Advanced LED lighting system applied to cultural heritage goods

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ABSTRACT

Nowadays LED lighting devices are incorporated to most important lighting companies. Advantages of these systems are very well known: timelife, size, compact, variation of output flux,... One of the most applied characteristic is the possibility to obtain with the same system different colors. It is possible without complex and expensive systems to obtain a tunable spectral light. In cultural heritage lighting system it will be a very important characteristic since it will make possible to obtain an optimized spectral source. Art works lighting is a very complex problem where needs for display and conservation are in conflict. Electromagnetic radiation is an agent which causes changes in material composition of painting and therefore degradation of them. In the other hand displaying art works in good conditions requires visible radiation onto the surface of paintings. This idea is applied in the problem which arise when illuminanting Paleolithic cave paintings. In this work the authors have applied a methodology which permits optimize the color reproduction and to reduce the damage of paintings.

Keywords: Light and architecture, color in architecture, Color in art works, Applied Colorimetry, Lighting cultural heritage.

1. INTRODUCTION

There is not a good solution for lighting cultural heritage goods. We never can light a piece of art without an irreversible damage, therefore conservation of cultural heritage and its associated artistic production raises two major problems. On the one hand, it is necessary to exhibit the artistic production which is the historical patrimony of a country. It is necessary to get high quality in luminance, uniformity, contrast and color reproduction. On the other hand, an adequate conservation of them requires, in order causing the minimal damage, to minimize the interaction of the artistic production exposed with the electromagnetic radiation [1-6]. In any case, two major requirements should be satisfied: to minimize the damage and to obtain a good color reproduction. For solving this complex problem we have to look for a compromise solution for the spectral reflectance since damage will be done by absorbed light and lighting quality will be obtained by reflected light. A parametric system will permit to study and to find out optimized solutions.

Depending on wavelength when light fall onto paint surface it can be reflected or absorbed in different grades. Reflected light will permit to people see the painting and absorbed will cause damage in paint. No matter what wavelength of light we are using always a percentage of light will be absorbed even in that spectral region where pigment has not color. In figure 1 we show a reddish pigment but we can see as even in blue region the pigment is absorbing around 10% of light. Therefore the first necessary data is spectral reflectance. We have measured the spectral reflectance of paintings located in El Castillo Cave which is one of the named by UNESCO as World heritage in Cantabria. Although it will not be important for conservation criteria the spectral reflectance of the rock in the surroundings of the paint has been also measured since we need to evaluate how will be the contrast. A very important criteria for optimizing the illuminant is to answer this question: when the paint is well seen or at least enough well seen?. In this case In order to answer that questiont, we have considered that the rock paintings are illuminated with the spectral radiant distribution of a blackbody radiator at temperature T_t=1850 K (section 2). We have used this illuminant because this is the approximate temperature of a torch, which we assume that was the lighting source used by the original artists. In this way, the tristimulus values obtained with this illuminant are associated with the color stimulus perceived by the person who created the painting. In all this work we will consider these tristimulus values as the reference ones. Of course, when adopting this criterion, we have assumed that the color perception of the visual system of the human in the Upper Paleolithic was similar to that of the human at present. The Section 3 of this work an analysis of the colorimetric changes in the perception of the painting and rock when different sources of light are used is done: blackbody radiator at different temperatures, 38 illuminants recommended by the CIE [7] and a halogen lamp). The colorimetric changes are quantitatively evaluated by computing the distances in the CIELAB space between the color stimulus evoked to the observer when illuminating with the torch (reference tristimulus values) and that color stimulus generated when other different illuminant is used. By using the relative spectral response function (damage function) proposed by the CIE [6], we have computed in Section 4 the effective irradiance damaging the painting for all the light sources previously used. The behavior of the different illuminants regarding to the produced damage is compared.

The rock paintings of this cave have a reddish tone fundamentally. This tonal simplicity will allow us to design a lighting source which spectral radiant power distribution minimizes the damage caused by the interaction of the pigment of the painting with the radiation without a significantly change in the color sensation as perceived by the original artists. In order to minimize the exposure of the pigment to the radiation, we will use low surrounding luminance levels. In the global project adaptation of the public will be the key. The spectator must pass from outside day luminance levels to very reduced luminance levels. It will be possible thanks to a visit time schedule where public will have enough time for change from photopic vision to almost scotopic (but with enough good color perception capacity). Other factor where lighting designer must be very careful is avoiding public see directly light sources or near surfaces of light sources. In the last part of this work, using a functional equation model, we propose an illuminant whose spectral distribution diminishes the damage by minimizing the absorption of radiation and optimizes the color perception of the paintings in this cave. The procedure followed in this study can be applied to optimize the lighting systems used when illuminating any other kind of art work.

2. CHARACTERIZATION OF THE ENVIRONMENT

In this case where we are trying to optimize cave paint the two important factors are spectral reflectance of rock and paint. Spectral reflectance of the pigment has been measured in four different zones of the painting. The average curve will be denoted in the following as $r_p(l)$. It has been also measured the spectral reflectance, $r_r(l)$, of the wall in the surrounding of the painting in absence of pigments (rock). In figure 1 we show where are placed the measured points in a bison drawing placed in Room 1 (Sala 1).

These measurements have been performed using an AvaSpec-2048-2 spectrophotometer in the spectral range from 270 to 900 nm with a step of 0,5 nm. Each panel has been measured in 5 zones. In each zone 10 data have been taken. The curves representing the spectral reflectances are shown in Figure 4. On each zone we have calculated mediam reflectance and its standard deviation. In figure 2 we show as an example the data for panel 1.

With the aim to evaluate the difference between zones of the same panel we have calculated tristimulus values when we light with CIE A illuminant, similar to the torch used by the prehistoric artist.

$$\left[X_z^{(a)}\right]^A = K_A \sum_{j=1}^{M} \overline{r}_z^{(a)}(l_j) S_A(l_j) \hat{x}_i(l_j) \Delta l \, , \qquad (1)$$

where $\overline{r}_z^{(a)}(l)$ is average reflectance (1), $S_A(l)$ is the spectral irradiance of illuminant A for a illuminance of 40 lx and $\hat{x}_i(l)$ (i=1, 2, 3) are CMFs of standard observer of CIE 1931. In table I we show tristimulus for in zone of panel 1.

Distances in CIELab space between each pair of zones in panel 1 is showed in table II.

2.1 Panel 1							
	z	1	2	3	4	5	Media
z'							
1		0	11.8	7.2	9.4	4.8	5.0
2			0	14.5	14.8	8.2	9.9
3				0	2.9	7.2	4.8
4					0	8.1	5.8
5						0	2.6
Media							0

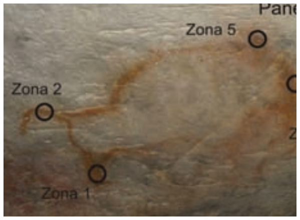

Figure 1:
Different places where spectral reflectance measures has been done.

Table I.- Distance CIELAB $\Delta E_{z-z'}^{a,A}$ between each pair of zones when are lighted with a illuminat A.

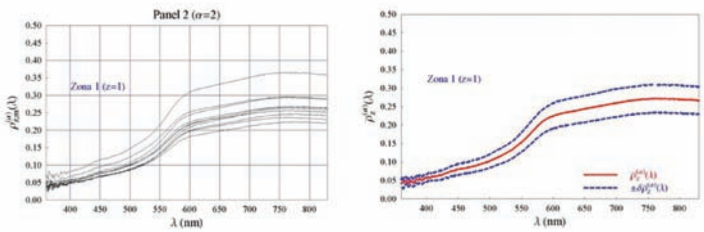

Fig.2.
Median reflectance and standard deviation in bison panel, point 1.

3. COLOR REPRODUCTION AND DAMAGE FOR DIFFERENT LIGHT SOURCES

When light source is not a torch the color will change. In this Section we will analyze the variations of the color when the painting and rock are illuminated with a lighting source different to a torch. In the first sub-section we will consider the chromatic displacements when the source of light is a blackbody radiator and its temperature is variated. The second sub-section is devoted to the analysis of changes of color when the lighting sources are those standard illuminants recomended by the CIE. A criterion for light the panels is to use a light source similar that was used by the author. If we think in a torch it would may be a balck body at 1850 ºK. For this source distance from pigment to rock, is to say the contrast is 12,3 CIELAB units and the damage factor, as it is defined in CIE 157(2004), is 5,7 W/m^2 .

In this case, the spectral radiant power exitance is given by $S(T,\lambda) = K(T)\frac{c_1}{\lambda^5}\frac{1}{e^{c_2/(\lambda T_t)}-1}$ W.m^{-3},)

where T is the temperature of the blackbody radiator. The value of K(T) is chosen in such a way that the total radiant exitance is coincidental with that of the blackbody radiator at the temperature T_{T_t} of the torch, i.e.,

In order to quantitatively compare the damage produced by different illuminants it is important that all of them have the same total radiant exitance, therefore the normalization from K(T) will play an important role when computing the damage that on the painting causes the lighting source. With the choice of K_T, we have done, we have assumed that in each case the reference white stimulus is the source of light used to illuminate the painting. The tristimulus values have been calculated in the range of temperatures running from T=100 K to T=7000 K in steps ∆T=100 K. We have compute de chromaticity coordinates $(x_1^p(T), x_2^p(T))$ and $(x_1^r(T), x_2^r(T))$ associated with the painting and the rock respectively.

The variation of the chromaticity coordinates exhibit an expected behavior. When the temperature of the lighting source is increased, the chromaticity coordinates of both, painting and rock, approache the center of the chromaticity diagram. It should be pointed out that the line describing the variation of the chromaticity coordinates of the rock is very similar to the Planckian locus. However, the painting has always a more reddish tone that the Planckian locus. This behaviour is an expected one if we analyze the spectral reflectances represented in Figure 2.

In order to quantitatively compute the differences between the color stimulus obtained when the painting and rock are illuminated with a torch a that color stimulus perceived when the lighting source is a balckbody radiator at temperature T, all the color stimuli specified in the CIE 1931 system have been transformed to the CIELAB color space [7]. As it is well known, in this space the coordinates (L*,a*.b*) of a color stimulus are related with the corresponding tristimulus values (X_1,X_2,X_3) in the CIE 1931 system by the following relations:

$$L^* = 116\left(\frac{X_2}{X_{2,w}}\right)^{1/3} - 16 \qquad a^* = 500\left[\left(\frac{X_1}{X_{1,w}}\right)^{1/3} - \left(\frac{X_2}{X_{2,w}}\right)^{1/3}\right] \quad b^* = 200\left[\left(\frac{X_2}{X_{2,w}}\right)^{1/3} - \left(\frac{X_3}{X_{3,w}}\right)^{1/3}\right] \tag{3}$$

and

where $(X_{1,w},X_{2,w},X_{3,w})$ are the tristimulus values of of the light source used in each case with $X_{2,w}$=100. By taking into account this transformation, from the tristimulus values, we have computed the coordinates $(L_{T_t}^p, a_{T_t}^p, b_{T_t}^p)$ and $(L_{T_t}^r, a_{T_t}^r, b_{T_t}^r)$ in the CIELAB space for the painting and the rock respectively when they are illuminated with the torch. In a similar way, the CIELAB coordinates $(L^p(T), a^p(T), b^p(T))$ and $(L^r(T), a^r(T), b^r(T))$ for the painting and rock when a blackbody radiator at temperature T is used as lighting source are also computed.

In the CIELAB space, the Euclidean distances can be used to represent approximately the perceived magnitude of color differences between two color stimuli. Thus, the colorimetric differences between the painting when illuminated by the torch and when the lighting source is the blackbody radiator at temperature T_t, can be computed as follows:

$$\Delta E_{T_t}^p(T) = \left[\left(L_{T_t}^p - L^p(T)\right)^2 + \left(a_{T_t}^p - a^p(T)\right)^2 + \left(b_{T_t}^p - b^p(T)\right)^2\right]^{1/2} \tag{4}$$

In a similar way, the color difference between the rock illuminated by the torch and illuminated by the blackbody radiator a temperature T is given by

$$\Delta E_{T_t}^p(T) = \left[\left(L_{T_t}^r - L^r(T)\right)^2 + \left(a_{T_t}^r - a^r(T)\right)^2 + \left(b_{T_t}^r - b^r(T)\right)^2\right]^{1/2}. \tag{5}$$

If we study black body behavior as a light source we can find other solutions around that point. In figure 4 we show the distance from **pigment** to rock as a function of black body temperature for an illuminance of 40lx. As it has been pointed out, in order to design an adequate lighting system for cave painting, or any other cultural good, it becomes necessary to analyze at the same time the color reproduction and the damage that the radiation produces on the illuminated object. In the following, we will compute the irradiance which produces damage for each one of the previously considered illuminants. We will refer to this irradiance as "damage effective irradiance". According with the recommendations provided by the CIE [6], this damage effective irradiance is given by $S(\lambda_j)D(\lambda_j)\Delta\lambda$,(6) where S(λ) is the spectral irradiance of the which is being tested and $D(\lambda)=e^{-a(\lambda-\lambda_0)}$ (7) is the damage factor proposed by the CIE. In the last expression the value of λ_0 is 300 nm and α is a constant whose value is 0.0115 nm^{-1} when oiled paints are considered (this is the more similar case to that of the cave paintings). By introducing in expression (7) the spectral distribution we have computed the damage effective irradiance as a function of the temperature of the blackbody radiator used as lighting source, $E_{dh}(T)$. Function $E_{dh}(T)$ is a monotonous increasing function of the temperature and, for the range of temperatures considered in this work (1000 K to 7000 K), the minimum and maximum values are 47 $W.m^{-2}$ and 985 $W.m^{-2}$ respectively. It should be pointed out that the damage effective irradiance produced by the torch is $E_{dh}(1850)$ =112 $W.m^{-2}$.

With these data we can state (afirmar) the optimal black body temperature is T_{min}=2194 K with a damage factor of $D_{mg}(T_{min})$=5.4 W/m^2. With this source the contrast would be higher and the damage is lesser.

Next, we will analyze the change of the color of the painting and rock when they are illuminated with a set of 40 different illuminants: the 38 illuminants recommended by the CIE plus a xenon and halogen lamps. The numbering used and the description of the illuminants are provided in Table II.

Table II. Description of the 40 used illuminants. The number in columns one and three is that assigned by us to each source of light. The nomenclature is that proposed by the CIE. 7-12: Standard fluorescent lamps; 13-15: Broad-band fluorescent lamps; 16-18: Narrow-band fluorescent lamps; 19-21: Standard halophosphate lamps; 22-24: DeLuxe type lamps; 25-29: Three-band fluorescent lamps; 30-32: Multi-band fluorescent lamps; 33: D65 simulator lamp; 34: High pressure discharge lamp; 35: Standard high pressure sodium lamp; 36-38: High pressure metal halide lamp.

α	Source	α	Source	α	Source
1	A illuminant	15	FL9	29	FL3.11
2	D65 Illuminant	16	FL10	30	FL3.12
3	C illuminant	17	FL11	31	FL3.13
4	D50 Illuminant	18	FL12	32	FL3.14
5	D55 Illuminant	19	FL3.1	33	FL3.15
6	D75 Illuminant	20	FL3.2	34	HP1
7	FL1	21	FL3.3	35	HP2
8	FL2	22	FL3.4	36	HP3
9	FL3	23	FL3.5	37	HP4
10	FL4	24	FL3.6	38	HP5
11	FL5	25	FL3.7	39	Xenon lamp
12	FL6	26	FL3.8	40	Halogen lamp
13	FL7	27	FL3.9		
14	FL8	28	FL3.10		

Let $S_\alpha(\lambda)$ be the spectral radiant power distribution of the illuminant α (α =1, 2, …, 40). This distribution has been normalized in such a way that the total radiant exitance is coincidental with that of the blackbody radiator at the temperature T_{T_t} of the torch. The tristimulus values obtained for the painting and rock when the illuminant is used as lighting

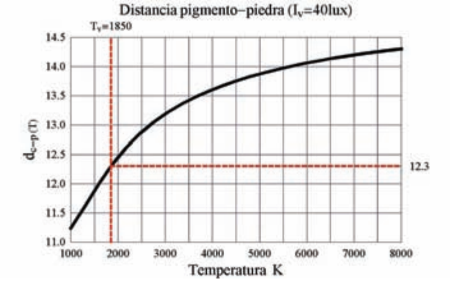

Fig.3
Distance in CIELAB units from paint to rock as a function of black body temperature for a illuminance of 40lx

source are respectively. When designing a lighting system for cave paintings, we must be careful in the choice of the source of light. In order to choice a such illuminant, we must to quantitatively stimate the color differences between the color reproduced with a given illuminant and the color that we like to reproduce. It will be done in the following. From the previous results, and taking into account Equations (11) we have transformed the tristimulus values in the CIE 1931 system to the CIELAB system. We will denote as (L_a^p, a_a^p, b_a^p) and (L_a^r, a_a^r, b_a^r) the coordinates in this spaces of the painting and rock respectively when the lighting source is the illuminant α. In order to quantitatively evaluate the colorimetric behaviour of the forty illuminants considered in this work, we hae computed the distance in the CIELAB space between the color stimulus associated with the illuminant α and the color stimulus obtained when the lighting source is the torch.

The values obtained for these distances are represented in Figure 5. A quickly inspection of this figure points out how the distances are considerably larger for the painting than for the rock.

It should be pointed out that, when the painting is illuminated with any of the forty considered sources of light, all the values of the distances are grater than three CIELAB units. In this way, the colour perceived by a standard observer is always different, with the illuminants listed in Table 1, than that perceived by the original artists. When the painting is considered, the larger value of the distance is obtained for the illuminant 34 (High pressure discharge lamp HP1) with $\Delta E_a^p = 4$ CIELAB units and the lesser value is reached for the illuminant 22 (DeLuxe type lamp FL3.4) with $\Delta E_a^p = 14$ CIELAB units. In any case, this distance is very large, in such a way that the corresponding illuminant does not provide an adequate color perception.

In a similar way, when the $s_a(l)$ spectral distribution associated with the illuminant α is used in expression (15) we obtain the damage effective irradiance, E_{dm}^{a}, for the corresponding illuminant. The results obtained are represented in Figure 9. The minimum value (E_{dm}^{1} =3,38 W.m^{-2}) is reached for the A illuminant (α=1) and the maximum (E_{dm}^{21} =10,65 W.m^{-2}) is obtained for the Standard halophospate lamp FL3.3 (α=21). In any case all the illuminants produce a damage effective irradiance higher than that of the torch.

The illuminants for which the damage is lesser are those with α=1, α=35, and α=34, but, as it is shown in Figure 5 (a), they have too large values of the distance in order to provide and adequate color perception for the painting. For these illuminants the distances ΔE_a^p are 18, 15, and 44 CIELAB units respectively. With these values it is not possible to obtain an adequate chromatic reproduction. Use of a standard illuminate as we have showed in previous section give us few flexibility levels for design and it can permit optimize design parameters. With the aim to improve the quality of the proposed solution we are going to study sources where we can modulate the spectral distribution as we can find in LED systems. This kind

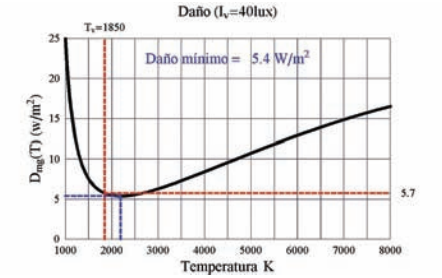

Fig.4
Damage factor as a function of black body temperature for a illuminance of 40lx

of device have other advantages when the are made with quality production controls: life, stability, start time, ... In this case we are going to study a system with 3 LEDs, red, green and blue, as we can find in the market, with subindex 1,2 and 3 respectively.

The spectral distribution $S_L(\lambda)$, of designed illuminant is obtained as a lineal combination of these three LEDs.,

$S_L(\lambda) = \sum_{\beta=1}^{3} K_\beta L_\beta(\lambda)$,(8) where K_β are the parameters used to optimize the illuminant. CIELAB coordinates for rock and paint are $\left(L_L^c, a_L^c, b_L^c\right)$ and $\left(L_L^p, a_L^p, b_L^p\right)$ respectively.

In order to define the functional which will optimize the spectral distribution of the illuminant we are going to use the next parameters:

Damage (D_{mg}): It is calculated carrying on the CIE recommendation.

Color contrast between paint and rock (d_{c-p}): It will be calculated as the distance in CIELAB space when we light with designed illuminant from coordinates of paint to the rock.

Torch to illuminant distance (d_a) :It is the CIELAB distance from color of paint when it is lighted by a blackbody at 1850ºK (torch) and when we use the designed illuminant.

In order to find out the best spectral distributions of light source we are going to use a functional. For making this functional we will use the previous parameters: Damage, contrast and distance. These parameters will have different weigh as consequence of the importance of each one. Most important parameter will be Damage, since we want to conserve the paint as well as possible, second will be the contrast, since we want public perceive the paints, and third will be the distance with original light source, the torch.

$F_2(D_{mg}, d_{c-p}, d_a) = \left(D_{mg}\right)^2 - \left(d_{c-p}\right) + \sqrt{d_a}$. (21) In figure 7 we show the relationship K_1 and K_2 of and constants. K_3 will be infer of them.

The solution of K_1, K_2 and K_3 which make minimum the functional (21) are $K_1=4$, $K_2=10$ y $K_3=1$.

For a illuminance of 40 lx damage, color contrast between paint and rock and torch to illuminant distance are

$D_{mg}=4.6$ W/m^2, $d_{c-p}=15.9$ y $d_a=23.8$.

4. CONCLUSIONS

Lighting of cultural heritage goods is a problem with requirements very severe as much from perception and conservation point of view. In this work we have analysed the change of the color sensation produced when different sources of light are used to illuminate a cave painting. We have also study the damage produced on the painting as a function of the illuminant used. As a consequence of this analysis, we have proposed as source of lighting an optimal illuminant. This illuminant provides very low values of the effective radiant exposure and a better color perception than that obtained with all the other considered illuminants. The Methodology followed in this work can be systematized in order to be applied to optimise the color perception and the produced damage in the design of any other lighting project applied to cultural goods. Results obtained in each project will be different and they will depend on the specific

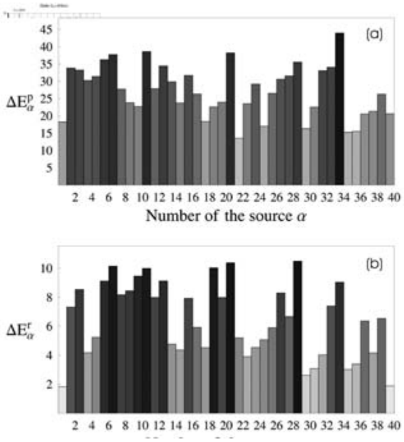

Fig.5.
Values of the distance between the color stimulus obtained when illuminating with the illuminant α and the stimulus generated when the lighting source is the torch. (a) Distances for the painting, given by Equation (19). (b) Distances for the rock, given by Equation (20).

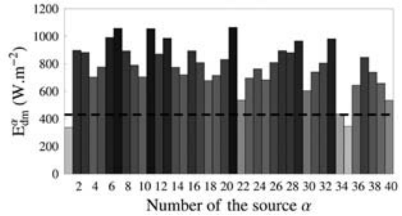

Fig. 6
Damage effective irradiance for the forty illuminants considered in this work. The dashed line corresponds to the value, E_{dm}^{opt}, obtained for the optimal illuminant.

circumstances of each considered case.

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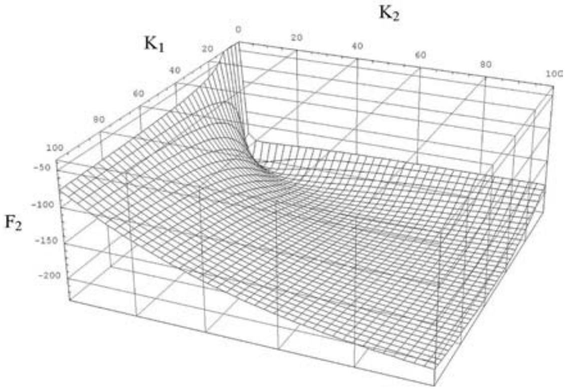

Fig. 7:
Relationship between K_1 y K_2 in Functional (21).

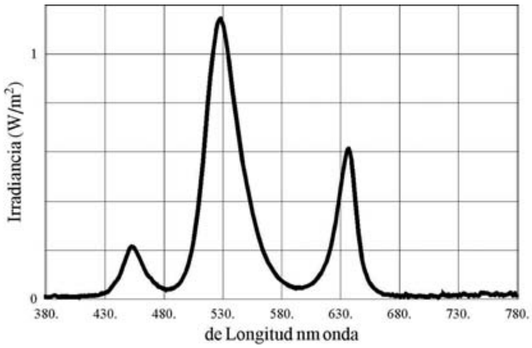

Fig. 8:
Spectral distribution of the solution illuminant with $K_1 = 10$, $K_2 = 4$, $K_3 = 1$.