the yellow/blue coordinate. To determine the total color difference between the three coordinates, the following formula is used:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

		<i>High-Sensitivity Blue Wool #1,#2,#3</i>	<i>Medium- Sensitivity Blue Wool #4,#5,#6</i>	<i>Low sensitivity Blue Wool #7,#8</i>
<i>Exposure Amount</i>	<i>Fade Amount</i>	<i>Time in years for fading</i>		
<i>50 lux</i>	<i>Just noticeable fade</i>	<i>1.5 – 20 years</i>	<i>20 – 700 years</i>	<i>300 – 7000 years</i>
	<i>Almost total fade</i>	<i>50 – 600 years</i>	<i>700 – 20,000 years</i>	<i>10,000 – 200,000 years</i>
<i>150 lux</i>	<i>Just noticeable fade</i>	<i>1/2 – 7years</i>	<i>7 – 200 years</i>	<i>100 – 2,000 years</i>
	<i>Almost total fade</i>	<i>15 – 200 years</i>	<i>200 – 7,000 years</i>	<i>3,000 – 70,000 years</i>
<i>500 lux office</i>	<i>Just noticeable fade</i>	<i>1/7 – 2 years</i>	<i>2 – 70 years</i>	<i>30 – 700 years</i>
	<i>Almost total fade</i>	<i>5 – 60 years</i>	<i>70 – 2,000 years</i>	<i>1,000 – 20,000 years</i>
<i>5,000 lux window or study lamp</i>	<i>Just noticeable fade</i>	<i>5 days – 2 months</i>	<i>2 months – 7</i>	<i>3 – 70 years</i>
	<i>Almost total fade</i>	<i>6 months – 6 years</i>	<i>7 – 200 years</i>	<i>100 – 2,000 years</i>
<i>30,000 lux av. daylight</i>	<i>Just noticeable fade</i>	<i>1 day – 2 weeks</i>	<i>2 weeks – 1 year</i>	<i>6 months – 10 years</i>
	<i>Almost total fade</i>	<i>1 month – 1 year</i>	<i>1 – 30 years</i>	<i>20 – 300 years</i>

Table 2 Blue Wool conversion by CCI [13]

Deltas for L^* (ΔL^*), a^* (Δa^*) and b^* (Δb^*) may be positive (+) or negative (-). The total difference, Delta E (ΔE^*), is, however, always positive.

$\Delta L^* = L^*1 - L^*0$, difference in lightness and darkness

$\Delta a^* = a^*1 - a^*0$, difference in red and green

$\Delta b^* = b^*1 - b^*0$, difference in yellow and blue

As to communicate the colorimetric data of material samples an illuminant has to be defined; to this scope in 1931 the International Commission on Illumination (CIE) standardized three illuminants: Illuminants A, B, and C, where illuminant A, CIE standard illuminant A2, was defined as a Planckian radiator of correlated color temperature 2848 K, later 2856 K, resembling the emission color of a tungsten filament source. Illuminant B was thought to represent direct sunlight, then abandoned, and illuminant C average daylight. A series of daylight illuminants were accepted in 1967 by CIE that suggested the use of one with an approximate correlated color

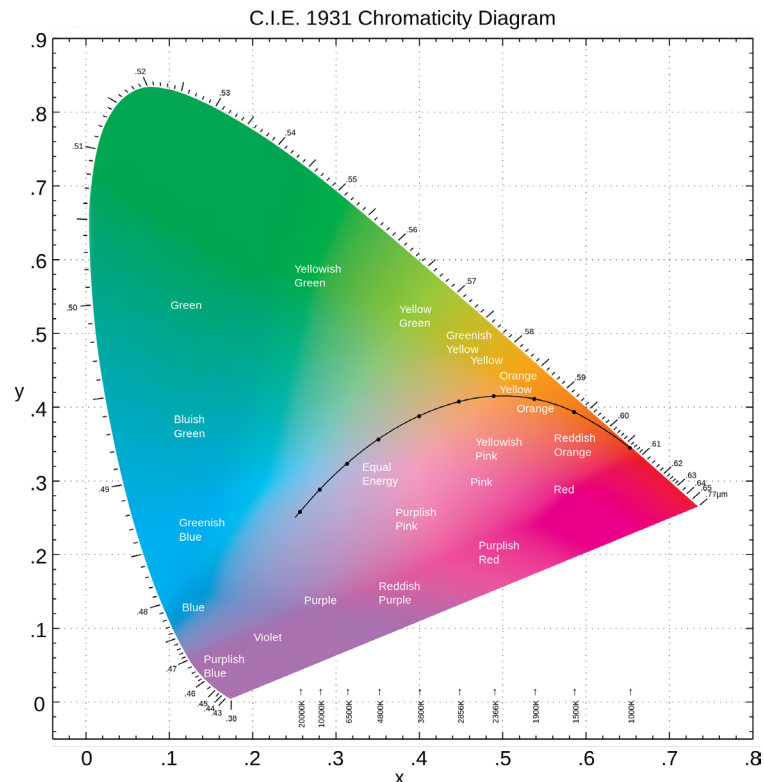
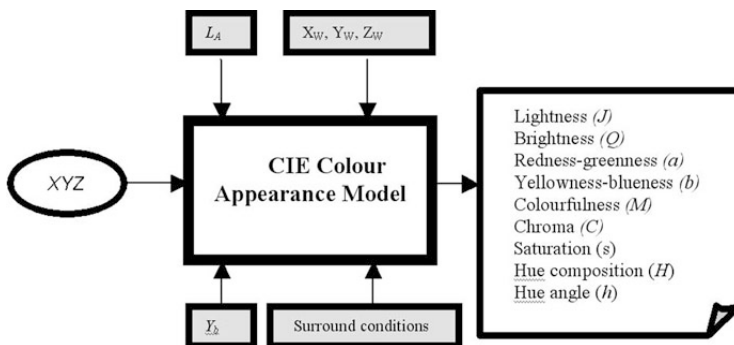


Figure 6 The output parameters from the model include Lightness (J), Brightness (Q), Redness–Greenness (a), Yellowness–Blueness (b), Colorfulness (M), Chroma (C), Saturation (s), Hue composition (H), and Hue angle (h).

temperature of 6504 K, CIE standard illuminant D65, as the most representative of the spectral power distribution (SPD) of daylight. The daylight illuminants were designed to resemble outdoor sunlight, and thus differed from illuminant C in the ultraviolet (UV) part of the spectrum considerably. Later investigations made by Gombos et al. [15] point the need of different standard illuminants for general colorimetric and graphic use though it represents the most common reference.

The definition of the CIELAB system has been of fundamental importance towards the exploration of progressive color change due to light exposure. Different color spaces have been used since but until the present worldwide literature is focused on CIELAB values. Nevertheless, some authors exploited the later model, CIECAM02 [16] for spectral distribution studies that have been shown to be a plausible model of neural activity in the primary visual cortex, compared to the earlier CIELAB model, and aims to model the human perception of color [17].

While the CIE system has been applied for over 70 years, its use is limited under only few viewing conditions, i.e., daylight illuminant, high luminance level, and some standardized viewing/illuminating geometries; industrial practice with small color differences have shown non-uniform effects with calculated values in different ranges and different directions in those spaces. Moreover, a change of external observing conditions may change the perceived magnitude of the color difference in a sample pair [18]. The CIEDE2000 total color difference formula corrects the non-uniformity of the CIELAB color space for small color differences under reference conditions; improvements have been made through corrections for the effects of lightness dependence, chroma dependence, hue dependence and hue-chroma interaction on perceived color difference.



In the decades between the 1970s–1980s a group of researchers investigated the previous work for National Bureau of Standards (NBS) and a broad range of light-sensitive materials have been used to reconfirm damage. The results evidenced damage per radiant unit of light exposure increased with a decrease in wavelength for photochemically stable materials, as rag paper, oil on canvas, textiles, and watercolors on rag paper, but to low-grade paper, the rate was much slower. Saunders and Kirby in the 1990s produce follow-up work to confirm again that shorter wavelengths are potentially more harmful than long wavelengths. They also observed that higher is the reflectance value less the damage since less radiant energy is absorbed in this region. The studies have been later elaborated and published by Cuttle in 1996 [19] and were finally embodied within the Commission Internationale de l'Éclairage (CIE)157 Report, Control of Damage to Museum Objects by Optical Radiation.

The CIE157 defined a model to evaluate damage due to optical radiation by determining the damage suffered by an object exposed to light DM as a function of the effective radiant exposure H_{dm} which is the effective irradiance over time E_{dm}

$$DM = f H_{dm} = f (E_{dm}, t)$$

Effective irradiance E_{dm} that causes damage to an object taking account of the spectrum of incident radiation and the relative spectral response of the receiving material is defined according to the formula:

$$E_{dm} = \int_{300}^{780} E_{e\lambda} s(\lambda)_{dm,rel} d\lambda. \quad (W / m^2)$$

		<u>Irradiance - Illuminance</u>
	<i>Direct - related to the irradiation of the light source</i>	<u>Exhibition Time</u>
<i>External</i>		<u>Spectral composition of the source</u>
	<i>Indirect</i>	<u>Relative Humidity</u>
		<u>Temperature</u>
		<u>Gases in the atmosphere</u>
		<u>Nature of the material</u>
<i>Internal or related to the artwork</i>		<u>Selective capacity to absorb energy</u>

Table 3 Deterioration factors in artwork objects

where $E_{e\lambda}$ is spectral irradiance and represents the amount of energy per wavelength emitted by a light source, $s_{dm,rel}(\lambda)$ the relative spectral sensitivity and $d\lambda$ the wavelength.

These factors may be used to define the threshold exposure or critical radiation time, defining the time after which starts the risk of visible damage:

$$t_s = \frac{H_{s, dm}}{E_{dm}} \quad (h)$$

where threshold radiation $H_{s, dm}$ describes the amount of radiation energy that must act on an object until a visible color change occurs $\Delta E^* = 1$.

The potential damage P_{dm} is the fixed proportion between effective irradiance E_{dm} and irradiance E valid for a material under a given lighting condition [7]:

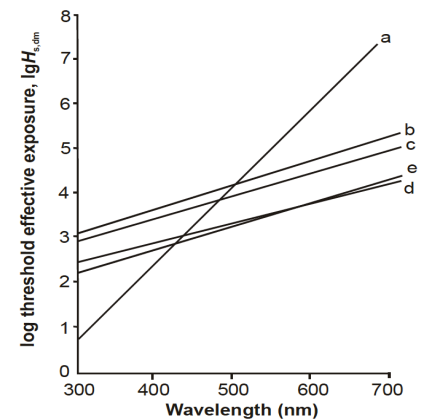
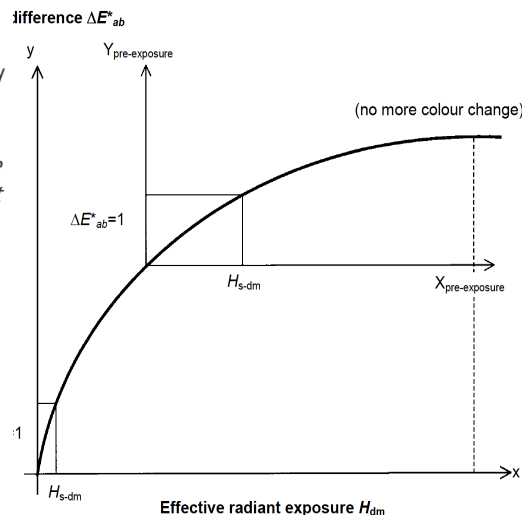
$$P_{dm} = \frac{E_{dm}}{E}$$

P_{dm} remains constant at different illuminance levels which makes it a factor well suited to describe the potential risk posed by a lighting source; higher value indicates more potential to damage.

In Figure 8 is plotted the basis of the Berlin model where the cause of damage is the effective radiant exposure, shown on the horizontal scale, and the effect is the

Figure 8 The cause of damage H_{dm} and the effect according to Berlin model.

Figure 9 The spectral distribution of the logarithm of threshold effective radiant exposure [19]



change of color, shown on the vertical scale. When the material is first exposed the curve is steep and the effect rapid, so that it requires only a relatively small level of $H_{s,dm}$ to cause one unit of ΔE^*ab to occur, but as damage continues the density of susceptible molecules reduces, so that greater exposure is required to produce the same visible effect. Eventually, the material stabilizes, and no more color change occurs [1].

The responsivity of any material is defined by its threshold effective radiant exposure $H_{s,dm}$ and its spectral responsivity $s(\lambda)_{dm,rel}$, which is decisive for the object's color and can be obtained via an exponential function. The normalized value of the function is 1 at a wavelength of 300 nm, as radiation below this wavelength limit very rarely occurs in museum lighting involving daylight or artificial light. The sequence of the function is described by material constant b, which determines a material's specific spectral absorptance shown in table 4 gives a summary of the material-dependent parameters for a variety of materials.

The values were based on investigations carried out at the Berlin Institute of Technology in 1983 by Aydinli. According to this model, $s(\lambda)$ can be expressed as:

$$s(\lambda) = \exp \left[-b (\lambda - \lambda_0) \right]$$

This function is normalized at a wavelength of $\lambda_0 = 300\text{nm}$; sample materials have been classified in five categories and values of $H_{s,dm}$, and b are given in table 4 showing the exposure required to cause a just noticeable color change for an incident monochromatic radiation of 300 nm. The action spectrum is the response of the material to each wavelength of light, which indicates the wavelength dependence of degradation; exposure under other wavelengths and the respectively threshold required exposures are plotted in logarithmic scale in Figure 9.

<i>Group</i>	<i>Material</i>	<i>H_{s,dm}</i> <i>[Wh/m²]</i>	<i>Material</i> <i>constant b</i>
a	<i>Low-grade paper</i>	5	0.038
b	<i>Rag paper</i>	1200	0.0125
c	<i>Oil paint on canvas</i>	850	0.0115
d	<i>Textiles</i>	290	0.0100
e	<i>Water colors on rag paper</i>	175	0.0115

Table 4 threshold effective radiant exposure $H_{s,dm}$ and b values for the relative spectral responsivity function for five categories of museum materials

control of damage

Moreover, the CIE report produced a classification of deteriorating factors in museums, shown in Table 3, among them, a first group can be divided into direct and indirect factors. Direct factors are irradiance and spectral composition of the light source and the overall exposure time of it meanwhile as indirect factors are considered the relative humidity, temperature and the number of gases in the atmosphere. Among the second group, it can be included: the nature of the material and its selective capacity to absorb energy, i.e. the spectral responsivity. The overall tendency of spectral responsivity to increase in shorter wavelengths is documented and an association of relative damage potential and the correlated color temperature of the source has been investigated by Cuttle [12].

In the following table 5 a summary of values of the relative potential damage ranging from 3000°K to 6000°K representing various full spectrum light sources. As to simplify the comparison, values were normalized based on an assignment of a value of 1.0 for Standard illuminant A (2856°K) and all wavelengths below 400 nm were excluded.

Another issue mentioned relative to the source, and the damage potential of the museum light sources is their spectral power distribution. Continues spectra sources and a high color index, efficiently responded by an incandescent lamp, has been traditionally employed by curators, but already in 2004, the CIE report states the implications of reduced damage by LED “tuned spectrum” where the Ra should not be relied upon to compare “good” sources. The experimental study of Cuttle tested the hypothesis that an art object illuminated by a light source comprising three narrow wavebands of light can match the level of viewing satisfaction given by a conventional tungsten halogen display lamp providing the same illuminance [20].

According to the normative, materials of cultural property are grouped into four classes of responsivity to luminous exposure and the relationship with ISO rating based in Blue Wool Standard is previously seen in Table 6. The indications to relate pigments to ISO rating and referenced estimation of probable fading are based on the observations of Michalski [9]. Likewise, two different UV-dosage categories are classified: one is 'UV rich' referring to a spectrum similar to daylight through glass; this spectrum is generally used for the lightfastness data as to derive the light responsivity of a colorant. The other 'no UV' means a UV-blocked light source. Estimates indicate a minor benefit of a UV-blocked light source for high responsivity colorants but substantial improvements for low responsivity colorants [21]. For each class, a limit in the cumulative annual luminous exposure ALE, measured in lux-hours per year, i.e. lx h a-1 has been established [22]. This threshold is calculated as a product of the allowed instantaneous illuminance level (measured in lux, i.e., lx) and the total annual exposure time AET, measured in hours per year, i.e., h a-1. As the cumulative effect is the main factor, ALE should be respected, while it is possible to increase illuminance level if the AET is adequately reduced, leaving unchanged their product. Material responsivity classes are as follows:

1. Irresponsive, e.g., most metals, stone, most glass, ceramic, enamel, most minerals;
2. Low responsivity, e.g., most oil and tempera painting, fresco, undyed leather and wood, horn, bone, ivory, lacquer and some plastics;
3. Medium responsivity, e.g., most textiles, watercolors, pastels, prints and drawings, manuscripts, miniatures, paintings in distemper media, wallpaper

<i>Color Temperature of a Planckian source</i>	<i>Relative Damage Potential</i>	<i>D series source</i>	<i>Relative Damage Potential</i>
2500 K	0.92	D55	1,63
3000 K	1.04	D65	1,87
3500 K	1,20	D75	2,07
4000 K	1.37		
5000 K	1.71		
6000 K	2.01		

Table 5 Damage Potential relative to CIE Standard illuminant A (2856 K) where $b=0,0115$ for a Plankian source and three D series sources [1]

and most natural history objects, including botanical specimens, fur;

4. High responsivity, e.g., silk, highly fugitive colorants, most graphic art, and photographic documents.

The “Mlx h for noticeable fade” data given in Table 6 indicates the illuminance related to the light-fastness category of the most susceptible pigment present. As an example consider a medium responsivity material with an ISO rating of 5 permanently on display (3000 hours per year), where the illuminance is 50 lux and UV is eliminated. The annual exposure would be therefore calculated as 3000 hours x 50 lux = 150 kilolux hours/year. In, indicates that after 30 megalux hours of exposure a noticeable fading will occur approximately after $30000/150 = 200$ years of display. Another example assuming a highly responsive material with an ISO 2 rating placed in the same display situation. Probable fading will occur after one megalux hour of exposure approximately after $1000/150 = 6,7$ years. That has been the reason that a “highly responsive” category has been included, and it is recommended that materials in this category are not placed on permanent display [1].

The report refers to a series of acknowledgments for museum lighting installations such as control of environmental conditions, classify zones for locating highly responsive objects, protect from both IR and UV radiation, recommendations on electronic flash usage, spectrum choice and correlated temperature of the sources and lastly as the most practical to measure exposure rate illuminance levels.

Lighting level of 200 lx is generally sufficient to provide adequate visibility and satisfy exhibition needs. When illuminance below 200 lx is required, visibility of the exhibit can be enhanced by lighting the background to a lower level; therefore visual adaptation will reduce making the exhibition the brightest part of the field of view the ratio 3:1 has been suggested by Loe et al. [23] for object illuminance to background illuminance.

	<i>High responsivity</i>			<i>Medium responsivity</i>			<i>Low responsivity</i>			<i>Irresponsive</i>
<i>ASTM</i>	<i>V</i>	<i>IV</i>		<i>III</i>		<i>II</i>	<i>I</i>			
<i>ISO Blue Wool Category</i>	<i>#1</i>	<i>#2</i>	<i>#3</i>	<i>#4</i>	<i>#5</i>	<i>#6</i>	<i>#7</i>	<i>#8</i>	<i>>#8</i>	-
<i>Mlx h for noticeable fade UV rich</i>	<i>0.22</i>	<i>0.6</i>	<i>1.5</i>	<i>3.5</i>	<i>8</i>	<i>20</i>	<i>50</i>	<i>120</i>	-	-
<i>Probable Mlx h for noticeable fade if no UV</i>	<i>0.3</i>	<i>1</i>	<i>3</i>	<i>10</i>	<i>30</i>	<i>100</i>	<i>300</i>	<i>1000</i>	-	-

Table 6 Relationship of sensitivity categories, ASTM, Blue Wool and recommended annual exposure [13, 1]

Satisfactory viewing could be achieved for medium responsivity material with less than 50 lx if the object is colored lightly and with no fine detail yet the limiting illuminance should never be quoted as the justification for unsatisfactory display. It is not considered good policy to display an object, that inevitably will suffer some damage, and to fail to present it adequately. If an illuminance greater than 50 lx is found to be necessary to provide accurate appearance, even in the case light-sensitive objects, the duration of the display should be restricted to comply with the limiting exposure value according to Table 7 result of extended research on the recommendations expressed by various authorities.

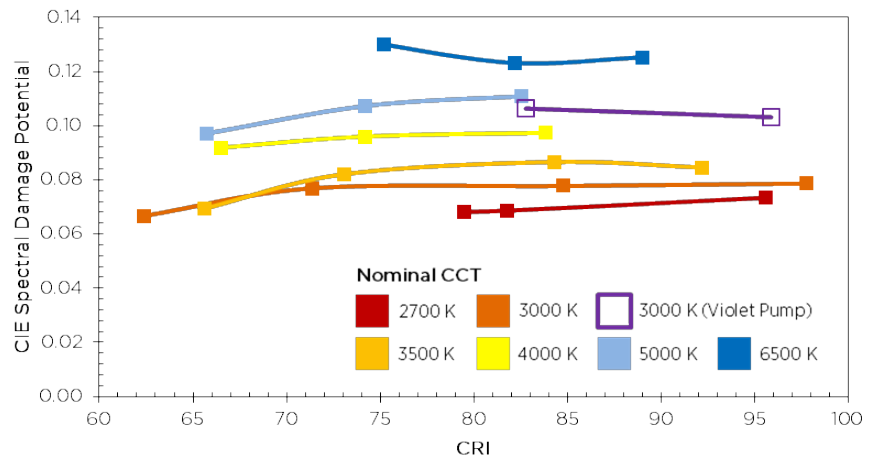
	1	2	3	4
	<i>Irresponsive</i>	<i>Low responsivity</i>	<i>Medium responsivity</i>	<i>High responsivity</i>
<i>ALE</i>	-	<i>600,000 lx h a-1</i>	<i>150,000 lx h a-1</i>	<i>15,000 lx h a-1</i>
<i>illuminance</i>	-	<i>200lx</i>	<i>50lx</i>	<i>50lx</i>
<i>AET</i>	-	<i>3000 h a-1</i>	<i>3000 h a-1</i>	<i>1300 h a-1</i>

Table 7 Limiting illuminance (lux) and limiting annual exposure (lux hours per year) [1]

Ongoing research

As previously described, see Table 3, the latest parameters to control damage are related to the plurality of materials a factor that historically made spectral responsivity a rarely used parameter to define risk of damage. Nonetheless to give insight to a proper museum lighting given the difficulty to determine it in the whole of an exposition; optimization of the spectrum as well. Control of damage and the conservation status of cultural heritage, especially in the case of paintings could though be evaluated by spectral reflectance. Indeed, spectral data are useful for pigment identification, especially when a database of frequently used pigments is available. The data are then used for physical characterization, forensic work, lighting purposes, and others. Even in areas where colors appear similar to the naked eye, the spectral curves can show differences because metameric effects can occur [24].

Figure 10 CIE spectral damage potential (S_{df}) versus CRI [28]



Currently, multispectral analysis of each specimen is becoming a standard technique by image mapping proposing new insights to illumination degrade. Compared to colorimetric imaging, multispectral imaging has the advantage of retrieving the spectral reflectance factor of each pixel of a painting; with this information, the spectrum becomes decomposed into its original pigments and their relative contributions. The output of pigment mapping is a collection of spatial concentration maps of the pigments classified in the painting [25]. Such an approach could evidence useful information to design customized lighting systems based on specific damage analyses and optimization of the spectral distribution, a case that with LED technology becomes somewhat simplified when a multispectral mapping is applied.

New technology is, in this regard, challenging and different authors have been exploring the effectiveness of CIE report with discontinuous spectral sources as LED, which initially were not investigated; the previous work underlined the overall impact of color temperature on damage, rather than the damage potential of each light sources. Likewise, general conservation aspects should be implemented; Weintraub [26] evaluates the need of new metrics using risk assessment tools for the use of LED in light-sensitive collections based on the phenomenon of "hole-burning" that isolated LED out peaks could, therefore, accelerate damage yet verifies CIE method.

Perrin et al. [27] have supported evaluations and demonstrations of high-performance solid-state lighting for the U.S. Department of Energy Gateway program evidencing that blue-pumped LEDs are the least likely to cause material degradation at any given correlated color temperature. As seen in Figure 10 & 11, there is a linear correlation between damage potential and CCT; the plot is normalized for equal light intensities. However, standard blue-pump LEDs have the lowest damage potential at a given CCT compared to unfiltered incandescent and halogen sources their radiation has been approximated by blackbody radiation. Even violet-pump LEDs pose a lower risk than a typical incandescent or halogen lamp [28].

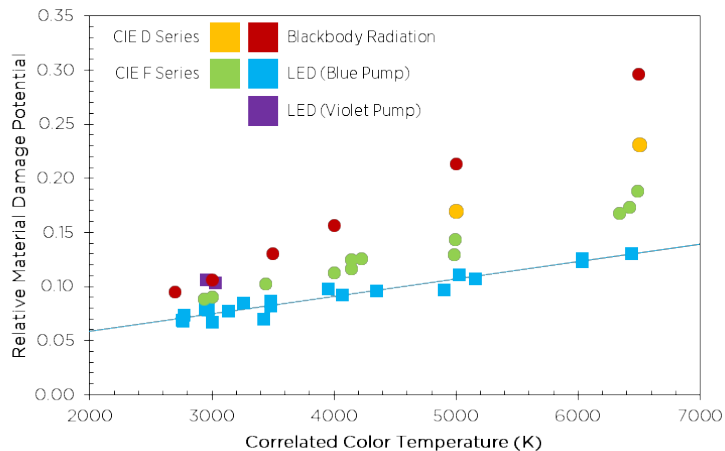
Piccablotto et al. [29] expressed doubts on the use of Blue Wool swatches as light dosimeter since faded slower under LED with a high correlated color temperature (CCT) and faster under halogen lamp: the use of CCT as an adequate predictor of material degradation is not consistent with LED. Moreover, the results indicate that

typically, white LEDs are less damaging than traditional lamps. Luo et al. [21] explore the damage to photographic material and confirm that white LEDs are safer than conventional light sources and the fading model could be satisfactorily used and provide a revised light dosage classification for photographs under tunable multi-LED source.

A worth to mention lighting project has been developed by Muñoz et al. [30] in El Castillo Cave in Spain, with the aim of minimizing the power consumption and the necessary equipment inside the cave; the critical problem with light inside the cave is the biological effect of this radiation, which makes the growth of fungus or algae possible. A spectral radiant distribution of blackbody radiator at $T_t = 1850$ K was considered the best as is approximately the temperature of the torch which was the lighting source used by the artists. An optimization study has been performed to define the spectral distribution of a tunable LED RGB source with a low value of damage effective irradiance. Meanwhile, a biological test was conducted to evaluate whether this irradiance level stops the growth of biological agents such as fungus or algae that can cause deterioration and degradation during a period of one year for 24 h a day. An illuminance of 40 lx has been given onto the rock inside the cave in a place with environmental parameters (temperature and relative humidity) similar to those of the panels. Among the authors, observations have evidenced that standard sources do not provide enough design parameters to optimize both the perception and conservation of the rock-paintings.

A recent investigation proposed by Farke et al. [7] over the effect of light by different light sources concluded that among low voltage halogen lamps, metal halide lamps, or LED lamps all evidenced a mixed picture, with no clear-cut advantage

Figure 11 CIE spectral damage potential (S_{df}) versus CCT [28]



for any of the light sources. A result that is somewhat surprising: according to the CIE 157 LED source should have been the least harmful. The research has been held considering doses as hour exposition to light: an interesting insight of the author's critics issue of 'acceptability levels of light damage' and that shouldn't be addressed through instrumental studies alone, ignoring interaction between visitor, lighting, and exhibition.

The damage curves described in the CIE report provide the universal method for evaluating relative damage based on the spectral distribution of any light source. Because the probable rate of damage per wavelength is based on results from a broad range of materials, it avoids the inevitable problem of making assumptions about damage based on unique photochemical sensitivity of a particular substance. The values provide the most useful means for calculating wavelength specific damage since they consider the higher damage potential of shorter wavelengths. Szabò et al. in their publication regarding Sistine Chapel new lighting installation in 2012 concluded that preservation request could be reached by LED technology for pictures, especially frescos, much better rather than the presently available artificial light sources, and far safer than natural daylight under the same illumination levels [31].

For risk assessment and potential damage, the predominant limitation provided by LED technology is actually a less "mature" source. The technique applicated to predict their potential change in pigment appearance according to its lux-hours of light by microfading, i.e. bombarding a material with high illuminance, over a known period could be highly inaccurate [27] in comparison to real performance museum light levels of controlled exposure to 50 lux. Hence, research will continue on different materials and results will have to be integrated with data of the effective stress.

LED performance on Art Energy-saving

The international request for energy saving is implementing the development of technologies that guarantee sustainability, bringing to the forefront critical points such as energy consumption from lighting. The recent monitoring of the European Commission's GreenLight program, which promotes the adoption of technologies for efficient light energy in non-residential areas, shows a progressive saving of 50%, with an emphasis on the improvement of the lighting environment from an economic point of view thus energy and the quality of light. Under the general heading of these percentages for lighting and public buildings, the problem of energy requalification of Cultural Heritage is hidden, where light and lighting engineering play a vital role.

In the report of Druzik et al. [27] the example of the relamping of J. Paul Getty Museum is described, a large project with three galleries, where Sylvania 60W PAR38 30° flood lamps have been replaced with Cree 12W LED PAR38 2700K (LRP-38) sources. Gallery operating hours per year data allows calculating kWh savings and converting that to annual carbon footprint reduction based on published tables of summary records. In Table 1 are shown calculations based upon some institutions provided by the American Association of Museums, Canadian Heritage, Network of European Museums, and International Council of Museums for the average annual emissions in greenhouse gases and the life-cycle reduction on a 10-year base. Likewise, the benefits of the adoption of LED technology is of large significance in other economic aspects as their long life-time will reduce the maintenance costs, their increasing output and their easy integration to control systems that offer comfort, adaptability and therefore more energy reduce. Yet upgrading lighting systems can offer both opportunities and potential drawbacks; this recent change has risen the interest of research, as previously seen, on their non-visual effects i.e the potential damage on artworks, as well as, the visual aspects.

Type	Base Case	Alternative	Reduction	Life-Cycle reduction 10 years
J. Paul Getty Museum				
CO ₂	1,422.5	241.8	1,180.7	11,805.2
SO ₂	0.35	0.06	0.29	2.91
NO _x	0.58	0.10	0.49	4.85
		<i>North America</i>		
CO ₂	28,837,095	4,904,130	23,932,965	239,228,325
SO ₂	7,092	1,216	5,877	58,971
NO _x	11,753	2,027	9,930	98,285
<i>Europe</i>				
CO ₂	21,345,000	3,630,000	17,715,000	177,075,000
SO ₂	5,250	900	4,350	43,650
NO _x	8,700	1,500	7,350	72,750
North America + Europe				
CO ₂	50,182,095	8,534,130	41,647,965	416,303,325
SO ₂	12,342	2,116	10,227	102,621
NO _x	20,454	3,527	17,280	171,035
<i>World</i>				
CO ₂	78,265,000	13,310,000	64,955,000	649,275,000
SO ₂	19,250	3,300	15,950	160,050
NO _x	31,900	5,500	26,950	266,750

Table 1 Greenhouse Gas Emission Reduction Summary Units in kilograms of emissions [27]

Visual aspects

The human vision is not uniform; responses to stimulation of the central part of the visual field are different from those of the periphery and the system will tend to adapt to brightness and color of the prevalent illumination, the most significant in the first 60 sec after the exposure, a phenomenon called adaptation. The required time to adapt to a change in retinal illumination depends on the change level, involving photoreceptors, the direction, the transition time and the visitor's age [32]; if the change in luminance is in the range of 100:1 adaptation occurs within 1 second. When changes in retinal illuminance are substantial (luminance range greater than 1000:1), photochemical adaptation is required, to this, the direction of change is since changes to a higher retinal illuminance occur faster than changes to a lower one. When only cone photoreceptors are involved, a few minutes is sufficient for adaptation to happen, while transitions from cone photoreceptor operation to rod photoreceptor operation may take tens of minutes; older people may take longer to adapt and achieve a less complete adaptation.

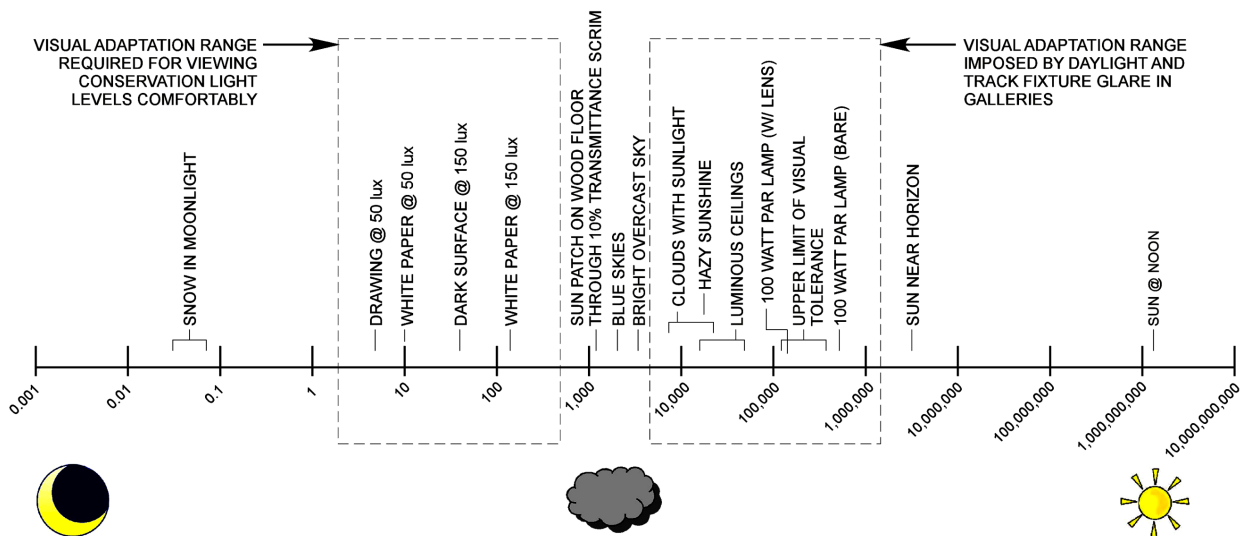
Thus, moving in the museum environment is an experience of a series of adaptation changes through photopic, mesopic and dark-adapted scotopic function along with change on the sensitivity of the spectrum [33]. In Figure 12 the naturally occurring luminance rates are plotted in logarithmic scale, the human visual system makes as able to navigate the twelve orders of magnitude between moonless night sky noon sun. However, the observer can only comfortably view an adapted range of two to three orders of magnitude.

Similarly, color temperature difference will affect the adaptation of color vision and the various types of cones activated; this influences the impression and defines color-constancy, a feature of the human color perception system; the perceived

color of objects remains relatively constant under varying illumination conditions. Correlated Color Temperature (CCT) is defined as the temperature of the Planckian radiator having the chromaticity nearest the one associated with the Spectral Power Distribution (SPD) of the light source and describes the appearance of illumination along a red-white to blueish-white dimension, different color spaces are used for this evaluation.

Traditionally this sector of research, based on empirical experiments, has been occupied to define a pleasant room illumination or to improve performance in workspaces: the Kruthof curves. Moreover, these studies have provided the canonical set of data for museum settings. First presented in 1941 the graph that plots preferred combinations of illuminance and CCT for interior lighting conditions; the chart shows lower and upper illuminance thresholds for a range of CCTs that bound the region of pleasing illumination. He supposed that beneath the lower boundary, lighting is judged as dim at low CCT or cold at high CCT, whereas above the upper threshold, color reproduction is unpleasant and unnatural. However, the basis of his curve has not been validated; there are several insufficient pieces of evidence to support the proposed combinations even if is “probably the most reproduced diagram in the history of lighting” [34, 35, 35].

Figure 12 Luminance range encountered in nature and the museum setting candelas/m² (logarithmic scale) [55]



The most extensive study on Kruthof curve and the later experiments over his theory have been validated with CIE recommended best practice by Fotios [36] after review of experimental design and reporting, to provide credible evidence, tend to reject the proposed relationship. Some awareness though has been suggested concluding that: a. Variation in CCT has a minor effect on ratings of brightness and pleasantness; b. Low illuminances (less than 300 lux) may be perceived as unpleasant, an illuminance of 500 lux is sufficient to provide a pleasant environment and a further increase in illuminance above 500 lux is of little benefit; c. Higher illuminances are perceived to be brighter, and this effect appears to be stronger than for other relationships.

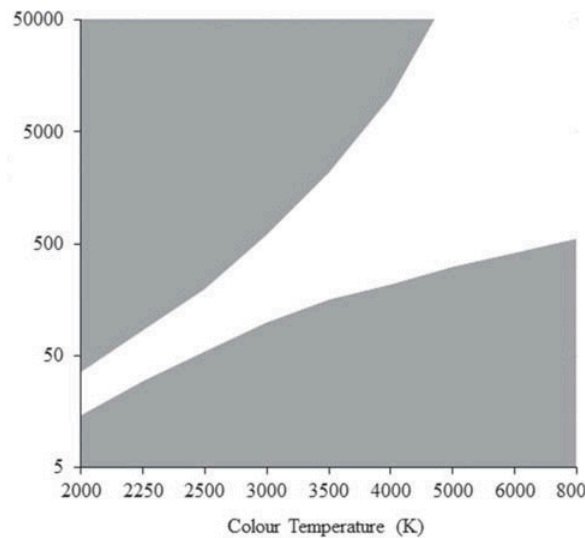


Figure 13 The Kruthof graph 1941

There are instead few relevant researches that consider the limitations imposed by the human visual system when viewing artworks; an overview of the literature though made by Zhai et al. [37] showed some empirical studies and investigated the principal visual perceptions and the LED parameters for viewing museum paintings. Different LED illuminants were evaluated to light oil and gouache paintings where 'visibility' and 'warmth' raised as the main perceptions for viewing paintings. Results evidenced that a CCT around 3500 K, a color on

the purple side of the blackbody locus and high color rendering index can achieve 'visibility' factor.

The first direct tests and quantitative verifications of viewers preferences simulating a museum environment have been conducted by Scuello et al. [33], and the results confirm that Kruthof curves have not been verified. A CCT of 3600 K is the preferable still temperatures of approximate daylight (5500-6500) K are also acceptable. Sedwick and Shaw in the 2000 London Conference on Daylight design and Research [38] consider that during daytime lights used to compensate and balance daylight need to match the colder CCT of it meanwhile excluding it from night time

that such temperatures could reveal harsh for visual experience. Commonly, warm temperatures as the ones of tungsten halogen ~3000 K in predominantly daylight galleries, 4000-6500 K at overcast sky, and up to 30000 K under clear sky, create noticeable warm pools of light.

Zhai et al. [39] conducted an experiment with twenty-four observers, and the method of categorical judgment was used with fourteen word-pairs of visual perception to evaluate each painting under different lighting conditions. An increase of illuminance from 50 lux to 200 lux has an immediate raise of the rating yet tend to show a smaller increase at 800 lux; exceptions for the Soft/Hard and Artistic/Business perception. CCT had a negative correlation to all the scales except contrast, brightness and clearness perceptions. Factor analysis revealed that there are three dominating visual factors: Comfort, Vividness, and Definition. These three determine the quality of LED lighting for observing fine art paintings. Based on the results they consider that a CCT in the range 2850– 4000K and a moderate illuminance level of 200–800 lux is deemed to be comfortable or pleasing for LED lighting of paintings in museums.

Traditional empirical studies have explored the appreciation of paintings under different CCT; Nascimento et al. [40] found that the average CCT preferred for real and monitor viewing conditions were very similar, 5500 and 5700 K, respectively is higher than typically used in museums, and the viewing conditions, real or simulated, have only a minor effect. Feltrin et al. [41] explored that the predominant hue of the paintings has no impact on the preferred CCT meanwhile warm and cold lighting arrangements were the least appreciated. A CCT of 4000 K was the favorite and rating results for a pleasant background lightness - black, grey and white – don't evidence essential differences.

Szabò and Schanda [16] express the opinion that in picture galleries the perceived hues of the pictures seen under artificial illumination should be similar to the perceived hues under natural daylight, since artists painted and presented their artwork during day under sunlight for centuries; has been the introduction of incandescent light in galleries to change dramatically color appearance. Shanda's approach for a full spectrum light could give an overall answer as the most complete wherever colors need to be differentiated and so their reproduction, as close as to daylight hues. Many different SPDs share the same CCT, so specification of CCT alone does not represent precise SPD; different authors have explored the tailoring of SPD with LED technology.

Findings of Chakrabarti et al. [42] developing a suitable SPD system for golden items in display cases notice that color properties as chroma and hue converge in

increasing color temperature.

Fotios and others [36] consider that as a sole metric CCT fails to predict the perceived brightness of a scene and provides an insufficient definition of the spectrum, however, such statement is correct when attempting to define any visual perception with a single metric. His proposal consists of an improvement, defining two metrics as spatial brightness and color rendition of illuminated objects. Other authors report a range of spectrum-based metrics CCT, Ra, R9, Qa, Qg, Qf, Duv, and x–y chromaticity, yet color rendering for museum installations is relevant to color fidelity, and different metrics have been proposed and used to this end.

Color Quality Metrics

The human response in light is vision, and spectral luminous efficacy is the unique physical quantity in the international system of weights and measures that is derived from human capabilities. Nonetheless, judgments of white light since based on an average over the relevant photoreceptors though is not accurate in predicting brightness judgments of colored light, which require specific information about stimulation of individual photoreceptors [43]. Based on the photopic weighting function, V_l , the maximum luminous efficacy of 683 lm/W could be reached if power is at a wavelength of 555 nm. However, a monochromatic single-wavelength light similar to that from low-pressure sodium lamp generates no color information; to perceive the natural color appearance of the objects the light sources should deliver radiant energy across the visible spectrum.

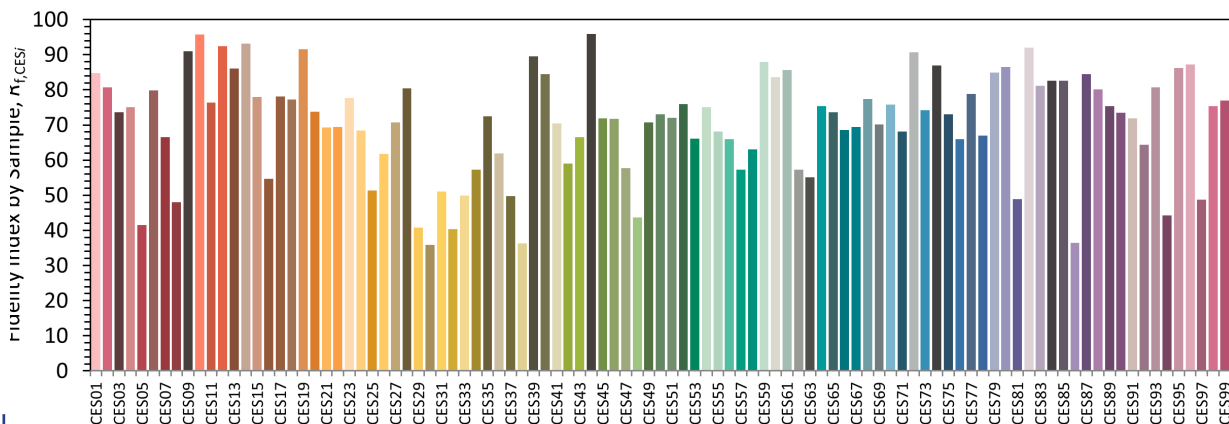
The predominant use of CIE general color rendering index R_a (CRI) and the broad acceptance that features an adequate measure of color fidelity for the last 50 years has set as a goal a high score for the sources used in galleries. Nonetheless, CRI is only a measure of how similarly a light source renders colors in comparison to a reference source at the same CCT, either blackbody radiation or daylight. Its limitations and deficiencies have been furthermore evidenced with the advent of solid-state lighting whereby the R_a values do not always correspond to the visual evaluation by general users [45]. The CRI penalizes lamps for hue, chromatic saturation, and lightness shifts of the reflective samples between reference and test sources [46]. Both inaccuracies of the CRI and perception-related color quality effects beyond color fidelity have been revised by CIE report 224:2017 Colour Fidelity Index for Accurate Scientific Use following the method previously evolved by the Illuminating Engineering Society (IES) TM-30-15: IES Method for Evaluating Light

Source Color Rendition that has been recently adopted by CIE.

The notable improvements of the measure are the update of the color difference calculation and the incorporation of 99 CES test-color samples, as shown in Figure 14, which provide a more uniform distribution as a function of wavelength and which have color appearance values that are distributed in the three dimensions of a uniform color space [47]. Samples have been statistically selected from a library of approximately 105,000 spectral reflectance function measurements for real objects. The IES TM-30-15 method utilizes the CAM02-UCS (uniform color space), which offers substantially better uniformity than the CIE $U^*V^*W^*$ color space initially used to define Ra. The improved uniformity allows more accurate calculations of color differences as well as a reduction in undesirable CCT-related effects [44]. A similar index to the original color rendering index, Ra, color fidelity index, Rf, has been defined that combines in a single value the computed color differences for all test-color samples and represents how color appearance of the entire sample set are on average reproduced by a test light compared to those under a reference illuminant. Nevertheless, CIE recommends that the index does not imply the replacement of the CRI along with the development of a harmonized set of new color quality metrics to evaluate further perception-related effects.

The measures proposed by IES TM-30-18 [48] seen in Table 9 offer insight on what will be the future of color quality metrics since the CRI and new design criteria shall, therefore, emerge as the target values of the metrics for given applications. Csuti et al. [49] described the optimization of the SPD of LED technology for picture gallery illumination, based on a metric described by Davis et al. [46]. The Color Quality Scale (CQS) metric had already adjusted the non-uniformity of CIE color space to CIECAM02-UCS; Uniform Color Space extension includes an improved chromatic

Figure 14 The sample fidelity scores (Rf, CESi) plotted together in hue order create a "signature" for the source that indicates the consistency of color rendition [44]



adaptation transformation and so more effective calculations when the test source is over the blackbody locus and englobed parameters as saturation and chromaticity. The target of Schanda as seen previously was to minimize color distortion of mixed LED lighting of 3500 K to D65 daylight.

<i>Measure</i>	<i>Abbreviation</i>	<i>Description</i>
<i>Fidelity Index</i>	<i>R_f</i>	<i>Analogous to CIE Ra (CRI). Describes the average color shift of the 99 CES to define the overall level of resemblance between the test source and the reference illuminant. Values range from 0 to 100.</i>
<i>Gamut Index</i>	<i>R_g</i>	<i>Compares the area enclosed by the average chromaticity coordinates in each of 16 hue bins to define an average saturation level of the test source compared to the reference illuminant. A neutral score is 100, with values higher than 100 indicating an increase in saturation and values less than 100 indicating a decrease in saturation. The range in values grows as fidelity decreases.</i>
<i>Color Vector Graphic</i>		<i>Provides a visual representation of hue and saturation changes based on the average rendering in each hue bin, relative to the reference. The graphic provides a quick understanding of how different hues are rendered in different ways.</i>
<i>Color Saturation Graphic</i>		<i>Provides a simplified visual representation of only saturation changes based on the average performance in each hue bin.</i>
<i>Hue Fidelity Indices</i>	<i>R_f, h_j (j = 1 to 16)</i>	<i>Provides a numerical characterization of color fidelity in each of 16 hue bins (j), which can be used to evaluate how similarly the test source renders reds, yellows, greens, blues, or in-between hues compared to the reference. Values range from 0 to 100. Specific values may be used to supplement average values if one hue type is of particular concern. Specifying limits for all values is also possible. These scores are analogous to the specific indices of the CRI system (e.g., R_g), but are more robust because they combine several samples with different spectral features.</i>
<i>Chroma Change by Hue Indices</i>	<i>R_g, h_j (j = 1 to 16)</i>	<i>Provides numerical values for relative chroma change in each of 16 hue bins (j), which can be used to evaluate saturation (positive values) or desaturation (negative values) of reds, yellows, greens, blues, and in-between hues compared to the reference. Supplementary criteria could be set for all values, or just specific values, such as red (bin 1).</i>
<i>Skin Fidelity Index</i>	<i>R_{f,skin}</i>	<i>Characterizes the similarity of skin tones (CES₁₅ and CES₁₈) as rendered by the test source compared to the reference source. Values range from 0 to 100. R_{f,skin} can be used to supplement other values when skin is an important consideration.</i>
<i>Sample Fidelity Indices</i>	<i>R_f, CES_i (i = 1 to 99)</i>	<i>Characterizes the similarity of each CES (i) as rendered by the test source compared to the reference source. Values range from 0 to 100. Individual values may have little predictive power for other objects, but examining the scores in a combined chart can indicate the source's object-to-object consistency.</i>

Table 9 Description and use of the measures described in IES TM-30-18

Towards 'dynamic' guidelines

Light damage needed to be managed and could not be avoided entirely, but it was only recently that concepts of risk management have been introduced and showed that rules could be stretched, or violated, for a reasonable need as long as proper monitoring and documentation is maintained to ensure that long-term exposure is controlled [4]. In this case, risk assessment includes balancing "situation-specific resolutions" as proposed by Stefan Michalski during AIC's -American Institute for Conservation of Historic and Artistic Works- annual pre-meeting workshop ² involving: object sensitivity, object visibility, lamps, fixtures, space, buildings, viewers' reactions to each of these and to the intier collection, budgets, and finally the influence of the whole of these on the particular museum's goals.

Literally, in collections housed in historic buildings is recognized that a broader range of environmental conditions does not dramatically increase their damage. Biological deterioration, rather than mechanical damage from relative humidity (RH) fluctuations, is the biggest challenge and for example solar gain could reduce RH

"environmental standards should become more intelligent and better tailored to clearly identified needs of collections and visitors"

to below 65 percent in the summer, as reported by Staniforth S. [51]. The need to decrease energy demand initiated discussions among UK conservation institutes, museums and heritage organizations, and finally in 2008 a set of principles was embraced to museum's carbon footprint [52]. Point 1 outstands: environmental standards should become more intelligent and better tailored to clearly identified needs of collections and visitors.

Contemporary, and as result of Michalski's presence, the Canadian Conservation Institute [13], has actually appeared to implement their lighting recommendations

² Workshop took place in Richmond, Virginia and was entitled Museum Exhibit Lighting 2007: Classic Issues, New Light

in higher light levels to enhance the experience of the museum visitor under a few specific circumstances. Through his premise writes: "In terms of risk management trade-offs, we must make a decision that minimizes the loss of value due to poor visual access and the loss of value due to permanent damage. In terms of ethics and visual access, we must balance the rights of our own generation with the rights of all future generations. In terms of practical reality, we must generalize across a multitude of such decisions because objects differ in both their sensitivity to light and their visibility."

The specific circumstances are objects with low contrast details or dark surfaces when a complex visual task may be required and older viewers are shown in Table 10. The benchmark light intensity of 50 lux may be employed as three times - compensated by proportional "dark periods". When older viewers are viewing dark colored textiles according to these recommendations light levels could reach $3 \times 3 \times 50 \text{ lux} = 450 \text{ lux}$ for a total of up to $\sim 4,000 \text{ lux}$ for an old viewer looking for subtle patterns in fine detail in a dark object. To limit the overall light exposure, compensation in exposure time must be applied – again depending on the objects belonging to one of three sensitivity classes. Together with these "dynamic" lighting guidelines CCI recommends lowering, where practical and possible, the UV content of the radiation to max. 10 microwatts per lumen.



Figure 15 Risk Management Concept [50]

A detailed lighting policy within a wider framework of risk-management acknowledges explicitly that colorants fade and that visibility improves with more light, to manage this subjective model Michalski invites reflection over four parameters: a. Establish a criterion for acceptable rate of fading as risk, usually expressed as the period that causes just noticeable fading; b. Assess sensitivities such as important sub-groups, a specific genre, or even a particular object of great value, or characterize the whole group by the highest sensitivity colorant; c. Consider visibility assuming the 50 lux benchmark and higher if a collection does not contain any high or medium sensitivity. In alternate mix short periods of better visual access with long periods of minimal visual access, primarily to accommodate older viewers or special inspections by scholars; d. Determine exposure time as result of calculating what display rotation respects the fading criterion set at the start. The less period for the appearance of a just noticeable fade of the high-sensitivity category is 1.5 years; therefore, high-sensitivity colorants can only be on display about 1.5% of the time, given a 100-year criterion. At the moment policies following similar steps have been described by the Montreal Museum of Fine Arts and the Victoria and Albert Museum.

To help decision-making using a risk management strategy, CCI has developed a light damage calculator for the web. It allows exploring the possible fading of different objects under a wide range of lux levels and display schedules as sensitivity data provided by researchers worldwide are continuously updated. The intent behind is to move beyond a rule-based approach towards a strategy of risk assessment that aims not only to museums that can handle the full control of lighting installation but also in smaller museums. Small collections could now focus their efforts, to place artifacts strategically within the varied light levels of their rooms, and to relax where the fading risk is small or non-existent.

<i>Details</i>	<i>Adjustments</i>
<i>Benchmark value, reasonable visibility for the young viewer:</i>	<i>50 lux</i>
<i>For dark surfaces:</i>	<i>Up to 3 times the lux</i>
<i>For low contrast details:</i>	<i>Up to 3 times the lux</i>
<i>For excellent details or complex time-limited task:</i>	<i>Up to 3 times the lux</i>
<i>For older viewers:</i>	<i>Up to 3 times the lux</i>

Table 10 Adjustments to provide equal visibility for fine details [13]

Novelties in museum recommendations

Important acknowledgments based on Michalski's contribution, currently the most influence among authors, have been inherited in the 10th edition of the IESNA Lighting Handbook [53]. Authors gathered the knowledge over visual aspects in a museum environment where the design must be developed the control of damage to the objects accordingly; levels of light and duration of exposure can be manipulated.

The background environment is established by circulation and general lighting, and reflectance values are there for stabilized by IES-standard 90-60-20 (ceiling-wall-floor percentage light reflectance values - LRV); lower room surface LRVs will result in more dramatic lighting effects, guarantying 10 lx minimum horizontal illuminance on the floor plane. Navigation experience is categorized for focal points: dramatic, moderate and subdued and targets are shown in Figure 16 for objects reflectance values over and led than 0.5. Illuminance criteria should be based on the visual ages of more than half the intended observers the program is not specified the rang between the ages of 25 and 65 years old should be satisfied. A maximum recommended value of UV radiation is 75 $\mu\text{W}/\text{lm}$, and filters should be applied to light sources that exhibit UV radiation.

Harsh transitions to and from the exhibit areas should be avoided: maintaining a 5-to-1 ratio from one room illuminance to another minimizes the disorientation when traversing from high-illuminance zones to low-illuminance zones; low-illuminance spaces with high reflectance average and high-illuminance spaces lower could mitigate the harsh effect. Light locks as spaces separate bright space from a dark area could be inset for the same reason. Illuminance uniformity targets in combination to luminance uniformities and surface reflectance must be all ad-

dressed as part of the design to avoid visual discomfort, glare, and strain. Limiting the duration of light exposure through viewing hours and rotating artworks from display to storage periodically, are all methods of limiting the duration of exposure. The reference to lux-hour limits for artworks based on light sensitivity is considered as maximums and not entitlements. Accepting the infinite number of finishes and materials, the infinity points from which these are viewed and the 2- or 3-dimensional nature of exposed objects general rules expressively avoid to recommend rules of thumb on the types of lighting equipment and the number of lighting positions and aiming angles to consider.

Daylighting should only be considered where objects are not sensitive to UV and visible radiation or were automated, and control of daylight is employed to avoid direct sun. North skylight, considered the source of choice for masters in painting, can be adequately controlled and glazings and can be used to reduce significantly daylight levels; interlayers and films that reduce UV should specify coverage at the range below 400 nm and the damage-factor transmittance of glazings, T_{df}, should be kept low³. Skylight wells, light tubes or splays' finishes of titanium dioxide can be used to reduce UV for sensitive artifacts further. Shades, louvers, and other mechanical devices should be automated to limit daylight to the maximum allowed.

Figure 16 IESNA table 21.2 Art Facilities Illuminance Recommendations [53]

Applications and Tasks ^a	Notes	Recommended Maintained Illuminance Targets (lux) ^{b,c,d}									Uniformity Targets ^e			Typical Area of Coverage ^b	
		Horizontal (E _h) Targets			Vertical (E _v) Targets			Over Area of Coverage			1 st ratio E _v /2 nd ratio E _v if different uniformities apply	Task Proper or Task Area	Room or Designated Area		
		Visual Ages of Observers (years) where at least half are			Visual Ages of Observers (years) where at least half are			Max:Avg	Avg:Min	Max:Min					
EXHIBITS AND GALLERIES	Display of preservation-worthy artworks, artifacts, and antiquities, rare books and materials, or objects deemed of monetary or sentimental value for future generations and all referenced below as objects.	<25	25-65	>65	<25	25-65	>65								
* Circulation/General^{1,4,5,m}	Illuminance for circulation and general background in galleries is based on the intended degree of visual attraction of displayed objects. See TRANSITION SPACES/Circulation Corridors for circulation illuminance criteria where no art is displayed.														
* Displays are Dramatic Focals	Circulation and general background in galleries to set scene for displayed objects to appear as a dramatic focal points.														
• With Object Reflectance >0.5	E _h @floor; E _v @5' AFF	Avg = 0.1 times object E _o or as cameras require, but with min ≥10 lx			Avg of 0.1 times object E _o or as cameras require			4:1							
• With Object Reflectance <0.5	E _h @floor; E _v @5' AFF	Avg = 0.05 times object E _o or as cameras require, but with min ≥10 lx			Avg of 0.05 times object E _o or as cameras require			4:1							
* Displays to Moderate Focals	Circulation and general background to set scene for displayed objects to appear as a moderate focal points.														
• With Object Reflectance >0.5	E _h @floor; E _v @5' AFF	Avg = 0.2 times object E _o or as cameras require, but with min ≥10 lx			Avg of 0.2 times object E _o or as cameras require			4:1							
• With Object Reflectance <0.5	E _h @floor; E _v @5' AFF	Avg = 0.1 times object E _o or as cameras require, but with min ≥10 lx			Avg of 0.1 times object E _o or as cameras require			4:1							
* Displays are Subdued Focals	Circulation and general background to set scene for displayed objects to appear as a subdued focal points.														
• With Object Reflectance >0.5	E _h @floor; E _v @5' AFF	Avg = 0.5 times object E _o or as cameras require, but with min ≥10 lx			Avg of 0.5 times object E _o or as cameras require			4:1							
• With Object Reflectance <0.5	E _h @floor; E _v @5' AFF	Avg = 0.2 times object E _o or as cameras require, but with min ≥10 lx			Avg of 0.2 times object E _o or as cameras require			4:1							
* Objects⁶	Over the area of the artworks, artifacts, antiquities or other preservation-worthy objects. Consult owner or steward to categorize object's sensitivity to light. For preservation purposes, these are the maximum recommended illuminances. Time exposure should be limited to minimum practical for patrons' viewing. Consider vacancy sensors or timers to limit exposure.														
* High Sensitivity to Light^{1,4,5}	See Table 21.3 for definition	K	25	50	100	Max	K	25	50	100	Max	2:1	4:1		
* Low Sensitivity to Light^{1,4,5}	See Table 21.3 for definition	O	100	200	400	Max	O	100	200	400	Max	2:1	4:1		
* No Sensitivity to Light^{1,4,5}	See Table 21.3 for definition	T	500	1000	2000	Max	T	500	1000	2000	Max	2:1	4:1		

³T_{df} account radiation in the 300 nm to 600 nm range.

Fail-safe modes should block all daylight, and curators should further evaluate the program scrutiny.

Museum guidelines are transforming, but still, critics over established criteria for lighting quality is a large-scale discussion over lux laws. 50 lux benchmarks could be bypassed over collection through guided steps as described above and for sure exposition can be over a risk of fade yet issues regarding general assumptions over lighting quality raise. Thomson's only further recommendation in picture galleries, of minimum uniformity of 2:1 over the whole picture hanging area would appear to have been inspired by the implications for excessive dosage rather than viewing criteria, and it is assumed that those areas receiving the highest light levels should still be within recommended maxima. [54]

Pairing energy-saving demand and quality is a significant challenge; adjust the control of existing daylight screening systems or convert obscured windows and skylights to openings can lead to many benefits. The use of daylight within display spaces when used successfully can reduce a considerable amount of electric lighting use and give significant benefits for museum staff since access to daylight and views can improve wellbeing and productivity. The control of daylight and the management of artificial lighting is fundamental to the success of any museum and gallery installation. Control systems often need redesign to ensure that energy and conservation targets are achieved. Relamping with LED sources provide opportunities for simplified control systems and installation of smart control systems respond adequately to occupancy or user preference.

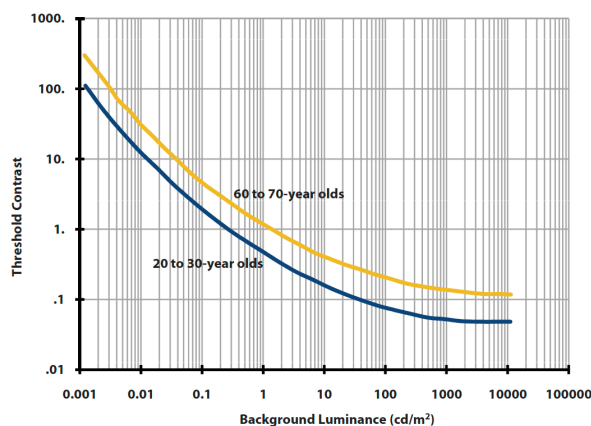


Figure 17 Two threshold contrast sensitivity curves for a luminous disc target. Blue curve is for 20- to 30-year-olds, gold curve for 60- to 70-year-olds [53]

Daylight

The overcast sky of Northern Europe initially influenced the development of architecture museum forms and art galleries; during the 18th and 19th century when the request of high availability of daylight, and less concern on windows which were thought a source of glare, defined the general adopted solutions: clerestory windows, light wells, and skylights or luminous ceilings [55]. Until the decade of the 1930s museum architecture was concentrated on daylight in galleries as a vital issue maximizing its use, later through sophisticated means and studies to improve viewing conditions; a theme that has been arrested since the first systematic research of damage of exposure gain publicity.

Already in the 1945 report of the IES committee regarding the naturally lighted galleries declares them “technically obsolete” and the later codification during the 1960s of Thomson’s recommendations [2] for low daylight factor excluded daylight from galleries where exhibits were classified as highly light-sensitive objects. Daylight has been abandoned in the majority of side-lit galleries; meanwhile, in top-lit buildings with less sensitive objects, elaborated systems appeared to provide ‘controlled’ daylight [56]. Careful and systematic treatment of the existing windows by solar screens, blinds, partially closed curtains, and outdoor shutters closed during peak daylight, has been applicated to reduce the fading and glare risks while trying to achieve a more intact visual connection to the outdoors. By deprive of view and lack of variation of intensity can be hard to determine whether an interior is daylight [57].

Meanwhile, management of historic properties and museums raised their concern over quantification of damage to light-sensitive materials, and daylight performance has been investigated; by the use and data registration of handheld illumi-

nance meters, museum experts on material sensitivity, conducted the placement of art objects in non-daylit interiors. Another issue though emerged from such practice considering the “lost” atmosphere of historical buildings that host collections once the daylight was eliminated, sometimes in the critical absence of electrical light installation. The psychological appeal of windows and skylights has, therefore, declined over the years based on predictions by the proxy of daylight factor, which is limited and can’t compete on the prediction of damage to light-sensitive materials. The National Trust ⁴ owner of many historic properties, through practice, extended monitoring and respecting historical patterns of house management generated site-specific regimes for the opening and closing of shutters and blinds, not only to make use of the daylight for viewing but also to control light exposure [56]. The Trust’s effort to hourly schemes has been the first known example and at today



Figure 18 The Raphael Cartoons under Skylight

still represents a worth to mention solution.

Acquisition of illuminance data for daylight in interiors is a complicated and challenging task as it requires much more effort and appliances compared to other environmental factors that concern deterioration of art, such as temperature and relative humidity; light should be monitored continuously over long periods and to all the room surfaces since its variation is substantial. Only a few institutions have the resources to achieve this goal and placement of light dosimeters or data loggers has been based on risk analysis and proven a complicated task that could therefore only be provided to selected locations. Typically chosen the most critical light-sensitive materials placed close to windows or areas that receive the highest exposure; illuminance performance has generally relied on estimated damage, observation and experience and actual daylight on exhibits remain vague.

A conventional technique to reduce overall daylight admission has been the installation of absorbent materials to remove UV light through films that in the years have expanded their offerings and continued to upgrade their technology but museum have not directly addressed their demand so has been relied on museum staff to determine their specific qualities. Reports of experts on art deterioration are concerned over the efficacy of such installation and the complete blocking of UV radiation reducing visible light to the needed balance without altering color values. Evaluation of UV-blocking films is long run research and have met a variety of goals and different types of measurements and performance criteria. The first extended research on their spectral properties and durability by Boye et al. [58] represents a validated guide to film selection even if data over UV rejection and appearance change with time of exposure under daylight is still in progress.

Among the control mechanisms that have been suggested in recent decades selective reflectance of the internal finishing materials have been proved a passive technique to undertake and preserve the museum collections; lowering the reflectance value assures the reduction of illuminance levels. A mean reflectance tilt from 0.4 to 0.6 will increase the illuminance level by 50%, and from 0.4 to 0.7 by almost 100% [59]. The larger area that the walls occupy usually determine that wall material incises drastically on illumination levels. Thus, wall color may have an essential effect

⁴The National Trust, formally the National Trust for Places of Historic Interest or Natural Beauty, is a conservation organization in England, Wales and Northern Ireland, and the largest membership organization in the United Kingdom. The trust describes itself as “a charity that works to preserve and protect historic places and spaces—forever, for everyone”.

on conservation issues and dosages, yet overall luminance distribution is needed for a balanced composition of the luminance reflected back by the object and the luminance of the surrounding surfaces of the visual field that defines the perception of displayed objects. High reflectance surfaces used to uniform uncontrolled light offer bland contrast ratios with small objects and unsaturated colors.

In practice when daylight is admitted to galleries intensity varies, and cumulative dosages are rarely monitored, but the view of daylight as described in literature could not and has not been abandoned as preventive conservation recommended. Trying to define performance criteria for daylight in galleries Cannon-Brookes [57] specifies that sensibility of light is composed of two factors, view to the exterior and variability. Electric lighting was static, lacking modulation of intensity and blinds or complex roof structures, excluding the direct view of sunlight shouldn't interfere with color temperature, intensity, and non-uniform distribution which guaranty the time variable of natural light.

Following some examples of museums where daylight has been suggested and controlled in the last decade of the 20th century when technology has bloomed by engineering prototypes, and owners of collections have raised their interest of both conservation and sunlight request.

In the Menil Collection by Renzo Piano located in Houston, Arup developed a system to supply air to the galleries from below to allow uniform daylighting in the gallery spaces and achieve the architectural form desired, now known as 'displace-



Figure 19 Menil Collection by Renzo Piano located in Houston

ment' ventilation. Conservation request has been answered by a recommended target of 4% of daylight factor, twice the most European museums [38], with an active shading system. Arup's total design theory meets for the first time the museum environment where control of daylight achieved by a roof design into separate 'beam light trusses,' later known as 'light leaves.' The multi-layer scanning of daylight by the roof composed firstly of an outer layer of fixed brises Soleil made by translucent material that leaves a 30% of penetration of natural light which is later filtered by a double-glazed glass with UV film removing the most damaging frequency of the spectrum. Immediately below, computer-controlled motorized aluminum blades permit control of light levels independently in each space of the gallery. In the Rijksmuseum historic 19th-century museum in Amsterdam where the original architecture relied predominantly on daylight has been recently reintroduced by Spanish architects Cruz A. and Ortiz A. The refurbishment consisted of replacing the skylight glazing of the upper floor to add diffusion and replacing the large suspended diffuse-glass boxes called "lay lights" to improve uniformity. Arup's lighting

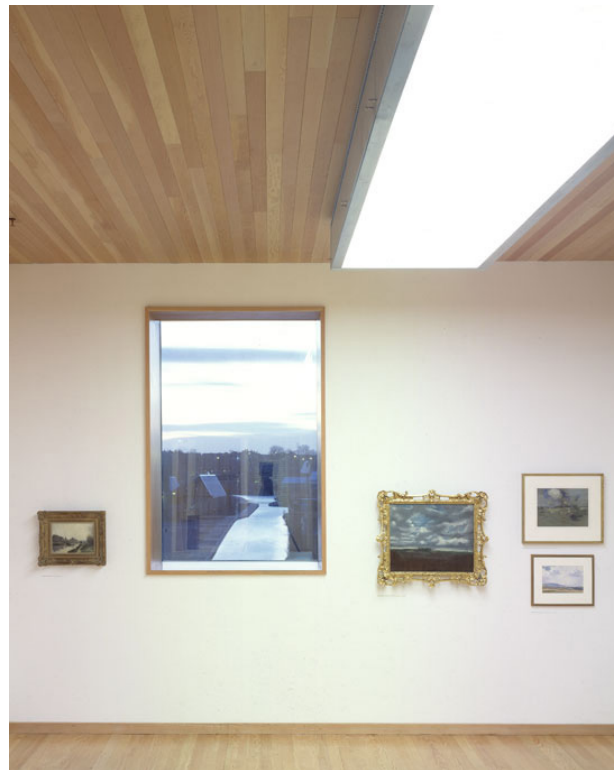


Figure 20 Garman-Ryan galleries New Art Gallery at Walsall

team has been involved of the design of adjustable louvers in the loft space between the “lay light” and the skylight glass, providing the ability to tune daylight with seasonal daylight availability, to avoid over-exposure from daylight while maximizing the daylight experience.

In the Garman-Ryan galleries, New Art Gallery at Walsall is characterized by a kilolux-hour per year strategy and not constant lighting, so the natural variation of illuminance is introduced. Windows are positioned off-center as to emphasize the side-lighting characteristics allowing higher and less sensitive artworks placed in the same room. The design studied the window depth of 600 mm combined with a metal sputtering on the glass achieves the needed uniformity and distribution. Fabric blinds allow a 10% of diffusing light to enter and are controlled manually when direct sunlight enters the room [38]. The “lay lights” contain fluorescent tubes that can automatically be dimmed to balance daylight. The Temporary Exhibitions high requisites on conservation have been answered by a clerestory window system composed of two light-diffusing layers of glass.

Based on several similar study cases Sedwick and Shaw in the 2000 London Conference on Daylight design and Research [38] conclude in some observations for the use of daylight in galleries where the combination of active and passive strategies permits better control of sunlight. They notice that the diffuse translucent materials easily incorporate UV filtration and are effective on uniform scattering and asymmetric disposition of windows could prove useful for artworks of various grades of sensitivities to be placed together. The annual “lux-hour” approach is the basis for the variable source of daylight to participate in the design and through control of either electric lighting, blackout blinds, and daylight louvers or all of them, conservation concern can be respected. The conclusions simultaneously have been reached by other authors as described by Cannon-Brookes [57].

Climate-based daylight modeling

Daylight performance in buildings is influenced by an unusually high number of parameters and traditionally has been of limited prediction; therefore, the simplified formula of daylight factor (DF)⁵ has been the most diffused metric for the last century, constraining performance criteria under a unique CIE overcast sky condition. Around the turn of the millennium Mardaljevic and Reinhart proceeded on publications presenting software possibilities on annual daylight simulation and the daylight factor that still was the base of applied rules of thumbs revealed for the first time limited since the climate-specific approach of the simulations progress. Climate-based daylight modeling (CBDM) is the prediction of any luminous quantity, irradiance or radiance, using realistic sun and sky conditions derived from standardized meteorological data. Their approach has been primarily based on the Daylight Coefficients theory developed by Tregenza and implemented with the use of Radiance a physically accurate rendering engine; Radiance simulates the light distribution in a view-field and constitutes the most rigorously validated lighting simulation program currently available providing high accuracy predictions and a de-facto standard for researchers [60]. The discipline has been gradually associated with the use of the Perez-all-weather luminance distribution, especially after the contribution of Reinhart and the introduction of DAYSIM as a Radiance-based back-end engine for various building modeling software. Evaluations in CBDM modeling are usually carried out for a full year at a time-step of an hour or less to capture the daily and seasonal dynamics of natural daylight and is possible to represent both the instantaneous and the cumulative behavior

⁵The concept of daylight factor regards a static calculation based on diffuse illuminance, manual simplified for architecture applications see Appendix I

of daylight during a complete reference year. The software implementation of the '4-Component' method computes the four individual components of: direct sun; direct sky; indirect sun; and indirect sky is schematically shown in Figure 21. 'Direct' refers to the calculation point receiving light directly from the sun or sky without reflection or diffusion, and 'indirect' to the reflected ambient light and the most rigorous approach to the prediction of daylight performance [62].

A series of validation studies have been published using data collected by the BRE as part of the International Daylight Measurement Programme – the data are sometimes referred to as the BRE-IDMP validation Dataset. The dataset prescribes real-time measurements of the sky luminance distribution, the direct illuminance and the illuminance inside a full-size mock office. The study of Maraljevic [63] showed

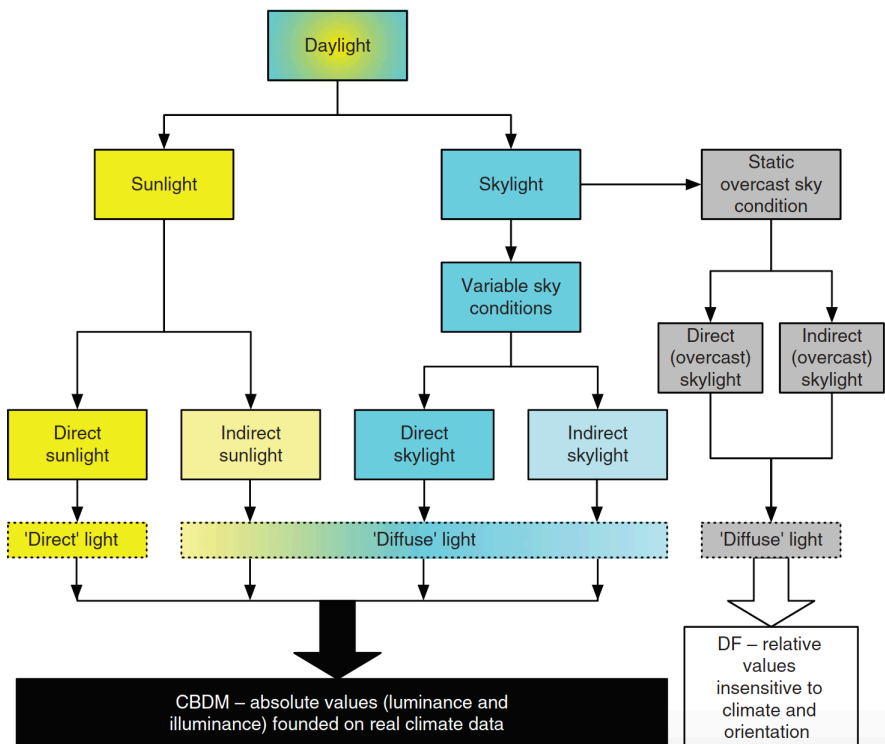


Figure 21 The components of daylight and their relation to the DF and climate-based modelling approaches [61]

that illuminances predicted using Radiance remain within $\pm 10\%$ of measured values, as well as accuracy error of measuring instruments. Furthermore, validations of Radiance performance for Complex Fenestration System (CFS), such as translucent panels by Reinhart and by McNeil of the 3-phase method simulation method that could be used for example to evaluate "light-pipes" light redistribution.

In 2013 the UK Education Funding Agency made CBDM a mandatory requirement for the evaluation of designs submitted for the Priority Schools Building Program (PSBP). A school participating in the program have to respect 'target' criteria for the useful daylight illuminance metric. This mandatory daylight requirement is considered the first significant upgrade since the introduction of DF. In the US, two climate-based daylight metrics have appeared in the latest version of LEED v4 and described in the 10th edition of the IESNA Lighting Handbook [53] Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE). This recent development led to a continually evolving number of different software that can perform CBDM (e.g., Diva for Rhino, Grasshopper, Ecotect, etc.).

Daylight performance in museums

The growing use of daylight modeling and the search for new metrics for daylight illumination recently adopted by IES has brought a fresh perspective to how daylight exposure may be used in display environments predicting annual daylight exposure in rooms used for displaying light-sensitive collections. Mardaljevic has introduced the term CBDM in 2006 CIBSE National Conference paper No.67 [64] where some examples of its use are presented, among others, the prediction of annual illuminance in the Hermitage museum in St.Petersburg. The author describes what later would be defined by IES the methodology of daylight metrics creating twelve cumulative monthly climate files using the period of operating museum hours. Sun and sky components have been separated generating 24 cumulative luminance maps. Inter-reflections have been calculated separately, and the component of direct light has been evidenced as shown in Figure 22 is indicated by magenta shading to the lower part of the bar; plots also show mean illuminance as the total height of the bar. The total annual exposure is given in units of Klux hours based on the opening hours.

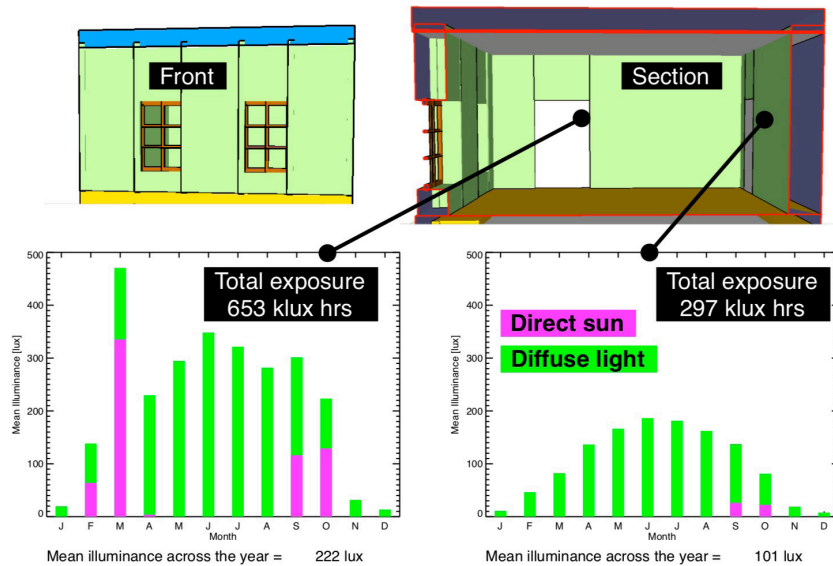
The methodology proposed by Mardaljevic raised the interest of the National Trust emphasizing the dichotomy between predicted performance in false color plots and the complicated task of monitoring daylight. The Trust has engaged the Ickworth House in Suffolk as the first of its properties to gain a new perspective of daylight. An exemplary space for the rooms has been used by Mardaljevic et al. [56] the Smoking Room to explore cumulative daylight exposure in different orientations generating an 'atlas' of daylighting performance that could give insight for the management of opening hours or a room-specific operation schedule for closing shutters, blinds and curtains.

Glare Analysis

The expensive equipment and the variable nature of scenes with daylight made difficult historically to conduct luminance-based analysis methods in scenes with daylight; data recorded by hand-held luminance meters in a space with daylight have substantial limitations and are difficult to evaluate. High Dynamic Range photography techniques have made far more feasible to generate luminance data from real daylight spaces, and computational methods are facilitating the rapid development of new luminance-based metrics and analysis criteria. The technique has been available in digital daylight simulations for many years, but the development of real spaces is recent.

The accuracy of the luminance values in an HDR image is typically better than ± 20 percent, often in the range ± 10 percent, with calibration against a spot measurement with a luminance meter. Additionally, with wide-angle lenses, vignetting correction is applied to compensate for light fall-off away from the image center. The photograph of the Smoking Room shown is one of the actual HDR image captures. Knowing the luminance and reflectance of a surface, it is then possible to derive the incident illuminance, provided that the surface finish mostly approximates a Lambertian reflector. Cumulative daylight illumination fields will be compiled from multiple HDR exposures taken over several weeks/month.

Figure 22 Mean illuminance for each month and total annual exposure for two points in the General Staff Building, St.Petersburg (west facing 10.00 to 18.00) [64]



Case Studies

Among the projects and installations made by the National Trust in their research program a case study by Blades et al. [62] to protect one of the most important paintings from excessive daylight exposure is described. Hambletonian, Rubbing Down, painting by George Stubbs, hangs below the roof lantern on the main staircase at Mount Stewart, Northern Ireland. In one of the first applications in a UK heritage building, the research employed climate-based daylight modeling (CBDM) to understand the fall of daylight on Hambletonian, its annual light exposure and the effect of proposed light control measures. The use of CBDM, combined with measured light data, in developing a practical and effective light control solution is detailed and the light control measures implemented by a perforated surface on the top lighting. In Figure 23 the results of the simulation are shown.

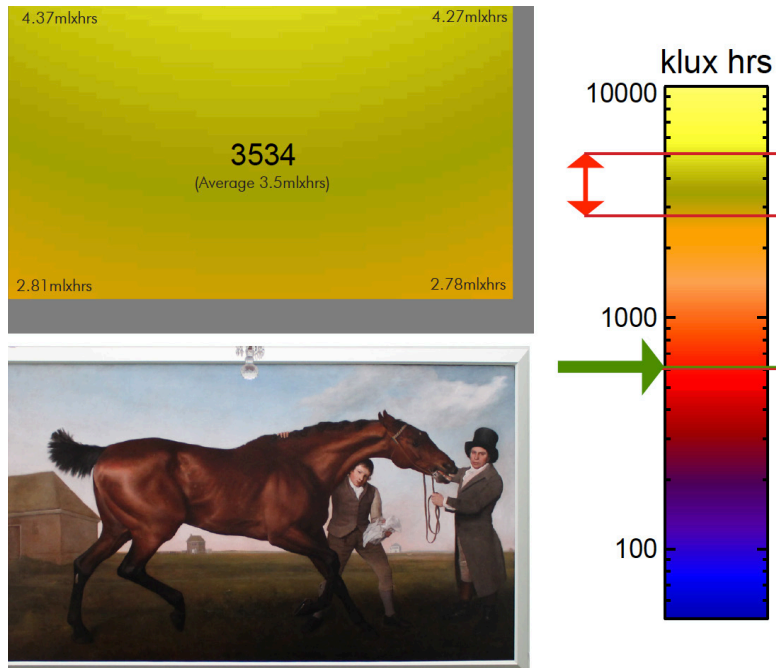


Figure 23 Hambletonian, Rubbing town painting and the evaluation of annual exposure.

Lighting Quality

“To play with light is to play with magic-it demands (1) a trained eye, to recognize real and relative values (2) experience and knowledge of the cultural and psychological effects of light on people (3) experience and knowledge of physical techniques.” Richard Kelly [65]

The extended review of the literature over museum lighting thru the historical development of research on damage and on museum recommendations evidenced the parallel advance of principles with that of the lighting design as part of what determines visual quality and perception. Lighting quality is an interdisciplinary field of research affecting human activity and under a requested task, visual performance meanwhile improving well-being. In this sense, the role of the lighting designer is to match and rank the human needs with the economic and environmental aspects as well as the architectural principles, and translate the results into a feasible design and efficient installation [32]; the human needs served by lighting are identified in Figure 24.

Veich & Newsham [66] argue that lighting quality is a particular case of a general model of the effects of the consistent environment on behavior and well-being and psychologists should actively contribute to the study. Wahab et al. [67] hypothesis that prediction of human visual quality as a function of the lighting conditions thus essential to focus on human visual systems its discomforts and variable performances of visual perception.

Druzik et al. [4], in preview of the later inherited insights to the IESNA museum recommendations, express the opinion that ‘visual performance’ in terms of ‘visual satisfaction’ should be a concern as for color differentiation, contrast sensitivity, viewing of small details for young an old mutually of disabling glare, visual confusion caused by clutter, large contrasts. Likewise affirms that unanimity protocols of human evaluation for aesthetics and visual performance are still missing.

Visual perception

The range of the parameters influencing visual perception and hence visibility are the fundamental quantities of: luminance, the amount of light entering the eye and falling on the retina, the size of a visual task, a visual task's luminance and chromatic contrast, spatial frequency, and flicker [53] ; their changes influence threshold and suprathreshold performance.

Brightness is the perceptual response to luminance and fundamentally represents visual perception. Other stimuli apart of luminance may affect brightness as object luminance, surround luminance, state of adaptation, gradient, and spectral content. Its related perception is lightness; a surface appears to reflect or transmit more or less light and so the judgment about the property of it. Constancy characterizes both brightness and lightness.

Acuity is the ability to resolve fine details; several different kinds are recognized and involve various levels of visibility, from detection to recognition. Acuity continues to improve with increasing background luminance as long as the background field is large; when the background field is small, there is an optimum luminance for visual acuity, above which acuity declines.

Contrast sensitivity functions define the minimum contrast required for targets to be seen as a function of target or viewing characteristics. The ability to detect a target against a background can be quantified by its threshold contrast. Many factors affect threshold contrast the more critical are target size and retinal illuminance.

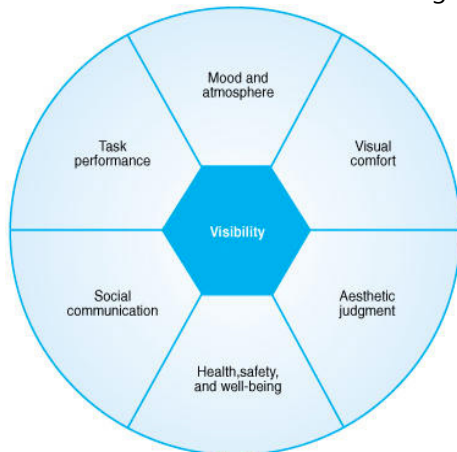


Figure 24 Human needs served by lighting [32]

Figure 25 Lighting quality concept IALD International Association Lighting Designers

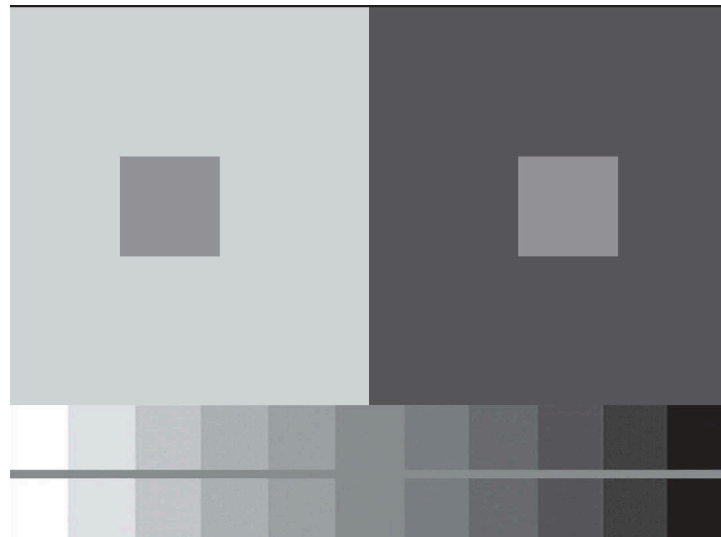


Visual performance

Visual performance research started in the 1930s to help establish a concrete parameter for recommended illuminances. Two approaches one by Weston in Great Britain and the other by Luckiesh in the United States, have led to differently recommended illuminances in the two countries. During the energy crisis in the 1970s applied research into visual performance was emphasized to resolve the discrepancy, resulting in a model of relative visual performance (RVP) which became the basis for lowering recommended lighting levels in schools, offices and other commercial spaces [68].

The RVP model by Rea & Ouellette [69] is an attempt to represent the efficiency of the visual process and is independent of the nature of the visual task. RVP is a quantitative model based on an extensive data set consisting of the changes that occur in reaction time; the conditions covered represent a wide range of adaptation luminance, luminance contrasts, and visual sizes showing the effect on suprathreshold visual performance in absence of nonvisual components for the detection of visual stimuli seen by the fovea. Suprathreshold is the condition of visibility above the threshold where additional lighting continues to influence the speed and

Figure 26 Effect of surround luminance on the brightness of an object. The two small squares centered in the larger squares have the same luminance but differ in brightness due to their surround luminance. The bar across the series of patches at the bottom has the same luminance across its length, but its brightness varies since it is affected by the local surround luminance. [53]



accuracy with which the visual information can be processed. The model ranges from 0 at 'readability threshold' to 1; higher values to improve visual conditions could be associated under diverse conditions such as large targets seen at higher background luminance.

Figure 27 shows the form of the model the overall shape of the RVP surface has been described as a plateau and an escarpment. In essence, it shows that the visual system is capable of high-level visual performance over a wide range of visual sizes, luminance contrasts, and retinal illuminations (the plateau) but if one of the parameters becomes insufficient, visual performance collapses rapidly (the escarpment) towards a threshold state.

The RVP model has been used to establish recommended lighting levels focusing on task performance of the visual system hence using speed and accuracy; more complex or cognitively based performance is not predicted. Other critical parameters as light polarization and distribution that could affect visual performance for tasks that involve specularly reflecting materials and could change luminance contrast are not described. In that case, light distribution can produce veiling reflections that can make luminance contrast larger or smaller, depending on the specific arrangement of the materials that could affect vision in exhibit cases. The change in luminance contrast can be, but it is difficult to control because it depends criti-

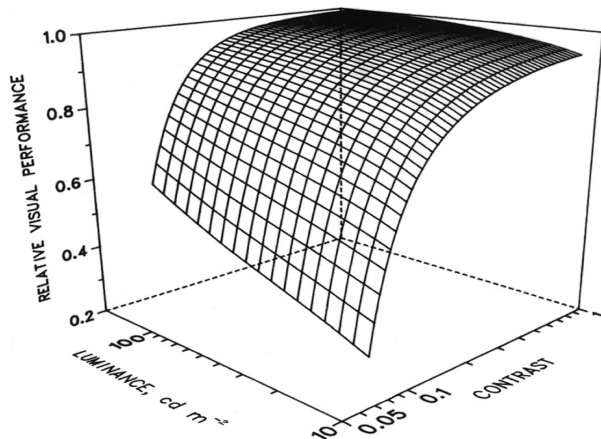


Figure 27 Three-Dimensional representation of RVP as a function of target contrast and background luminance based on the numerical verification task by Rea [69]

cally on the geometry between the source of luminance being reflected, the task, and the observer; a small change in position of any of these entities can markedly change it as well as for polarization, magnitude, and nature of it.

O'Donnell et al. [70] evidence a contribution of luminance and color perception to visual performance: under low luminance contrast below 20%, color perception permits at the visual system to be activated; the effect depends on the chromatic characteristics of the stimuli. Based on this observation later studies [71] evidenced that a mean excitation purity of 30% for stimuli with a reddish, magenta, violet, and greenish-blue appearance and >80% for lime, greenish-yellow, and orange will score a higher RVP value. The same authors approaching other functional vision barriers found that an increase in glare is equivalent to a reduction of adaptation luminance. In visual tasks in the mesopic range, considering the transient effects of glare, and with very low levels of surround luminance within the scotopic range, brightness can be as low as 20% of the brightness that would be perceived if there was no glare. Moreover, reduction of brightness caused by glare cannot be generalized and strongly depends on the surrounding luminance.

These insights of performance-based approach have extended over the years the parameters that affect task visibility and comfort such as contrast rendering and discomfort glare. Cuttle describes the current era as the third stage of lighting profession [35] whereas the second stage based on visual performance has failed by his opinion, to provide adequate illuminance to human needs; he concludes that standards provide requirements of lighting levels that have inappropriate metrics to measure them. The obsession on delivering lux levels over a horizontal surface reduce the overall importance of other global parameters as perceived brightness and doubts that RVP model is still a useful tool.

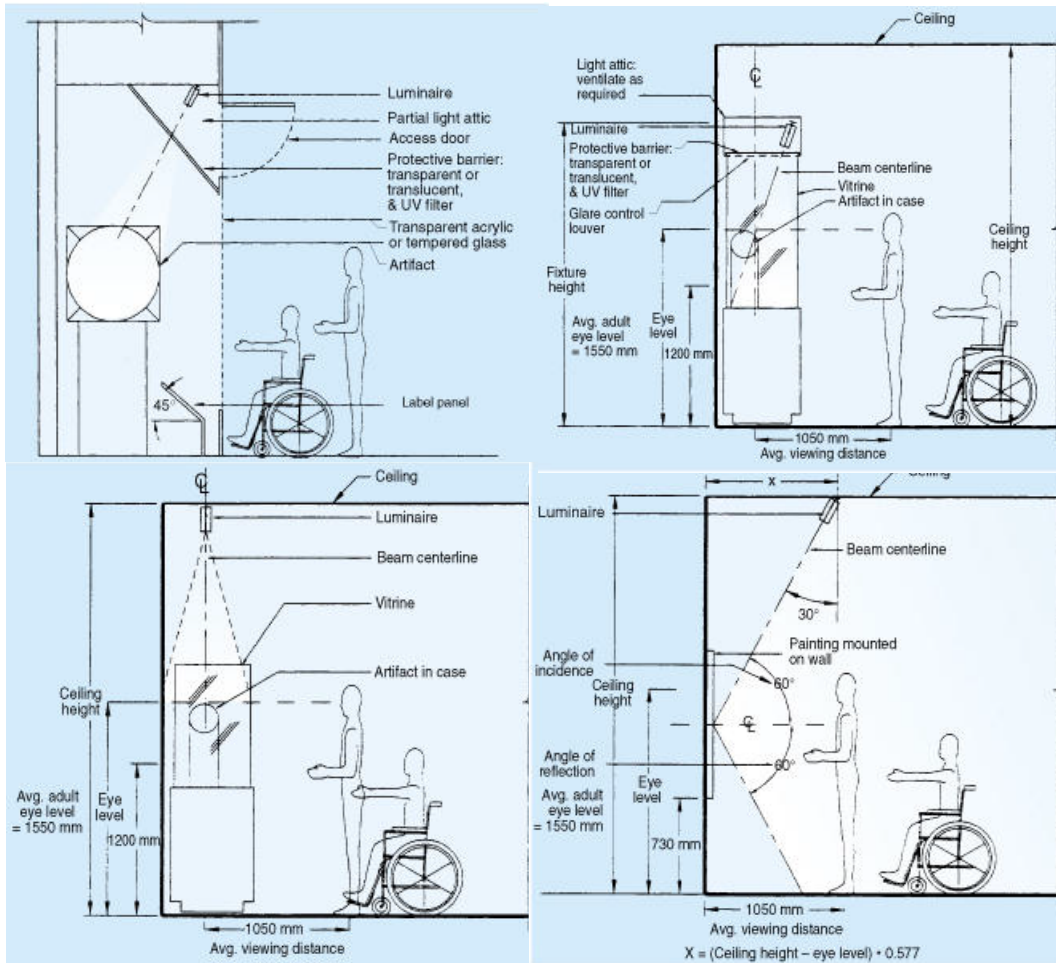


Figure 28 Guidelines for luminaire mounting position [32]

Metrics towards quality

The museum environment is characterized by a strong relationship between the lighting installation and the perceived experience of the exhibits. The illumination values regard to damage can be controlled, but lighting quality has to be achieved through a total design where luminance distribution has an equivalent important role. A preliminary study by Rossi et al. [72] regarding the observation of ancient paintings and frescos to evaluate perception from a quantitative, i.e. metrological point of view through video-photometers and CCD visual meters that permit the reconstruction of luminance values in a scene evidenced lightness as crucial. Thus, propose a new lightness image-based measure established only on luminance information and other 'geometric' parameters as the distance from the maximum value, the relative position and the visual field.

Software progress and technology made calculable a new generation of luminance-based metrics through simulation tools. Many studies demonstrate a higher correlation to visual performance with luminance-based metrics than the traditional illuminance-based. [73]

Howlett et al. [74] use luminance maps to describe a series of Luminance-based daylight metrics to quantify the quality of lighting. Being analogous to the visual field of view some threshold metrics based on human vision as disability glare can be easy extracted, and prediction can be achieved by software simulation through Radiance.

Rockcastle et al. [75] [76] proposed a new family of metrics that quantify the magnitude of contrast-based visual effects and time-based variation within daylit space through the use of time segmented daylight renderings. The concept of annual spatial contrast provides to the designer a holistic understanding of when and where sunlight impacts the composition of light and shadow within a person's field of view. Moreover, they classified the current luminance-based metrics into two main categories. One is the metrics that can predict glare-based discomfort due to high ratios of contrast within the visual field, (e.g., DGP and DGPs). The other is metrics that can evaluate luminance ratios or ranges to infer human preferences for brightness and composition, (e.g., annual spatial contrast and annual luminance variability).

In the research for daylight metrics through Radiance Mardaljevic et al. [61] describe a metric as some mathematical combination of (potentially disparate) measurements and/ or dimensions and/or conditions represented on a continuous scale and may not be directly measurable in the field. A criterion is a demarcation on that metric scale that determines a specific qualification. Metrics inform decision making by combining various factors predicting better or worse performance; performance may be described by more than one metric. When metrics are sufficiently refined and their predictive capabilities validated, then performance criteria can be set for various guidelines and recommendations.

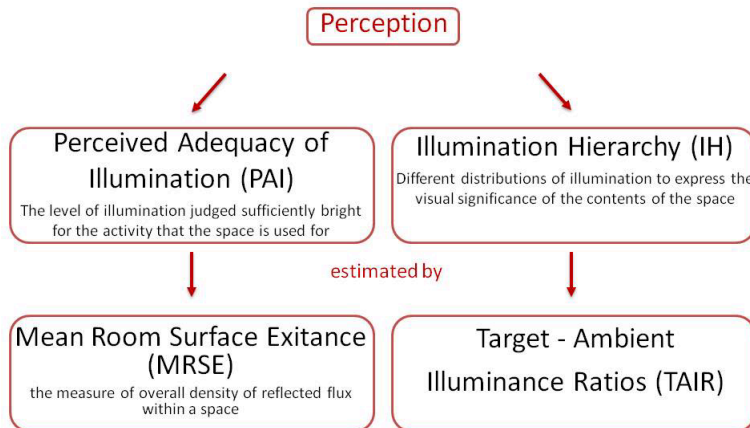


Figure 29 MRSE as the proposed metric for PAI and TAIR as the proposed metric for Illumination Hierarchy. Two new concepts measured by two new metrics. [77]

Brightness-based lighting design

The need for new metrics of the existing lighting design practice has been explored from different authors, and recent literature [77, 78, 79] has been produced over the latest metrics proposed by Cuttle called Mean Room Surface Exitance (MRSE) and Target Ambient Illumination Ratio (TAIR). MRSE is a metric invented by Cuttle [35] to measure perceived adequacy of illumination (PAI) and TAIR (Target- Ambient Illumination Ratio) refers to the designed illumination hierarchy in a room hence improve quality and is considered as a ratio between illumination at a point of emphasis compared to general lighting. Central to Cuttle's proposal is considering a more holistic design approach that better relates to what we see.

Mean room surface exitance (MRSE) is the average of flux densities existing, or emerging from all surfaces within the space measured in lm/m² [35]:

$$MRSE = \frac{FRF}{Aa} \left(\frac{lm}{m^2} \right)$$

where FRF represents the first reflected flux

$$FRF = \sum F_{s(d)} \rho_s$$

and Aa is the integrated room absorption

$$A_a = \sum A_s (1 - \rho)$$

MRSE is measured at a point (or points) within the volume of a space, rather than on a surface or plane. Whereas it is a reasonably straightforward metric to calculate, its measurement is complicated since direct flux has to be excluded. Currently, no suitable meters are available, but Duff et al. [79] demonstrated an MRSE measurement tool based on high dynamic range technology to enable sources of direct light to be first identified and so discount their effects. Duff furthermore, proposed a method that utilizes a Radiance lighting simulation engine to calculate MRSE, and high dynamic range (HDR) imaging to estimate levels of MRSE in the field.

The IH criterion focuses on the way direct flux is distributed to create a pattern of brightness, whilst the PAI criterion provides adequate quantities of reflected flux. The designer is called to select target surfaces and designate values of TAIR based on the desired level of illumination difference. MRSE provides the measure of indirect illumination within a space, and it is reasonable to assume that the incident illuminance on a surface will be the sum of the direct illuminance and MRSE:

$$E_{igt} = E_{igtd} + MRSE$$

And the TAIR

$$TAIR = \frac{E_{igt}}{MRSE}$$

Cuttle has proposed ratios of illuminance shown in Table 11 and Table 12 that indicate degrees of perceived differences in levels of subjective brightness. The quantity of direct illuminance to be applied to each surface or object can be determined from the above equation and using this data, the distribution of direct luminous flux from the luminaires can be established.

Cuttle's theory could represent the intention of quality metrics, but still, as noted by Mardaljevic [80] useful metrics should have an intuitive meaning for their users

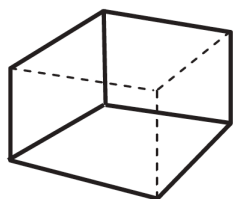
<i>Mean room surface exitance MRSE (lm/m²)</i>	<i>Appearance of ambient illumination</i>
<i>10</i>	<i>Lowest level for reasonable color discrimination</i>
<i>30</i>	<i>Dim appearance</i>
<i>75 - 100</i>	<i>Lowest level for 'acceptably bright' appearance</i>
<i>300</i>	<i>Bright appearance</i>
<i>1000</i>	<i>Distinctly bright appearance</i>

Table 11 Approximate guide to overall perceived brightness or dimness of illumination related to mean room surface exitance (MRSE)

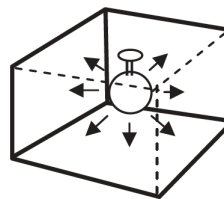
and be directly measured for validation; this implies a preference for simplicity so they can be intuitively understood, and a direct tie to measurable outcomes. New proposed metrics are software based, and Cuttle's supposed environment is windowless and regard artificial lighting as a unique system neglecting daylight. Effort should be made to achieve a holistic metric or define the criteria for both exitance and daylight as to integrate them to a holistic approach of lighting design.

Perceived Difference	Illumination Ratio
Noticeable	1.5: 1
Distinct	3: 1
Strong	10: 1
Emphatic	40: 1

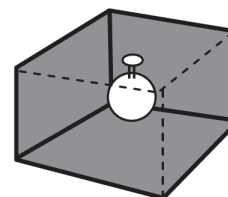
Table 12 Approximate guide to perceived difference of illumination brightness related to MRSE difference or TAIR



(a) Room surface area
 $A = 100 \text{ m}^2$



(b) Luminaire light output
 $F_L = 5000 \text{ lm}$



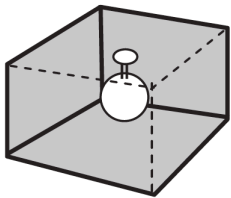
(c) Room surface reflectance $\rho = 0.5$, and illuminance $E = 100 \text{ lx}$

Luminance-based recommendations

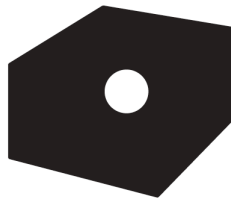
Kit Cuttle's argument and the new metrics should focus on luminous exitance of surfaces as the most important of quality criterion. They represent the perceived brightness and is based on his affirmation that visual performance is not any more useful. Technological success has overpassed visual performance: illuminance can be easily adjusted by the user to achieve the task where detail is difficult, and paper-based reading has mainly been replaced by self-luminous screen-based reading. Lighting design is passing to an era that the focus is the lit appearance of the overall brightness (or dimness) of a room, by the reflected light reaching the observer's eyes, instead of light arriving at work planes. The statement has been accepted by other authors [77, 78, 79] nonetheless visual performance is a key criterion when small details need to be seen or reading fine print and furthermore as Rea underlies in outdoor environments [68] where visual performance seems to affect traffic safety directly.

Road lighting represents one of the cases where recommendations are related to visual performance criteria: small target visibility and luminance. The "small target visibility" (STV) model, proposed by Adrian [81] considers the ability to detect a small target standing on the road at a long distance ahead as a quality index of the lighting installation. The model computes the detection threshold for a small target situated on the road, knowing the contrast threshold of the Human Visual System (HVS).

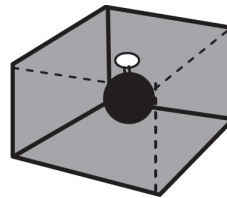
Figure 30 Mean Room Surface Exitance, A thought exercise [35]



(d) Increase ρ to 0.8, and E increases to 250 lx



(e) Reduce ρ to 0, and $E = 50$ lx, and has no visible effect



(f) Mean room surface exitance $M_{rs} = FRF/A\alpha$

The adaptation luminance, which is needed to compute this threshold, is taken as the road luminance around the target. Adrian proposes to use the Visibility Level (VL) index, which is the luminance contrast ΔL between the target and the background, over the threshold luminance contrast. Assessments are made with the hypothesis of a vertical square target of 20 cm. width standing 86 meters ahead of the driver, with a contrast of 0.2, and observation time is 0.2 s. The second criterion for road lighting quality regards luminance based on road classification, where minimum photometric values are proposed for mean luminance, uniformity, glare and surround ratio.

As observed by Brémond [82] links between this classification and visual performance thresholds are not explicit; this approach allows us to take some parameters into account by a described methodology. Thus, recommendations by CIE propose standard grids, and a simplification method allowing to use photometric characteristics of the road to compute luminance values from illuminance values through the luminance coefficient $q=L/E$. The CIE model uses two photometric parameters: Q_0 (degree of lightness) and S_1 (degree of specularity).

Luminance recommendations could guide another aspect of the lighting design process which poses closer to the concept of lighting quality, i.e. to provide appropriate surface brightness in the space, limit discomfort, and disability glare, and establish or control brightness variations for aesthetic, architectural, balance or form-modeling purposes. Luminance recommendations are based on the way visual system maps luminance to brightness. Brightness is a function of adaptation state and the luminance of the object. Considering foveal tasks, adaptation state is determined by the central 10° of the visual field. Brightness ratio is a function not only of adaptation and object luminance but also of luminance gradient and chromaticity. In the Table 13 a historical overview of luminance ratios and values is given by Veitch et al. [66] in their reconstruction to the parameters that define lighting quality.

Designers examine real and digitally simulated spaces via advanced computational methods, and emerging luminance-based metrics give assess to a new era of visual comfort and aspects of quality. However, there is currently very little guidance for designers seeking to refine design solutions based upon these metrics because it is still an emerging research area.

	Luminance (cd/m ²)	Task: wall Luminance ratio	Ceiling: wall luminance ratio	Wall maximum : minimum
Tregenza et al. (1974)		2 to 1	1.6 to 1	
Ooyen et al. (1986/1987)		3.3 to 1		
VDT work (wall)	20-45			
Other tasks (wall)	30-60			
Miller (1994) 75	75			3 to 1
Miller et al. (1995)				
Direct/indirect systems			1:3 through 3:1	
Parabolic direct systems			1:5 and 1:3	
Loe et al. (1994)	5		1:1	161 to 1
Berrutto et al. (1994)				
Free choice	117-179			
Restricted power use	60-109			

Note. For Loe et al. (1994), the values are those of the configuration rated as most interesting, and the luminance value is the average wall luminance in the field of view. For Berrutto et al. the luminance values are mean values for walls on the right or the left of the desk in a room with VDTs.

Table 13 Preferred Luminance Ratios and Luminance values (Veitch & Newsham, 1996)

Methodology

Museum lighting is definitely in need of defining quality factors involving color fidelity and damage as previously examined along with visual perception; useful metrics are therefore needed to establish these criteria. Recent studies on damage limitation of light-sensitive materials in galleries through climate-based simulations prove that a daylighting strategy could be undertaken. The challenge for the museum and the holistic design of natural and artificial light is still missing of substantial metrics, yet some literature findings give us an insight into the workflow to establish.

Meanwhile, compliance to standards of lighting an art gallery makes part of a complicated task that includes visual quality and non-objective sensations; curators often propose a museum route, telling a story, enhancing sentiments, creating contrasts and unexpected hierarchies; lighting is actually involved in viewing scenes and visitor's visual perception. Integration of lighting and architecture first addressed by Richard Kelly in the early 1950s in the United States referring to three elements of light: ambient Light (shadowless general illumination) which is often mentioned as spatial brightness; focal glow or highlight; sharp detail or play of brilliants, this excites the optic nerve and stimulates the spirit. These insights still seem to be the most adequate to create nonuniform illumination thus enhancing visual and museum experience.

Kelly's approach to lighting quality, luminance-based design metrics, and contrast criteria are used in this study as key strategies for museum lighting connected with comfort as far as for viewing fine arts. Advanced computer rendering gives us the opportunity to an investigation of luminance distribution not neglecting daylight contribution; this permits a preliminary hypothesis of the relationship among

background luminance and target contrast requirements for the perceived visual performance of museum collection in a holistic approach.

It may be proposed to separate the levels for an overall museum lighting quality as follows:

- Ambient light - Functional: guaranty control of damage and viewing by color fidelity
- Focal glow - Simulation: modeling the vision and the appropriate thresholds by metrics
- Sharp detail- Exhibits: target detection in the relationship with luminance and brightness

The Italian territory holds the highest concentration of Cultural Heritage in the world, maturing for this patrimony a leading role in the research and development of conservation and restoration. Among the environmental parameters that effect exhibited artifacts, light exposure is the most complex and the only one that is essential to the viewer as to appreciate the objects consisting at one of the most critical variables of art exposure. The research of strategies to be adopted for energy saving and the renovation of light destined to Heritage is examined in the museum environment by daylight admission and LED technology.

Object of the study is the exploration, through simulation, of the transition inside a daylight gallery since moving in the museum environment offers an experience of a series of adaptation changes through photopic, mesopic and dark-adapted scotopic function along with change on the sensitivity of the spectrum. Harsh transitions to and from the exhibit areas should be avoided from one room illuminance to another as to minimize the disorientation when traversing from high-illuminance zones to low-illuminance zones. Illuminance uniformity targets in combination to luminance uniformities and surface reflectance must be all addressed as part of the design to avoid visual discomfort, glare, and strain.

The luminance appearance and the transition adaptation lack of examination; the relationship of prescriptive requirements and luminance-based design has been explored initially in the field of road lighting where the relative visual performance has been evidenced to be in the center of the CIE standard for tunnel lighting. Daylight simulation via climate-based modeling introducing daylight filters as solar shading devices has been proposed as the object of several experimental pieces of research connecting light "filtering" with luminance; this workflow could be applied in several fields of research considering museum environment and give responses

in the preservation of artwork involving daylight.

In tunnels, high energy consumption is required for guarantying the visual adaptation to the light contrast between daylight and tunnel luminance. The opportunity to graduate daylight in the threshold zone could create an area of adaptation of the human eye to the tunnel' s interior luminance, reducing consumption. A daylight "filter" structure, called pre-tunnel, is placed before the tunnel's portal, to investigate how a gradual reduction of luminance maintaining uniformity could be achieved; the structure presents very small circular holes on the ceiling giving access to natural light

In the first study, a 1:20 scale model has been constructed to test the effect of different diameters of holes on luminance and to evaluate the reduction of the lighting percentage. Results show the ability of this solution to have a potential control daylight management at the entrance of the tunnel. In the second study a 1:10 scale model of this adaptation zone, has been constructed to investigate uniformity and luminance reduction under panels with different percentages of holed ceiling surface. The trend of the luminance curve compared to the CIE curve of luminance led to the optimization of panels' position along the tunnel. Results confirmed the possibility of implementing drivers' vision introducing daylight through the "filter" structure. A third study has been carried out employing 3D daylight simulation software. The 1:1 scale model of the tunnel and the pre-tunnel as been realized and two different sequences of filtering panels have been simulated. The first sequence reproduces the panels experimented in a previous study with a real scale model; the second sequence is aimed to optimize the filter effect, acting on the grid of the panels.

The investigations for the pre-tunnel structure led to a more in-depth knowledge of simulation use and permitted the hypothesis of a case-study where the filter zone can be applied in a museum environment. The parametrization of the holes can lead to successive workflows for similar applications and strategies for general applications of 'trama' surfaces in Heritage. For this cause a location in Rome has been identified for MIBAC La Quadriennale Di Roma - Institution for Contemporary Italian Art at former Papal Arsenal after Porta Portese; buildings destination as a gallery for fine arts based on a recent project is evaluated.

For this scope current platforms such as Grasshopper for Rhino are used for parametric modeling; mathematical operations, dependencies, and functions are used, instead of an accurate drawing of geometrical objects. These generated elements contain many variables within their internal structure that may be used in the gen-

eration of design solution alternatives. Moreover, it allows exploration of design solution space, which is not possible using standard modeling tools.

Rhino+Grasshopper, the most widely used parametric modeling tool, supports a wide range of couplings to various tools via 3rd-party modules such as Ladybug, Honeybee, and DIVA. Ladybug can perform energy and daylighting analysis coupled with EnergyPlus, Radiance, and DAYSIM. It simplifies the process of analysis, automates and expedites the calculations, and provides easy-to-understand graphical visualizations. Honeybee is the extension of Ladybug for more advanced lighting and energy studies.

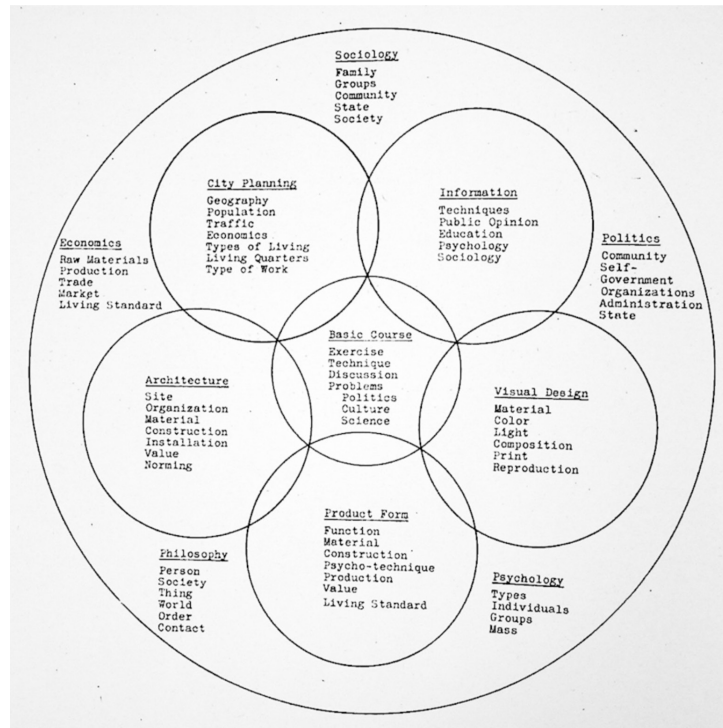


Figure 1 A diagram that illustrates the school's holistic approach to design. (source: Scholl, I. & Aicher, O. ca. 1951. School of Design—Research Institute of Product Form. Updated script)

The following chapters of the thesis have been published in three steps in successive IEEE Conferences 2015th, 2016th and 2017th editions

Daylight 'filter' zone in roadway tunnels

The case of road pre-tunnels, a luminance-based requirement

The photometric requirements of lighting installations in Commission Internationale de l'Éclairage (CIE) in the Technical Report CIE 88:2004 Guide for the Lighting of Road Tunnels and Underpasses to obtain installations of sufficient quality concerning safety and comfort [83]. The rules contained in it, based on the human visual system, impose the crucial need for high illumination levels in the proximity of the tunnel's portal; values that are generally provided employing artificial lighting, with consequent high energy demand, during daytime [81].

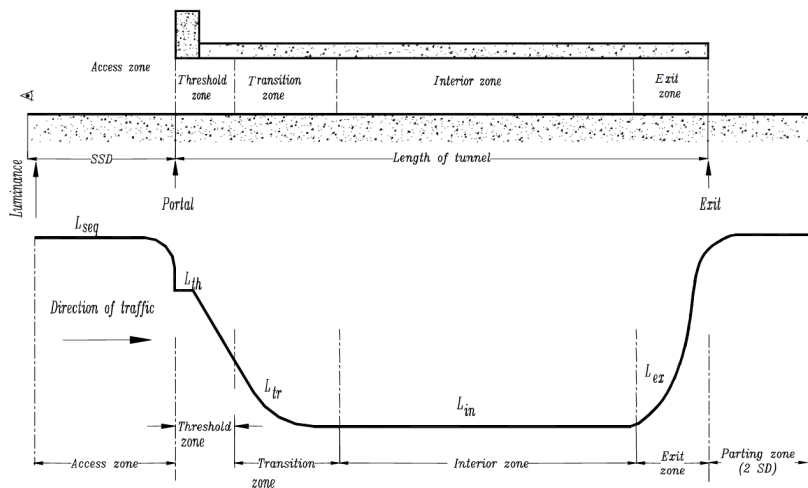
Drivers approaching the tunnel tend to decelerate quickly or to drive erratically perceiving the entrance as a black hole, an effect provoked by the significant light contrast between daylight and tunnel luminance. Furthermore, the glare from the bright visual zones surrounding reduces the capacity of recognition of traffic obstacles in the immediate entrance zone and decreases the detection distance for hazards [84]. Once entered the tunnel, the driver's sensitivity to obstacles with low contrast is reduced for visual adaptation, a process that requests at least 8 minutes [85]. In this state, the sudden change from the brightness of daylight to the darkness of the tunnel causes a limited performance to the human eye that is not entirely adapted in the prevailing retinal illumination [86].

Therefore, according to CIE regulation, road tunnels are divided into various zones, depending on the distance of the entrance and the different luminance requirements. The first part of the tunnel, directly after the portal is called threshold zone and, as shown Figure 33, the luminance in this section L_{th} is the highest in the longitudinal section of the tunnel to guarantee road safety. To calculate it, designers should start from standardized figures for contrast revealing coefficient q_c provided in CIE standard, and if necessary proceed to more precise values through the

perceived contrast method. Meanwhile, luminance along the tunnel is a constant percentage of the access zone luminance L_{seq} , the light veil as a result of the ocular scatter quantified expressed in cd/m^2 [87].

The critical luminance contrast in the access zone during daytime is generally balanced increasing the luminance and the illuminance levels at the tunnel entrance using artificial lighting. For this reason, the energy consumption in the threshold zone is extraordinarily high, and several studies have investigated the possibility to reduce it without negatively affecting the visual capacity of the drivers or limiting traffic safety, using LED technology and Smart Control systems. Differently, the assumption to introduce daylight in the threshold zone has been proposed by Pena et al. [87, 88, 89, 90] to create a larger area of adaptation of the human eye to the tunnel's interior luminance; among these daylight screens over the tunnel entrance have been widely used.

The position of the portal, in this case, is considered at the beginning of the screens and the contrast ratio L / E_v shall be determined in the same way as for artificial light, where L is luminance and E_v the vertical illuminance in 0,1m height. The value of L_{th} / L_{seq} ratio shall be kept between 2 for cloudy skies and 6 under sunny conditions, and specific care must be taken to avoid flicker effects. Road uniformity



Typical longitudinal section of a one way tunnel

Figure 32 Luminance distribution in tunnels CIE [83]

is another crucial issue when daylight is used and has to be provided on the road surface and the walls up to a high of 2 m. According to CIE indications a ratio of 0,4 for the minimum to the average value of luminance is recommended; the longitudinal uniformity ratio shall be kept at a value of 0,6 along the center of each lane. Once these parameters are fulfilled, the shift of the threshold zone outside the tunnel using a filter structure could be one of the tasks to uptake as to reduce the artificial lighting request and to decrease energy consumption. In this study a daylight 'filter' structure, called pre-tunnel, is placed before the tunnel's portal, to investigate how the use of natural light could achieve a gradual reduction of luminance maintaining uniformity; its feasibility and efficiency has been explored, and both luminance (L) and illuminance (E) has been measured in two scale models. Recent works propose alternative methods for introducing daylight in the threshold zone and reducing the artificial lighting component. Peña-Garcia et al. [91] suggested a combined system consisting in heliostats positioned before the tunnel which follow the solar orientation and direct the sun rays into a matrix of light-pipes placed inside the tunnel: this system distributed the natural light in the threshold zone, reducing the energy consumption above 20% [92]. Qin et al. [93] planned a system based on optical fibers catching light from the sun and introducing it inside the tunnel: here reflector panels redirect the light to the road. The hypothesis of Perforated solar screens⁷ positioned on the rooftop of a pre-tunnel structure in a horizontal position has been studied along with relative optimization through simulation in climate-based daylight programs. The structure's function to eliminate the black hole effect that the drivers perceive approaching the tunnel entrance and enhance the visual adaptation has been explored. Indeed, pre-tunnel gradually shadows the road before the tunnel, eliminating the high contrast of luminance between exterior and interior zone putting in evidence the possibility to achieve the lighting requirements prescribed in the normative [83] using a passive system, without the need of exceeding electrical lighting during daytime. The study has been carried out in successive phases. Firstly, a scale model of 1:50 has been built to investigate the impact of a filter structure placed before the tunnel in the L and E values under both the pre-tunnel and the first section of the tunnel; in this early work a single filter grid has been tested in the North, South and

⁷ Perforated solar screens (PSS) are flat opaque perforated panels, relatively thin in relation to their length and width, which have been suggested to improve daylight conditions and reduce energy consumption in building with fully glazed surfaces; relative optimization through simulation in climate-based daylight metrics programs. [91]

East directions. Then, a second work has been carried out in which five panels of different grids have been tested in a scale model of 1:20. In this study the percentage of daylight attenuation has been measured under each filtering panel and a parameter K characterizing the filter effect of the panels has been developed as the Empty/Full proportion to help define optimization of screens perforation based on required luminance trend.

Current research is often focused in daylight potential of design applying computer tools; in the third study the simulation of the filtering panels used in a 1:1 model of pre-tunnel has been performed through daylight modeling through Radiance daylight simulation system, validated by Mardajevic [94] with very high accuracy predictions. The software demonstrates a 66% of prediction with-in $\pm 10\%$ of measured values, and 95% were within $\pm 25\%$ compared with that of measuring instruments themselves and much higher than that demonstrated for scale models [95]. The work aims to manage the panels filter-effect for optimizing the decrease of E and L under the pre-tunnel and the tunnel, exploring and defining a methodology for Radiance simulation through DIVA for Rhino, radiance-based optimized daylight, and energy analysis software.

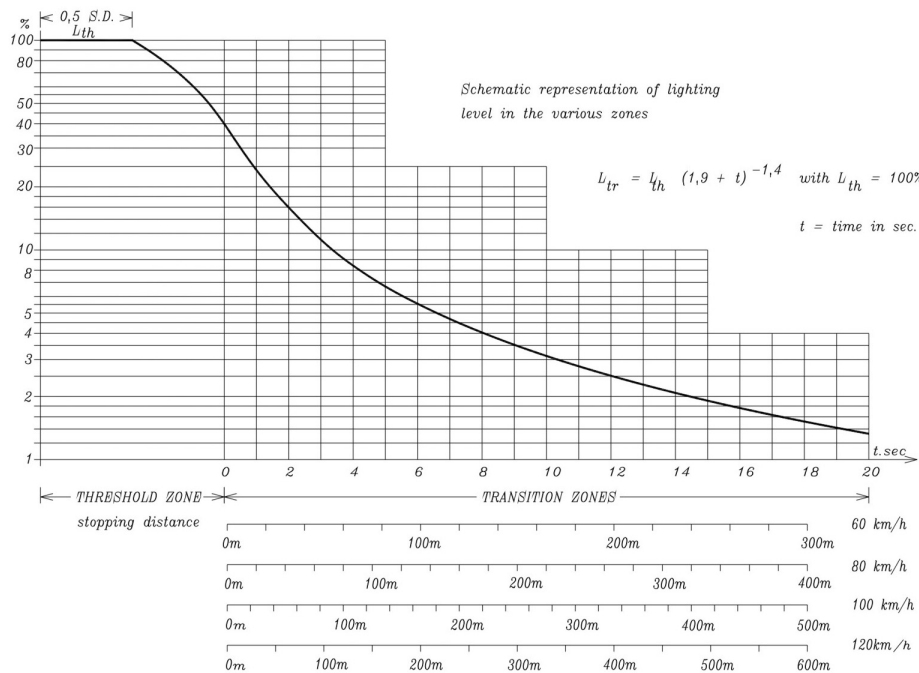


Figure 33 Luminance evolution along tunnel CIE [83]

First study – Scale model

Study of a daylight ‘filter’ zone in tunnels [96]

Materials and methods

A 1:20 scale model representing the structure of the tunnel and the pre-tunnel was used to study the natural light shielding shown in Figure 34. The model has been constructed simulating a one direction tunnel with two lanes; it was made of particle board, and it had a semicircular transversal section and dimensions 100 cm in length, 53,5 cm in width and 60 height. The pre-tunnel model had a rectangular section with dimensions 50 cm in length, 53,5 cm in width and 31,5 height; holes of 0.25 cm diameter, displayed on a grid of 2.5 cm, have been made on the ceiling of the pre-tunnel. The interior of the two elements has been covered with opaque black cardboard to limit reflections, and a cover has been positioned at the end of the mock-up tunnel.

Measurements of luminance and illuminance were performed outside and inside the pre-tunnel with a multichannel data logger (Babuc LSI Lastem) provided of

multiple lighting probes and a luminance meter (LS 100 Konica Minolta). The model has been exposed in Rome (41°53'37.40"N 12°29'35.70"E) and two campaign of measurements were performed.

The first set of measures have been taken with the model of the tunnel alone in four different po-

Figure 34 Scale model of tunnel and pre-tunnel.



sitions, facing North, South, East, and West, each half hour from 11:30 a.m. to 4:00 p.m. in four consecutive days. Four probes were recording illuminance value, where positioned on the base of the model in the center of the tunnel at equal inter distances: the first one is placed outside the tunnel, the second in correspondence of the tunnel entrance, the third in the middle of the tunnel and the fourth at its end. The second set of measures were carried out with the model facing South recording both the L and E with and without the presence of the pre-tunnel in the day 15th of April at three specific hours, 12:30 a.m., 1:00 p.m. and 2:00 p.m. Six probes were positioned on the base of the model in the center of the tunnel: the first three were placed outside the tunnel, the fourth in correspondence of the tunnel entrance, the fifth in the middle of the tunnel and the sixth at its end, as illustrated in Figure 35.

Results

The first set of measures allowed to observe the interaction of the sunlight with the tunnel as a function of the position of its axis in the direction of the four cardinal points. The variation in illuminance levels during the day in the critical zones of the tunnel were recorded: the access zone (1), the portal (2), the threshold zone (3) and the interior zone (4). Results obtained are plotted in ten curves corresponding to hours from 11:30 to 16:00 (4:00 p.m.) and showed in the three diagrams of Figure 36 under clear sky conditions [98].

The curves on diagrams evidenced the occurrence of two situations: the rapid tran-

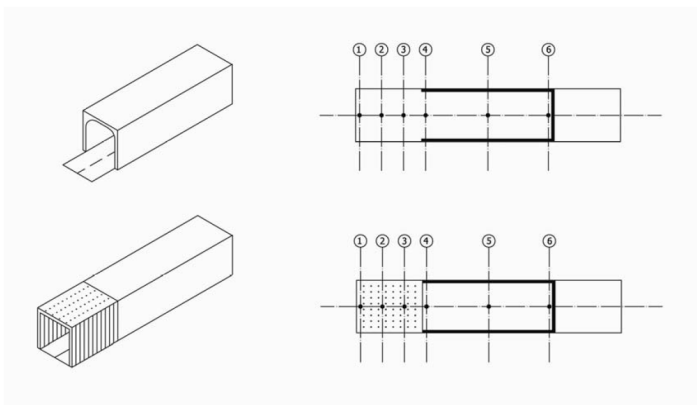


Figure 35 Probes position on the longitudinal axes of the scale model

sition from light to dark in correspondence of the portal, as in tunnel facing N, and the small luminous diminution between the outside level and the entrance one, followed by a rapid lighting reduction in the first zone inside the tunnel, as in S exposition.

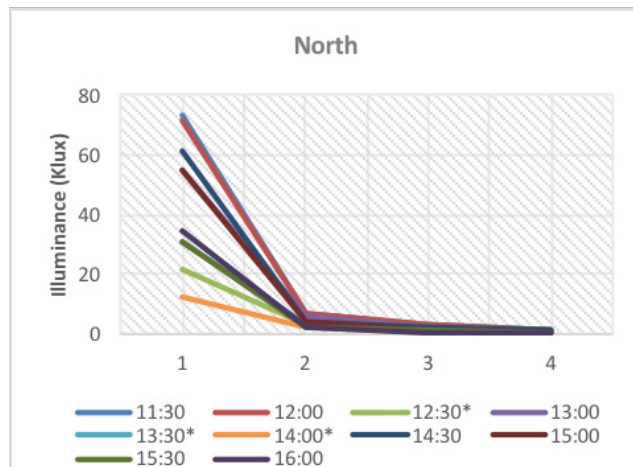
This difference is caused by the position of the sun respect to the tunnel entrance: in the first case, it produces the shadow in correspondence of the portal, while in the second case the rays enter in the initial segment of the tunnel. For the E orientation of the tunnel, both situations were verified: in the morning the sunlight penetrates the tunnel, then in the afternoon, between 2:00 and 2:30 p.m., the shadow moved in correspondence of the portal.

In the second set of measures, the effect of the insertion of the pre-tunnel on lighting immediately before and after the portal has experimented. Diagrams presented in Figure 37 report results of the variation of luminance and illuminance respectively, with and without the pre-tunnel in the day 15th of April at 13:00 pm.

Values of luminance and illuminance were recorded in six points: in the measurement without the pre-tunnel, points 1, 2 and 3 were located in the access zone, point 4 in correspondence of the tunnel portal, point 5 in the threshold zone and point 6 in the interior zone. Once placed the pre-tunnel structure before the entrance of the tunnel model, the portal and the threshold zone shifted out of the tunnel and positioned in the pre-tunnel; without modify the position of probes, point 1 was located in correspondence of the pre-tunnel portal, and points 2 and 3 in the threshold zone.

In the diagram representing the luminance, the curve "tunnel" has a rapid decrease in the threshold zone, passing from 2285 cd/m² in correspondence of the portal

Figure 36 Illuminance results under CIE clear sky in the critical zones of the tunnel: the access zone (1), the portal (2), the threshold zone (3) and the interior zone (4).



to 66 cd/m² in the successive point: in this case the probes registered the typical trend of luminance, occurring in the threshold zone of tunnels.

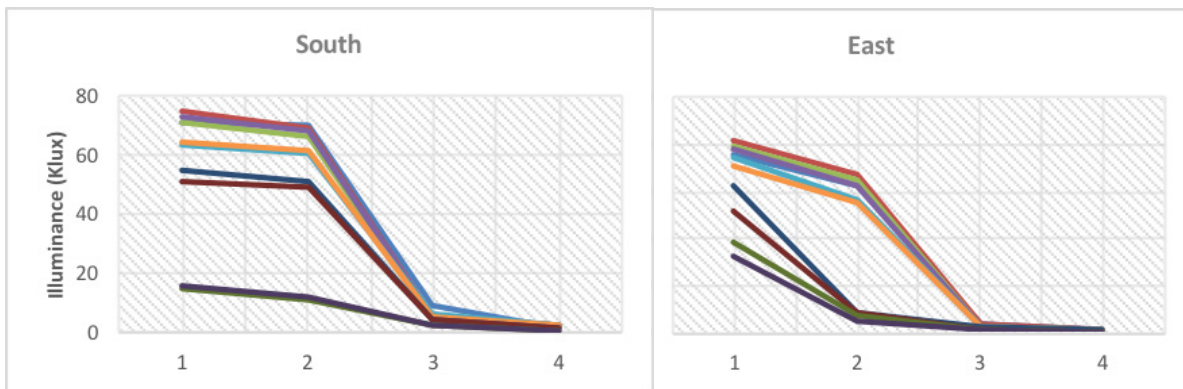
The presence of the filtering structure of pre-tunnel mitigates the high difference of luminance in the threshold zone, creating an intermediate zone in which the luminance softly decreases from 269 cd/m² to 66 cd/m², passing for the middle value of 213 cd/m².

The persisting difference in luminance just after the portal, even with the pre-tunnel structure, indicates the necessity of an optimization of the filter, for increasing the percentage of natural light entering the tunnel in the proximity of the portal. This goal could be achieved with a finer grid of points or increasing the diameter of the holes.

Conclusion

In the first step has been studied how to reduce the elevated luminance difference occurring at the tunnel entrance, which causes vision impairment in drivers approaching the portal; it has been investigated the effect of a punctured structure, placed before the tunnel portal, on the daylight filtering. The experimentation was carried on with a scale model of the tunnel and a filtering structure, the pre-tunnel, in which the ceiling surface presented holes.

A first study conducted with the model of the tunnel oriented facing North, South, and East, allowed to simulate the lighting variation from 11:30 a.m. to 4:00 p.m. in the critical zones of the tunnel. This simulation individuates orientations and hours in which the presence of shadow attenuate the contrast of luminance between the



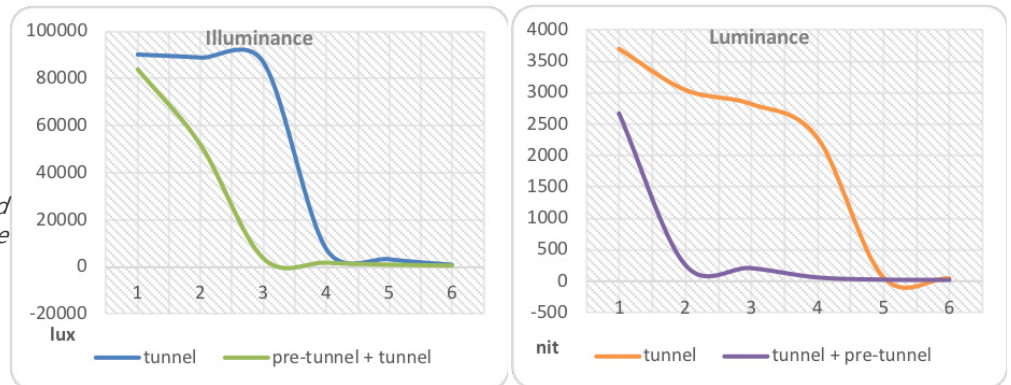
brightness of the daylight and the dark of the tunnel.

The most critical situation of the tunnel oriented to South was selected for investigating the effect of the insertion of the pre-tunnel on the lighting variation in the threshold zone. Results of measurements indicated that the presence of this filter, obtained performing a regular grid of holes on the structure ceiling, consented to reduce the high contrast of luminance in the threshold zone, producing a gradual reduction of its values.

This study, carried out with a scale model, evidenced the low efficacy of the pre-tunnel in the proximity of the tunnel entrance: this effect was attributed to the scarce contribute of daylight in this zone caused by the weak percentage of the holed surface of the ceiling panel.

This study confirmed the possibility of implementing the vision performance of drivers in tunnels with the pre-tunnel structure, without using excessive artificial lighting.

Figure 37 Results of illuminance and luminance variation introducing the pre-tunnel.



Second Study – Optimization of filtering

Study for optimizing the daylight 'filter' in a pre-tunnel structure [97]

The second study investigates the effect on daylight filtering under panels of different diameters of holes performed on the pre-tunnel ceiling, as to evaluate the percentage reduction of both luminance and illuminance. The aim is to optimize the holes diameters and their distribution on the roof of the pre-tunnel to enhance drivers' visual conditions, implementing street safety and reducing energy consumption.

Materials and methods

A 1:10 scale model has been built with a semi-circular transversal section of 1000 cm length, 100 cm in width and 60 height, while the pre-tunnel part had a rectangular transversal section and 1000 cm in length, 107 cm in width and 63 height dimensions. The model, as presented in Figure 38, was realized by a steel framework and an opaque plastic coating, with black color outer face and white internal; the ceiling of the pre-tunnel was composed of ten iron panels of 100x107 cm.

The model was placed in an external parking area with asphalt on the ground, located in proximity to Rome (N 41° 35' 39"; E 12° 39' 21") with SSW orientation.

A first measuring survey of many days was organized to observe the effect of daylight contribution in the pre-tunnel structure at several hours and under different sky conditions (clear, intermediate, overcast). Measurements of luminance and illuminance were performed outside and inside the pre-tunnel with a multichannel data logger (Babuc LSI Lastem) provided of multiple lighting probes and a lumi-

nance meter (LS 100 Konica Minolta). Probes were positioned on the ground, displaced in three lines following the longitudinal axis of the pre-tunnel: a scheme of the probe's position is presented in figure 39.

Measures were firstly collected with all ceiling panels without holes; then holes of five diameters, from 1.6 mm to 5.5 mm and diverse inter-distances Table 15, were carried out, one by one in a different time, with a punching machine on different panels. Measures with every single panel mounted on the ceiling were successively performed.

A second measuring survey with the same instruments of the previous was performed to collect luminance and illuminance levels with the sequence of punched panels as to verify the lighting condition obtained under the pre-tunnel.

Results

Data collected with the scale model were analyzed to quantify the percentage of daylight attenuation each panel produces within the pre-tunnel.

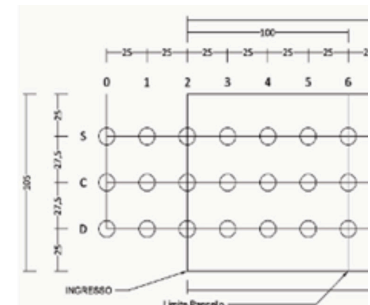
The Luminance Attenuation (%) has been defined by the difference ratio, where L_{ext} is the luminance measured before the entrance and L_{int} is the luminance in the pre-tunnel zone. Likewise, the Illuminance Attenuation (%) by the difference ratio.

Filtering effect has been experimented in the first survey for each panel, and the average values of luminance and illuminance attenuation percentages of daylight under them are plotted in the chart of Figure 40. The graphic shows the attenuation of the 5 panels, allowing the hypothesis of an optimal panel disposition on pre-tunnel ceiling: the sequence of panels, mounted starting from the entrance, could be

Figure 38 The 1:10 scale model



Figure 39 Scheme indicating the placement of the probes



Panel	Luminance Attenuation (%)				
	P ₁	P ₂	P ₃	P ₄	P ₅
11:30	90%	75%	66%	54%	44%
12:00	89%	86%	61%	57%	42%
12:30	91%	88%	60%	59%	45%
13:00	88%	85%	58%	51%	43%
Average	90%	83%	61%	55%	43%

Panel	Illuminance Attenuation (%)				
	P ₁	P ₂	P ₃	P ₄	P ₅
11:30	90%	66%	54%	55%	40%
12:00	89%	82%	56%	55%	43%
12:30	89%	81%	59%	56%	42%
13:00	89%	83%	56%	55%	41%
Average	90%	78%	56%	55%	42%

Table 14 Attenuation results under the panels


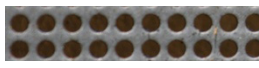


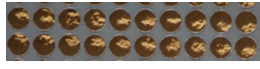
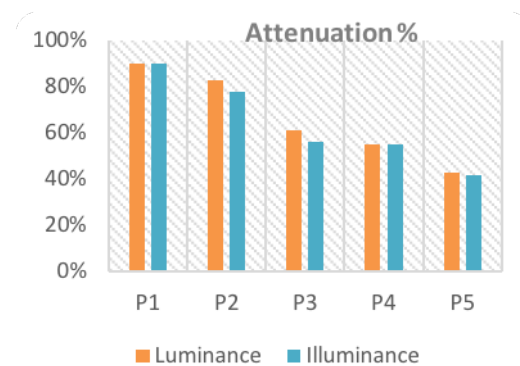
Panel	Filter surfaces		
	Hole diameter mm	In-ter-dis-tance mm	
P ₁	1,6	3,5	
P ₂	2,8	3,2	
P ₃	3,2	4,0	
P ₄	4,2	6,0	
P ₅	5,5	6,0	

Table 15 Filter Surfaces

Figure 40 Attenuation chart



P5, P4, P3, P2, P1, followed by panels without any holes.

Such a disposition has been experimented in the second survey and results are shown in Table 14 collected in several hours during day 17th June and reported as attenuation percentage for each panel defined by the attenuation ratio $(L_{ext} - L_{int}) / L_{ext}$ and $(I_{ext} - I_{int}) / I_{ext}$

Mean values of measures carried out at 12:00 pm under clear sky conditions in several days are shown in diagrams illustrated in Figure 41.

Both graphics of luminance and illuminance verify that the sequence of panels tested could gradually decrease illumination under the pre-tunnel structure during the daytime.

To calculate K parameter each panel has been considered a grid in which the diameter and inter-distance of the holes of each panel have been subscribed from a rectangle. Holes and rectangular surface described as Empty/Full proportion are put in comparison with Luminance Attenuation (%) in

Ceiling scheme with the sequence of the panels as previously described and measures made under clear sky conditions evidence the feasibility of the structure to filter light producing a luminance curve, Figure 41, which could be put in comparison with CIE curve in Figure 33. for the optimization of the K parameter.

Conclusion

The study investigated the effect of a punctured structure, placed before the tunnel portal and its effectiveness to reduce the high luminance difference occurring at the tunnel entrance, which causes vision impairment in drivers approaching the portal, using daylight.

The experimentation was carried at 1:10 scale model of pre-tunnel, with holes of different diameters displaced in a regular grid on ceiling panels, observing the at-

Panel	Luminance Attenuation (%)				
	Hole diameter mm	Empty mm ²	Full mm ²	K Empty/Full	Luminance Attenuation (%)
P1	1.6	2,01	12,25	0,16	90%
P2	2.8	6,15	10,24	0,60	83%
P3	3.2	8,04	16	0,50	61%
P4	4.2	13,85	25	0,55	55%
P5	5.5	23,75	36	0,66	43%

Table 16 Panels' Attenuation Percentage

tenuation of natural light; based on the measured data, a disposition of panels was studied as a function of the percentage of daylight attenuation.

Results demonstrate the efficacy of the pre-tunnel structure in reducing the luminance difference between the zone outside and inside the tunnel; moreover, a gradual reduction of luminance and illuminance levels was achieved with an optimal sequence of panels.

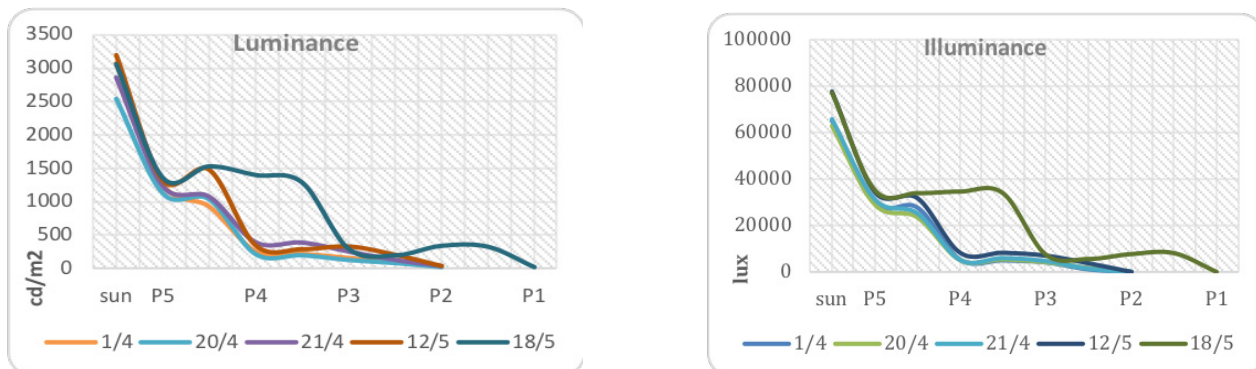
The K ratio, like the Empty/Full proportion of panel surface, was correlated to the percentage of Luminance Attenuation, to obtain a universal parameter describing the phenomenon of light filtering.

The CIE transition luminance curve will be analyzed in future studies to individuate the length of the road segment corresponding to a presumed percentage of daylight attenuation; this fragmentation can lead to:

- Optimize the K parameter for the ceiling 'filter' of daylight;
- Define position and length of panels for each K, according to the traffic speed.

The optimization of the scheme ceilings with diverse and variable K should be studied; for this cause simulation software will be used. Other parameters such as uniformity and flickering could be therefore examined using virtual calculation.

Figure 41 Illuminance and luminance distribution at 12:00 pm under clear sky conditions



Third Study - Exploring the daylight simulation

Exploring the daylight simulation of filter panels in a pre-tunnel structure [99]

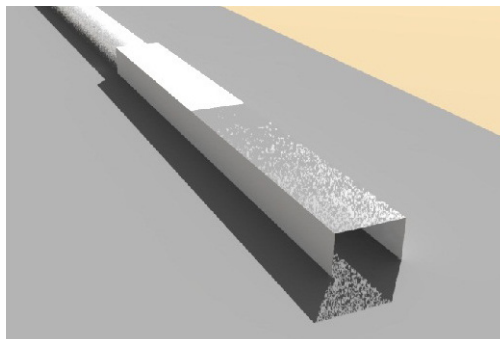
Materials and methods

This study has been carried out in two steps: firstly the filtering panels sequence experimented in the previous work has been simulated so that the ending point of the previous study was the starting point of this one. Subsequently, the holes grid and the length of the panels has been optimized with the aim of producing the closest visual conditions to those prescribed in the CIE guide.

A. Simulation setup

The 3d model has been constructed with Rhinoceros 5 software simulating a copy of the tunnel, and pre-tunnel real model experimented in the previous work. Differently for the real model, which was in a 1:20 scale, the actual tunnel copy was reproduced in 1:1 scale; indeed, the panels have been simulated with the same holes dimension and grid, for reproducing the same lighting conditions obtained in the 1:20 scale model.

Figure 42 The 1:1 3D model of the tunnel and pretunnel



The 3D model simulated a two lanes tunnel having a semicircular transversal section of 20 m in width and 12 m height; while the pre-tunnel has a rectangular section measuring 21,4 m in width and 12,6 m height. Has been positioned in the same SSW orientation of the 1:20 model has been set, with the intent of reproducing as bet-

Surface	Radiance Material	Author
Ground	material type: opaque void plastic OutsideGround_10 0 0 5 0.1 0.1 0.1 0 0	suggested by IES-LM-83
Cover	material type: reflective void metal metal_diffuse 0 0 5 0.5 0.5 0.5 0.90 0.175	Christoph Reinhart
Tunnel structure	material type: opaque void plastic 0 0 5 0.5 0.5 0.5 0 0	Christoph Reinhart
PSS	void glass open 0 0 3 1.0 1.0 1.0	Mixfunc radiance-online.org
PSS	void plastic plastic 0 0 5 0.1 0.1 0.1 0 0	Mixfunc radiance-online.org

Table 17 Materials simulation characteristics

Filter	Panels				
	P ₁	P ₂	P ₃	P ₄	P ₅
Hole diameter (mm)	1.6	2.8	3.2	4.2	5.5
Inter-distance (mm)	3.5	3.2	4.0	3.2	6.0
K parameter	0.16	0.60	0.50	0.38	0.66

Table 18 Puncturing of the covering panels

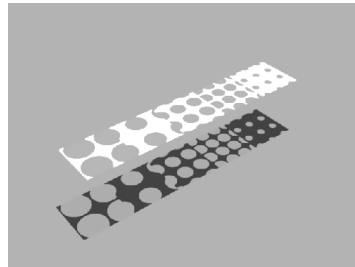


Figure 43 Visualization of the perforated panels in small surfaces showing perforation

ter as possible the conditions experimented in the previous work. Also, the same day, hours and daylight conditions have been simulated for obtaining lighting results as similar as possible of those measured under the 1:20 real model.

Daylight calculations have been carried out using DIVA for Rhino Radiance tool. The climate file used is International Weather for Energy Calculation (IWECC) for Rome, at (N 41° 90' 28"; E 12° 49' 64"), as the most closed to real geographic coordinates of the scale model at the Italian city Pomezia (N 41° 35' 39"; E 12° 39' 21"). Measuring surfaces of 0.2x0.2m have been positioned on the central axes of the structure on 0.2m height describing the upper surface of the CIE reference obstacle. Their inter-distance has been defined in 5m starting 10m before tunnel's portal. Results report mean illuminance value for 9 nodes at each surface.

Simulation parameters have been set according to typical scene 2 used in Radiance [100] Ambient bounces:7, Ambient division:1500, Ambient sampling 100, Ambient accuracy 0.1, Ambient resolution 300, Direct threshold 0, Direct sampling 0 under CIE clear sky. Materials RGB reflectance, specularity, and roughness have been set as in Table 17.

As to maintain model's file dimension to reduced size and as to simplify daylight

<i>PSS</i>	<i>RadianceMaterial</i>
<i>P1</i>	<i>void mixfunc perforated_so35_ro23</i> <i>6 plastic open uv_hole perforate.cal -s .0035</i> <i>o</i> <i>1 0.23</i>
<i>P2</i>	<i>void mixfunc perforated_so32_ro44</i> <i>6 plastic open uv_hole perforate.cal -s .0032</i> <i>o</i> <i>1 0.44</i>
<i>P3</i>	<i>void mixfunc perforated_so4_ro40</i> <i>6 plastic open uv_hole perforate.cal -s .004</i> <i>o</i> <i>1 0.40</i>
<i>P4</i>	<i>void mixfunc perforated_so6_ro35</i> <i>6 plastic open uv_hole perforate.cal -s .006</i> <i>o</i> <i>1 0.35</i>
<i>P5</i>	<i>void mixfunc perforated_so6_ro46</i> <i>6 plastic open uv_hole perforate.cal -s .006</i> <i>o</i> <i>1 0.46</i>

Table 19 Panel's definition of simulation material

calculation given the complexity of the scene, the perforated screens have been simulated by the application of a mixfunc material. We have defined a very transmissive glass and a plastic material and combined them in such a way as to create our screens; a perforation function for approximately horizontal surfaces has been used see Appendix III

B. Simulation of the panels sequence

Five covering panels of 20x20 m with different puncturing have been simulated; in Table 18 the holes diameter, their inter-distance and the relative K parameter for each panel are reported.

In the simulation model, as in the previous scale model, the panels were disposed one after the other from P5 to P1 starting from the tunnel entrance to the end of the pre-tunnel, according to the hole diameter as in the scale model.

A mixfunc material has been applied to each of the panels surface as showed in Table 19,, using the perforate.cal; visualization on a small surface of such perforation and the shadows under daylight is shown in Figure 43.

The day 17th of June at the hours 11:30, 12:00, 12:30, 13:00, with a clear sky condition have been simulated.

C. Optimization of the panels

The scope of the second part of the work was to obtain lighting conditions inside the pre-tunnel and the tunnel so that the illuminance trend is close to that represented in the CIE graph reported in Figure 33.

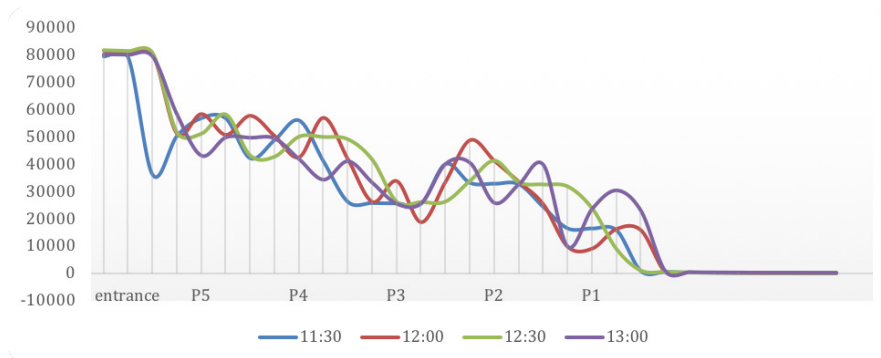
A new set of 5 panels having the same dimensions (20x20 m) but different puncturing have been tested; the puncturing has the same square grid of 5 mm of side in all the panels and different holes diameters, as shown in Table 20.

This second 3D model with the new panels disposed from P5 to P1 starting from the tunnel entrance to the end of the pre-tunnel has been calculated, and the same settings of the previous simulation have been set.

Filter	Panels				
	P1	P2	P3	P4	P5
Hole diameter (mm)	1.5	2.5	3.0	3.5	4.0
Inter-distance (mm)	5.0	5.0	5.0	5.0	5.0
K parameter	0.07	0.2	0.28	0.38	0.5

Table 20 Puncturing of new the set of panels

Figure 44 First simulation: mean illuminance trend along the pre-tunnel



Results

The results of the first simulation are showed in Figure 3, where the illuminance along the pre-tunnel is reported: in the graph, the trends for each hour of the mean illuminance (E_m) in the surfaces of measure is showed.

The results obtained with the simulation are very similar to those obtained in the previous work with the 1:20 scale model. Indeed, the simulated curves of mean E present an irregular trend: in particular, the E level rapidly diminishes under the P3 panel and then rise again under the P2 panel. For improving this trend, a new set of panels has been developed in the second model.

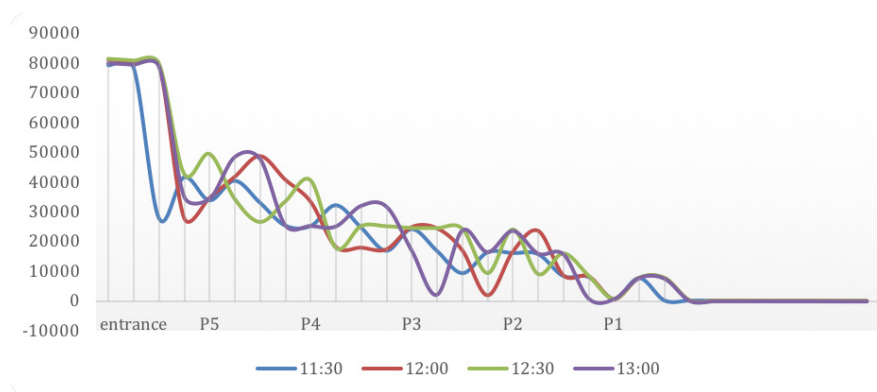
In the second sequence of panels, the primary variable is the diameter of the holes that increase, but their inter-distance is fixed (5 mm); this permitted to obtain a more regular trend, as shown in Figure 45.

For evaluating the performance of the panels the attenuation percentage has been defined as $A(\%) = (E_{int} - E_{ext}) / E_{int}$, where E_{int} is the mean illuminance in the measuring surface under each panel and E_{ext} is the illuminance in the external measuring surface.

For both the simulation models the $A(\%)$ has been calculated under each panel and plotted with the correspondent value of K parameter, which represent the empty/full ratio of the panel. In the first model, where the holes inter-distance is variable, there is not a linear relationship between $A(\%)$ and the K parameter. In Figure 46 is shown that the P4, having $K=0.38$, produces higher attenuation respect to panels P2 and P3, having $K=0.6$ and $K=0.5$ respectively.

In the second model, the K parameter has been used with a standard matrix of perforation, producing a more regular sequence of panels. In this latter case a linear

Figure 45 Mean illuminance trend along the pre-tunnel



relationship between the A(%) and the K parameter of the relative panel is noticeable in the graph of Figure 47. Notice also that in the second graph, the order of the K parameters corresponds to that of the panels in the simulation, while in the diagram of Figure 46 the order is different.

Conclusion

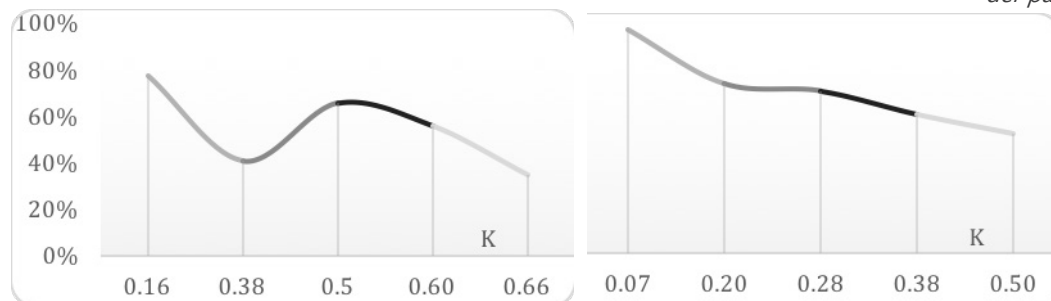
In this work, a study on filter panels has been performed using the simulation software methodology. Other studies used the same software for simulating the daylight interaction, demonstrating high accuracy prediction; indeed previous works used software with vertical surfaces, while this work simulated the behavior of horizontal panels. The similarity with results obtained in the authors' previous study [97], where a real scaled model had used, indicated that the software produces good results also in case of horizontal settings, and it can be a valid instrument for the simulation of the pre-tunnel structure.

In this work, the software allowed to enhance the sequence of panels of the pre-tunnel respect to that realized in the previous work: in fact, the panel disposition in the second case study produces a better illuminance trend under the pre-tunnel than that of the original configuration. The illuminance attenuation also confirms this result showed in Figure 47. Nevertheless, the 3D model can be improved for realizing a more comfortable E distribution.

The analysis of data obtained with the two simulation models indicated that the K parameter as defined in previous work is insufficient for optimizing the illumination trend through simulation. The correlation of K parameters with the illuminance attenuation produced under the correspondent panel evidenced the need to define a fixed holes inter-distance to use the K for optimization. Future work will be carried out for analyzing the relationship between K and hole inter-distance with the aim of finding a law that correlates these two parameters.

Figure 46 Illuminance Attenuation under panels with variable inter-distance

Figure 47 Illuminance Attenuation under panels with fixed inter-distance





CaseStudy: MIBAC - La Quadriennale Di Roma - Institution For Contemporary Italian Art At former Papal Arsenal, Rome

The Quadriennale di Roma is a national institution with the task of promoting contemporary Italian art. Its name is linked to the Esposizione Quadriennale d'Arte, the four-yearly exhibition that documents the latest trends in the Italian visual arts. The former arsenal of Ripa Grande outside Porta Portese in Rome, Figure 48, the recent acquisition of MIBAC, will become the main temporary exhibition building of the institution. The building, whose architect is unknown, was conceived as analogous to the arsenal of Civitavecchia and was erected in the 18th

century.

Flexibility design to host temporary art is the intent behind the proposal of the restoration and preliminary studies to identify the problems related to daylight admission regarding the variety of art collections are presented. The analysis of the lux hours in a vertical grid simulating the main exposition space and inherited data are plotted in graphs to guide architecture design for openings, blinds, automated screens. Moreover, provide insight to decision making as for the typology of collections and the period to be exposed.

Figure 48 View of the Arsenal



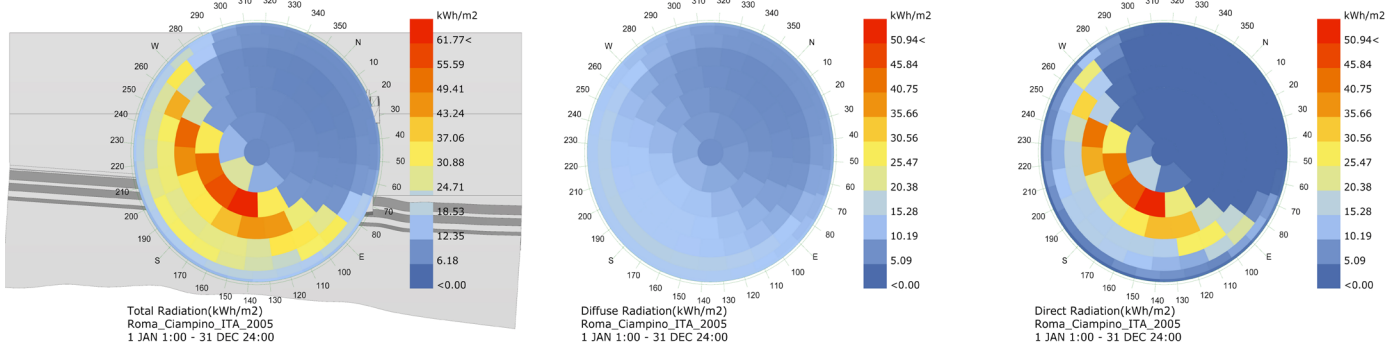
The critical volume of the building with big openings characterizing the arsenal is in conflict with preservation request for low lighting levels. Furthermore, the openings create a variable background meanwhile visiting the space and create harsh transitions and high contrast viewing. The hypothesis of the application of a 'filter' surface as previously examined [96,97,99] in horizontal ceilings, is examined through simulation.

The flexibility request doesn't permit to establish a criterion for acceptable rate of fading as risk based on Table 2. Though the period that causes just noticeable fading for Medium sensitivity objects at a level of 150lx and the range 7-200 years is a useful input for properties selection on art. The concept of alternate mix short periods of better visual access with long periods of minimal visual access is proposed and exposure time as result of calculating what display rotation respects the fading criterion set based on the temporary collection.

The proposed workflow for a holistic museum lighting study is pointed in three successive steps and include artificial and daylight considerations:

- I. Ambient light - Functional: guaranty control of damage and viewing by color fidelity

Figure 49 radiation dome Total, Diffuse and Direct



- II. Focal glow - Simulation: modeling the vision and the appropriate thresholds by metrics
- III. Sharp detail- Exhibits: target detection in the relationship with luminance and brightness

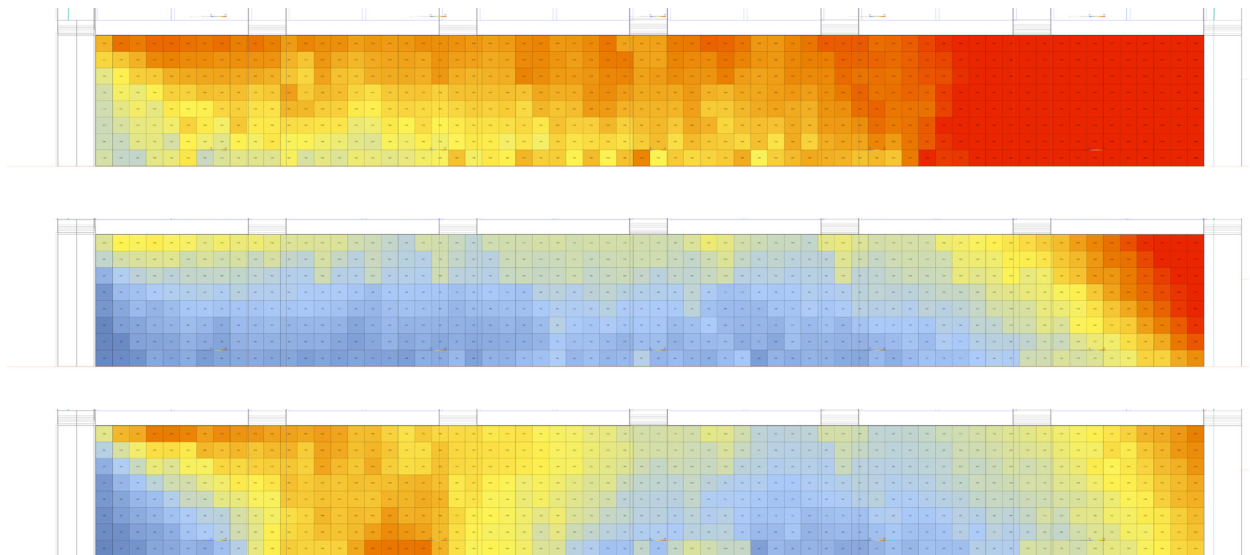
Materials and methods

Preliminary studies through DIVA for Rhino have been held and assessments regarding daylight levels when a single glazed glass is used to cover the big openings looking at the main square and entrance of the arsenal.

Daylight metrics have been evaluated through Grasshopper tool that is a graphical algorithm editor tightly integrated with Rhino's 3-D modeling tools. A workflow has been studied that calculated daylight metrics and verification of criteria described in LEED v4 have been explored.

The 3d model has been constructed with Rhinoceros 5 software Daylight calculations have been carried out using three different processes of Radiance simulation

*Figure 50 Daylight admission 20Sept.
h. 9.00, 12.00, 16.00 with clear glass*



tools provided by DIVA, Honeybee and Honeybee [+] including the 3-phase and 5-phase method which is the most accurate evaluation of the spatial distribution of direct sunlight.

The climate file used is International Weather for Energy Calculation (IWEC) for Rome, at (N 41° 90' 28"; E 12° 49' 64"), as the most closed to real geographic coordinates of the scale model at the Italian city Ciampino (41° 48' 8.7300" N; 12° 36' 7.7004" E). The measuring surface of 32mx3 has been positioned on the central axes of the left structure. Their inter-distance of the sensors is 1m and results report mean illuminance.

Simulation parameters have been set according to typical scene 2 used in Radiance [100] Ambient bounces:7, Ambient division:1500, Ambient sampling 100, Ambient accuracy 0.1, Ambient resolution 300, Direct threshold 0, Direct sampling 0 under CIE clear sky. Materials RGB reflectance, specularity, and roughness have been set as in Table 17.

As to maintain model's file dimension to reduced size and as to simplify daylight calculation given the complexity of the scene, the perforated screens have been simulated by the application of a mixfunc material. We have defined a very transmissive glass and a plastic material and combined them in such a way as to create our screens; a perforation function has been used see Appendix III. In the 5-phase method an .xml BSFD material has been introduced to simulate the perforation.

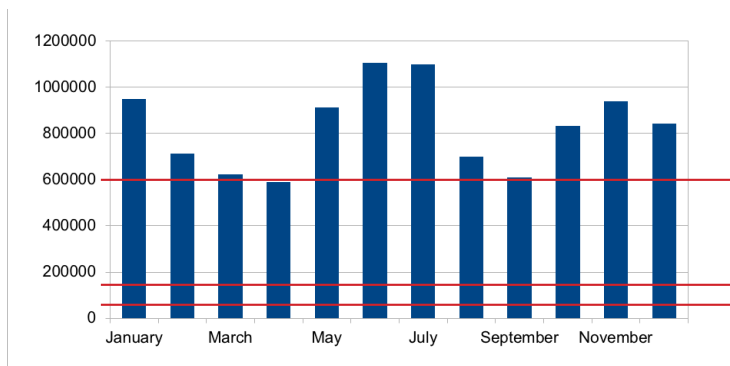


Figure 51 Plot of cumulative luxhour

Results

A. Simulation through Diva

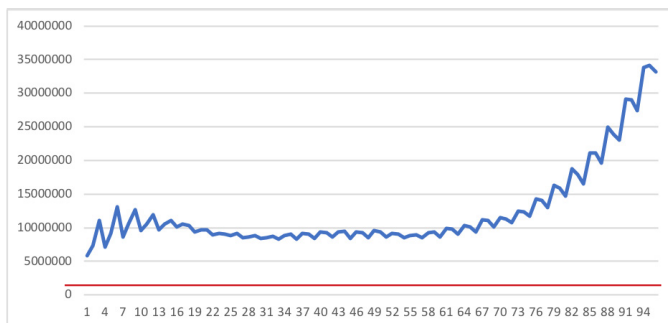
The tools provided by DIVA for Grasshopper plugin have been used for annual daylight simulation. The illuminance in Figure 50 simulated for 20 Sept at h.9.00, h.12.00, h.16.00 give information for the distribution of the daylight. The plugin is limited to hourly data but the ill files post production give as insight to cumulative lux hours. The file contains mean illuminance data for each sensor in 1hour step and results are plotted in Figure 51 for a random sensor. The red lines describe the benchmarks of limitation as described by CIE for the three categories of sensitivity. An occupational profile is inherited limiting data for opening hours 9-17 assuming that the space should have blinds to be obscured in the rest of the daylight exposure. Even though the annual lux hours recommendation is covered in a month's exposure for the selected sensor and mean values give the same result. ASE output has been extracted but the data are not helpful for direct illuminance only.

Figure 52 Plot of cumulative luxhour for the sensors across the section of the building

Figure 53 Plot of the distribution of lux-hours for the hours 9-19

B. 3-Phase simulation

The tools of Honeybee [+] for 3-phase simulation have been used for annual daylight calculations. Data exported for cumulative lux hour per sensor are plotted in Figure 52. The openings of the building contribute to an overexposed environment which necessitates of daylight restriction strategies. An occupational profile has been later added restricting the opening hours 9-19 reducing the daylight stress of 26%. The plot in Figure 53 shows the distribution of the lux hours during the opening



hours where the most critical are until the 14.

Changing the opening hours to 14-19 the cumulative illuminance decrease to 78% . In Figure 54 the amounts are plotted per sensor but still grid is over exposed based on the criteria for museum lighting.

Another parameter that should be controlled is the component of direct illumination whereas high temperature could cause degradation. The component of the diffuse and direct light has been divided and in Figure 55 is plotted. Screens are necessary to diminish the exposure to direct sun.

C. 5-Phase simulation

The tools of Honeybee [+] for 5-phase simulation have been used for annual daylight calculations. The BSDF material of perforated surface has been applied to the large opening of the main facade of the building and results are shown in Figure 54.

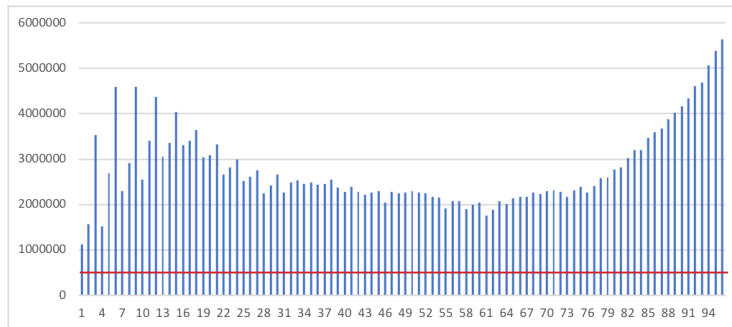


Figure 54 Plot of cumulative luxhour for the sensors across the section of the building

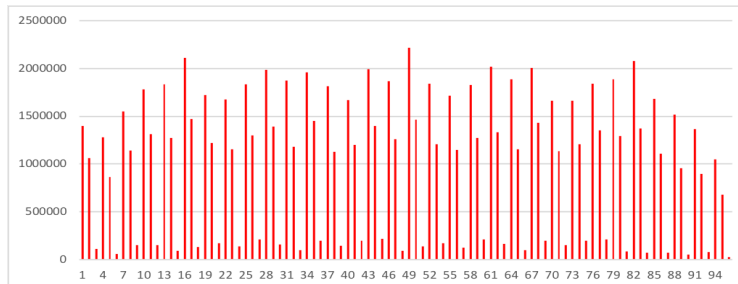
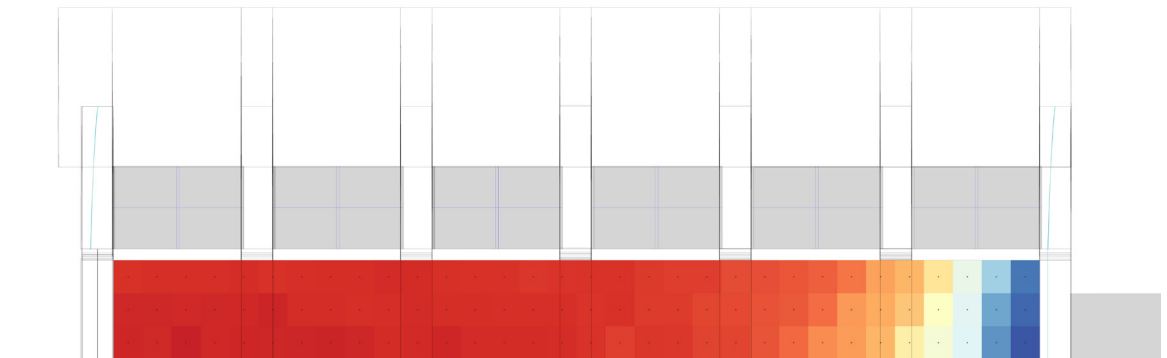


Figure 55 Plot of the distribution of lux-hours for the hours 9-19

Figure 56 Rendering of the exhibition space



Figure 57 Application of perforated material in the large opening of the main facade



Conclusions

Assessments of the pre-tunnel structure have been used to define a possible simulation workflow and permit the hypothesis of a case-study where the filter zone can be applied in a museum environment. The parametrization of the holes can lead to successive workflows for similar applications and strategies for general applications of 'trama' surfaces in Heritage. For this cause a location in Rome has been identified for MIBAC La Quadriennale Di Roma - Institution for Contemporary Italian Art at former Papal Arsenal after Porta Portese; buildings destination as a gallery for fine arts based on a recent project is therefore evaluated under the holistic approach via simulation.

In this study a 'trama' surface is studied to be installed on windows to reduce and control systems to ensure energy and conservation objectives are being achieved. New light sources and smart control systems are integrated into a holistic approach to museum lighting design.

Pairing energy-saving demand and lighting quality is an essential challenge in galleries; reviewing the control of existing daylight systems or re-opening windows and skylights that have been obscured can lead to many benefits. The use of daylight within display spaces, when used successfully, can reduce a considerable amount of electric lighting use and give significant benefits for museum staff since access to daylight and views can improve wellbeing and productivity. Therefore, control is fundamental to the success of any museum and gallery lighting installation.

Appendix

- I. *The concept of Daylight Factor (DF) was developed in the United Kingdom in the early 20th century describing a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under CIE overcast sky conditions only.*

Daylight factor is the most common metric used when studying physical models to test daylighting designs in 'overcast sky simulators. It is reasonably easy to calculate in real buildings or physical models with illumination meters.

Daylight Factor outputs are helpful in making quick comparisons of relative daylight penetration under overcast sky conditions and is arguably less useful in climates with a great deal of sun.

Early versions of the USGBC, LEED rating system originally required a DF ³ ₂ for at least 75% of the critical visual task zones to achieve indoor environment credit 8.1. British Standard Institution, BS 8206-2 requires DF ³ ₂ or 5 depending on electric lighting requirements to support human well-being.

Daylight Factor can be reported with static or dynamic measures; however, it is most commonly considered statically (at a single point in time) as shown above. In fact, the stability of DF regardless of the time of day and year (assuming an overcast sky) is one of the benefits of the metric.

The daylight factor is defined as the ratio of the natural illuminance at a particular point on a horizontal plane to the simultaneously occurring external illuminance of the unobstructed overcast sky. In Britain, the standard sky is assumed to give at least 5000 lx of illuminance on the ground.

$$\text{Daylight Factor (DF)} = \frac{\text{Internal Illuminance}}{\text{External Illuminance}} \cdot 100$$

*The daylight reaching any point inside a room is usually made up of three components:
Sky component*

Externally reflected component

Internally reflected component

If there is no external obstruction like trees, buildings etc. the externally reflected component is omitted. Several techniques, manual as well as computerized, may be used to calculate these components for a building.

In side-lit rooms, the maximum DF is near the windows, and it is mainly due to the sky component. In the early stages of building design, the average daylight factor may be used to assess the adequacy of daylight:

$$\text{Average DF} = \frac{W}{A} \frac{\tau \theta}{(1 - R^2)}$$

where: W is the area of the windows (m²)

A is the total area of the internal surfaces (m²)

T is the glass transmittance corrected for dirt

θ is visible sky angle in degrees from the center of the window

R is the average reflectance of area A.

The values of these quantities are determined from the given data and W, T and R are corrected by using factors publications.

**different manual formulas to calculate the DF can be found*

- II. *Daylight metrics are software based, dynamic input of local geographical and weather data, giving results in annual calculations, definitions are given in the 10th edition of The IESNA Lighting Handbook [53]*

Daylight Autonomy (DA)

The simplest and most widely applied annual metric is daylight autonomy. This is a measure of the percentage of the operating period (or number of hours) that a particular daylight level is exceeded throughout the year. This metric is used to address performance at individual analysis points, but can also be used to evaluate the magnitude and general distribution of daylight across a space. Because the metric tallies only the time when a target value is exceeded, it provides a measure of how well daylight can replace electric lighting when the electric lighting will be switched via a photosensor, and may be used to evaluate general daylight coverage and lighting control zone depth. Daylight autonomy can also be used to assess the number of hours or percentage of hours when a particular condition is exceeded, such as the illuminance on an artifact in a museum.

Continuous Daylight Autonomy (cDA)

A modified version of DA, which is referred to as continuous daylight autonomy, is more

appropriate for the evaluation of system performance when the electric lighting system is dimmed. With cDA, hours for which the target value is partially achieved receive partial credit. For example, if a space receives 300 lux of daylight over a one-hour period when the target is 500 lux, 0.6 hours of coverage are credited. cDA should correlate well to the lighting energy savings potential of a lighting control zone that applies dimming when analyzed at the critical task point that will be used for calibrating the lighting control system.

Zonal Daylight Autonomy (zDA)

Zonal daylight autonomy (zDA) is a metric for assessing daylight sufficiency across an entire space with a single value. This approach requires the designer to first define the limits of the space or area to be analyzed. Then the number of hours that each sensor meets or exceeds 300 lux is determined and then summed across all sensors. The resulting total for this analysis, which effectively computes the average daylight autonomy fraction for the defined space. Higher zDA values represent longer periods of usable daylight within and across the space. Research has suggested nominal occupant acceptance of daylight sufficiency begins at $zDA_{300} = 50\%$ and satisfaction increases proportionally as the value increases. The upper limit feasible for a standard 10 hour per day annual analysis is close to 90% for zDA_{300} .

Spatial Daylight Autonomy (sDA)

Daylight autonomy can also be used to assess daylight coverage using a metric referred to as spatial daylight autonomy (sDA). This metric reports the percentage of sensors (or building area) that achieves a minimum daylight illuminance level (typically 300 lux) for a minimum percent of the analysis year (time). It is recommended that the percent time component be locked-in at 50% of the time. For this approach, each sensor point that achieves at least 300 lux for at least 50% of the analysis year contributes to the area that meets the criteria. The qualifying sensor points do not need to achieve 300 lux at the same time, just for the same percentage of the year. This approach allows the designer to plot on a floor plan iso-contours of the percentage of time each sensor reaches this goal. Research has suggested that for a given room, occupants find the daylight levels nominally acceptable when $sDA_{300} > 50\%$, and are progressively more satisfied as the area increases above 75% to an upper feasible limit of approximately 95%.

Temporal Daylight Autonomy (tDA)

A space's temporal daylight autonomy is an estimate of the fraction of time that a target illuminance level, such as 300 lux, is achieved over 75% of the space. The value is computed by determining the 25% percentile DA value across all points within a space (this is the DA value that 25% of the analysis points are below). Since these points may not reach a particular illuminance value at the same time, tDA_{300} differs slightly from the fraction of time at which 75% of the points reach a particular target value

simultaneously.

Useful Daylight Illuminance (UDI)

Another proposed metric is Useful Daylight Illuminance [58]. This metric compiles the number of operating hours that fall into three different illuminance ranges at an analysis point (often <100 lux, 100-2000 lux and >2000 lux). Useful daylight is considered to occur when the daylight illuminance is between 100 and 2000 lux (UDI₁₀₀₋₂₀₀₀). UDI<100 evaluates the number of hours with insufficient daylight, while UDI>2000 considers the number of hours with excessive daylight that is likely to increase cooling loads and deliver higher levels glare and discomfort.

Direct Sunlight Hours

Another useful measure is the number of hours when a particular analysis point is likely to receive direct sunlight. This information signifies the length of time that operable shading devices may be required, and is helpful in evaluating exterior shading strategies and design solutions for sunlight penetration. Site weather data and neighboring structures should also be considered. A possible implementation of this metric would involve a tally of the number of hours per year when direct sunlight alone (with no sky, ground or interreflected contributions) exceeds 1000 lux based on Perez sky distributions based on site weather data.

The light damage calculator [101] is an online tool from the Canadian Conservation Institute that provides an estimation of the fading of colors exposed to light, based on the best available data. There are several sources of uncertainty: ambiguity in the identification of the colorants in the object, imprecise fading data for that colorant, inaccuracy in the representation of colors on a computer screen. Despite these uncertainties, the calculator can show the wide sensitivity range of colored objects and the influence of exhibitions on the future appearance of collections. Original and faded colors are presented as patches on the computer screen. Since some computer screens and many computer projectors, do not distinguish small changes in color, the height of the faded color patch also changes in proportion to the amount of fading.

There are three different uses for the light damage calculator. The three calculators are the following:

Fading of a single colorant - This provides an estimate of the fading of a single colorant under a single set of conditions. The scientific measurement of the fade, the color difference ΔE , is provided.

Fading of a single colorant in three different scenarios - This provides a side-by-side comparison of the fading caused by three different exposure scenarios.

Fading of a collection of colored objects

This presents the fading of collections of colors. These may be collections in the conventional museum sense (such as a textile collection or a watercolor collection), or they may be collections of colors in a particular type of object (such as the three dyes used in a particular kind of color photograph).

III. *The function was developed by Abel Boerema 2004, n.a.v. Georg Mischler 30. 04. 1993*

```
'xn = mod(Px, 1) - A2;
```

```
'yn = mod(Py, 1) - A3;
```

```
'zn = mod(Pz, 1) - A4;
```

```
{uv coordinate mapping}
```

```
'un = mod(U, 1) - 0.5;
```

```
'vn = mod(V, 1) - 0.5;
```

```
{uv mesh coordinate mapping}
```

```
'lun = mod(Lu, 1) - 0.5;
```

```
'lvn = mod(Lv, 1) - 0.5;
```

```
'outofcirc(x, y, r) = if(sqrt(x*x + y*y) - r, 1, 0);
```

```
z_hole = 'outofcirc('xn, 'yn, A1);
```

```
x_hole = 'outofcirc('yn, 'zn, A1);
```

```
y_hole = 'outofcirc('zn, 'xn, A1);
```

```
{uv coordinate mapping}
```

```
uv_hole = 'outofcirc('un, 'vn, A1);
```

```
{uv mesh coordinate mapping}
```

```
luv_hole = 'outofcirc('lun, 'lvn, A1);
```

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