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An Approach to Control the Illuminance Distribution on Vertical Display Surfaces

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Abstract
In museum exhibition halls, two-dimensional artworks are displayed usually on vertical surfaces. The uniformity of illuminance distribution in the exhibition area is significant. The control of the illuminance distribution depends on the dimensions of the exhibition hall, the size and location of the exhibition area, and the type, luminous intensity distribution, and position of the luminaire. This study aims to identify the optimal conditions to acquire the targeted illuminance uniformity. For this purpose, sixteen situations were composed concerning four different heights of the exhibition hall and four exhibition areas of various sizes. The luminaires used in the investigation were small and linear with symmetrical and asymmetrical luminous intensity distributions. The position of each luminaire was arranged in the mentioned sixteen situations to obtain optimum conditions. The comparison of the results referred to the energy consumption.
Keywords: Vertical Display; Illuminance Uniformity; Energy Consumption; Luminaire Features.

1. Introduction

Museums preserve and display works of art and valuable and interesting objects of artistic, historical, or cultural importance. International standards guide museum lighting to balance display and conservation needs. The works of art and other objects to be displayed in exhibition rooms are classified by the European Committee for Standardization (CEN) and the International Commission on Illumination (CIE) in four categories in terms of light sensitivity classification; insensitive, low sensitivity, medium sensitivity, and high sensitivity. The annual exposure time and the upper limit of annual luminous exposure as well as the limiting illuminance are defined for each of these categories (CEN, 2014; CIE, 2004).

An exhibit's background affects its perceived colour. The background against which an exhibit is viewed should be achromatic and medium-light to minimize the simultaneous contrast based on the chromatic adaptation mechanism. Wilson (2006) and Feltrin et al (2017) examined the influence of the background colour on the appearance of the exhibition items (Wilson, 2006; Feltrin et al., 2017). Wilson (2006) suggests a low chroma background with a reflectance of 20–60% depending on the circumstances. Feltrin et al., (2017) found that the change in the background (white, grey, black) did not have a considerable impact on the observers' assessments. Cuttle (1998) pointed out the general effect that the relative damage potential increases as the colour temperature of light increases. Several studies were conducted to determine subjects' preferences regarding the perceived appearance of objects at different correlated colour temperatures (Feltrin et al, 2017; Csuti et al, 2015; Garside et al, 2017; Vidovszky- Németh & Kosztyán, 2016; Luo et al, 2016; Scuello et al, 2004). Measures to avoid direct glare and glare by reflection in exhibition halls are contained in the literature (CEN, 2014; IESNA, 1996). The energy consumption in museum lighting is also taken into account and the advantages of LED lighting compared to conventional light sources are highlighted (Csuti et al, 2015; Garside et al, 2017). Care must be taken to ensure that the maximum illuminance on the display surface does not exceed the allowable illuminance according to the sensitivity class of the object. Illuminance uniformity is a further important aspect of lighting design. The required minimum illuminance uniformity (U_o) for specific tasks or activity areas is given in the European Standard (CEN, 2021). However, there is no recommendation in this or any other standard for illuminance uniformity ($U_o=E_{min}/\bar{E}$) for vertical display surfaces. As no reference has been found specifically for museum lighting, the recommended value (≥0.70) given in the EN 12464-1 standard for hand painting, colour inspection, art rooms in art schools is used as the reference value for artworks displayed vertically on surfaces (CEN, 2021). The perceived colours of the artefact may differ from the original work if the illumination isn't homogeneous. As a result of this, the meaning and effect of the work may deviate from the artist's intention.

The literature on uniform illumination of vertical surfaces offers general knowledge. General knowledge refers to calculating the optimal position of a luminaire depending on parameters such as ceiling height, object size, eye level, and optimal viewing angle. The distance (x) between the luminaire and the display surface shall be calculated using the formula "$x = y \times \tan 30^o$" according to the distance between the viewer's eye and the ceiling (y). The recommended angle of inclination of the luminaire is 30° to the surface (FGL, 2000; IESNA, 2000). This guiding information does not consider the luminous intensity distribution of the luminaire and the luminaire spacing for a regular array of luminaires. This study aims to develop an approach to uniformly distributed illuminance on vertical display surfaces using minimal energy consumption.

2. Conditions for Uniform Illumination on Vertical Surfaces

The theoretical luminous intensity distribution that enables homogeneous illumination on a vertical surface can be determined depending on the location of the light source and the size and position of this surface. Such a theoretical distribution produces the same illuminance on every point of the illuminated area. The required luminous intensities are to be calculated by the formula 1.

$E_v = I_\alpha \times \cos^3 \beta / h^2 \times \tan^2\alpha$

(1)

where

I_α is the luminous intensity of the light source in the direction of the angle α,

α is the angle between the direction of light and the vertical,

β is the angle between the direction of light and the surface normal,

h is the distance of the light source from the floor.

For simplifying the calculation, the distance of the light source from the surface ($h^2 \times \tan^2\alpha$) assumes '1', and the luminous intensities of the light source in the 90°-10° directions calculate proportionally by the formula 2.

$I_\alpha = E_v / \cos^3 \beta$

(2)

The luminous intensity in the direction of 90° to the vertical is 1 (I_{90} =1) according to formula 2. For example, to determine luminous intensities in the directions of 50° and 10°, this formula can be expressed as follows.

$I_{50} = I_{90} / \cos^3{}_{40}$

$I_{10} = I_{90} / \cos^3{}_{80}$

Figure 1 shows an example of the luminous intensity's proportional change towards the display surface. The limiting angle (21°-47°) of the incident rays changes according to the size of the display surface (DS), the ceiling height (h) and the distance (x) between the light source and the wall.

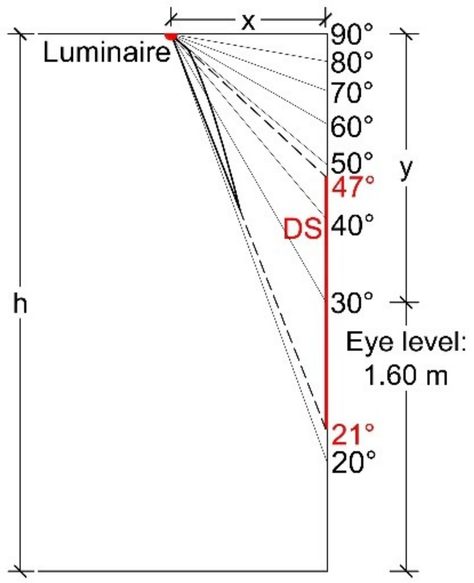


Figure 1. An example of luminous intensity distribution for uniform illumination.

The selection and placement of the luminaire should predicate the theoretical luminous intensity distribution. The similarity between the intensity distribution of the luminaire and the theoretical one leads to easier control of the illuminance generated by direct light. Reflected light in the room increases the uniformity of the illuminance. Selecting the appropriate luminaire is essential for the uniformity of illuminance in the vertical direction but is not enough. Large display areas are in exhibition halls, and for this reason, a regular array of luminaires is a prerequisite. Hence, it is significant to determine the appropriate luminaire spacing for uniform illuminance in the horizontal direction.

3. Material and Methods

The type and the position of the luminaire, the size and the location of the display surface and the characteristics of the exhibition hall play roles in controlling illuminance distribution. This study aims to identify the optimal conditions to acquire the targeted illuminance uniformity, and the stages of the study are as follows.

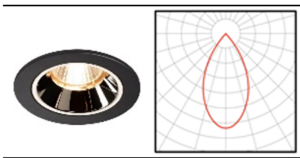
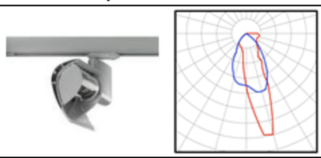
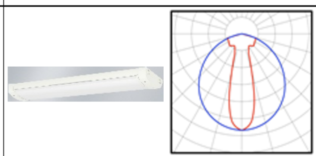
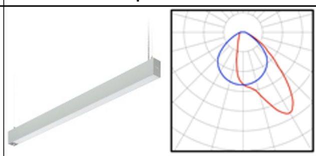
- Selecting the luminaire,
- Identifying the size of the display surface,
- Specifying the exhibition hall characteristics,
- Positioning the luminaire,
- Studies on glare by reflection,
- Determining the calculation method.

3.1 Selection of the Luminaire

In this research, four different luminaires (A, B, C, D) are used (Table 1). Care is taken to ensure the luminous intensity distributions of the selected luminaires are similar to the theoretical ones.

A. Small luminaire, symmetrical luminous intensity distributions
B. Small luminaire, asymmetrical luminous intensity distributions
C. Linear luminaire, symmetrical luminous intensity distributions
D. Linear luminaire, asymmetrical luminous intensity distributions

Table 1. Luminaire Characteristics

A	B	C	D
Slv Numinos	Sylvania Torus	Norka Brünn	Philips Trueline
			
28.4 W, LED, 2333 lm CCT: 3966 K, CRI: 91	42 W, compact fluorescent 2129 lm, CCT: 3951 K, CRI: 92	45 W, fluorescent, 3183 lm CCT: 4000 K, CRI: 80	28 W, LED, 3400 lm CCT: 3000 K, CRI: 99

3.2 Size of the Display Surface

The identification of the size and the position of the display surface depends on the factors such as the size of the art piece, the visitor's location, eye level and view angle. Due to the variety of the artworks to be exhibited and different possible approaches to exhibition concepts, literature information about the subject is limited. According to EN 12464-1, the eye level for a standing person is 1.6 m above the floor (CEN, 2021),. FGL states that the distance between the visitor and the display surface varies between 1 m-1.6 m (2000), and the distance between the luminaire and the display surface should be one-third of the ceiling height (2016). To create a comfortable viewing angle, Dean (2002) suggests the display surface centre the eye level. According to Panero & Zelnik (1979), the vertical visual field of vision is between sightlines +50° and -70°. The limit of the human visual field for colour discrimination is between sightlines +30° and -40°, maximum eye rotation is on sightline +25°, and optimum eye rotation is on sightline -30°).

Considering the above-noted information, the accepted eye level, visual field, and three different distances for the visitor to the display surface are 1.6 m, ±30°, and 1 m, 1.3 m, 1.6 m, respectively. Thus, based on formula no 3, the display surface sizes are defined as 1.15 m, 1.5 m, and 1.85 m. The fourth display surface for circumstances the exhibited objects cover the entire wall starts 0.5 m above the floor and ends 0.5 m below the ceiling (DS=h-1 m) (Figure 2).

$DS = d \times 2 \text{ tg } 30^0$

(3)

where

DS is the display surface,

d is the distance between the visitor and the display surface.

3.3 Definition of Room Dimensions

Exhibition halls have various dimensions. The height of the exhibition hall is assumed to be 2.8 m, 3.2 m, 3.6 m, and 4 m to monitor the influence of ceiling height on the outcomes. Generally, some walls throughout are allocated for exhibition purposes in these rooms. Ensuring uniform illumination depends on controlling the illuminance produced by the light falling directly from the luminaire onto the surface. The inter-reflected light generated in the room is distributed uniformly on interior surfaces. Thus, this study analyses the conditions to acquire uniformity of illuminance caused by direct light via a black room with a 5 m x 15 m floor area. A long wall of the room is regarded as the background of the display surface. Following the determination of the appropriate luminaire spacing and the inclination angle in the black room, calculations are repeated for the same conditions in the grey rooms. Consequently, the influence of reflected light on the illuminance and the illuminance uniformity is observed. The reflectances of the grey room are 0.70, 0.50, and 0.20 for the ceiling, the walls, and the floor, respectively. The wall colour chosen represents the optimum background in terms of simultaneous contrast. Various conditions regulated for the black and grey room dimensions and the number of walls allocated for the exhibition are as follows:

- Black room: 5 m× 15 m, exhibition on one long wall
- Grey room 1: 5 m× 15 m, exhibition on one long wall
- Grey room 2: 10 m× 15 m, exhibition on one long wall
- Grey room 3: 10 m× 15 m, exhibition on two long walls
- Grey room 4: 10 m× 15 m, exhibition on two long walls and one short wall

A total of 320 rooms are modelled by the DIALux evo lighting program, based on five rooms (1 black + 4 grey rooms), four ceiling heights, four display surfaces and four luminaires. The required investigations and calculations are conducted correspondingly.

3.4 Determination of the luminaire location

The position of the luminaire (distance from the floor and display surface) and its tilt angle are as significant as the luminaire type to control illuminance distribution. Different choices on the mentioned parameters will lead to different mean illuminance and illuminance uniformity. In this study, the distance (x) between the luminaire and the wall is calculated by formula 4, suggested in the literature (FGL, 2000; IESNA, 2000) (Figure 1). Luminaires are mounted on the ceiling of the modelled rooms.

$x = y \times \tan 30^{o}$

(4)

where

x is the distance between the luminaire and the wall,

y is the distance between the eye level and the ceiling.

For ceiling heights of 4 m, 3.6 m, 3.2 m and 2.8 m, the calculated distances between the luminaire and the wall are 1.39 m, 1.15 m, 0.92 m and 0.69 m, respectively. The related literature suggests a tilt angle of 30° towards the wall. However, in this study, the recommended inclination angle (30°) did not perform positive results. Therefore, the appropriate inclination angle needed to be adjusted separately for each room, display surface, and luminaire. The theoretical luminous intensity distribution was used to determine the suitable inclination angle. The luminous intensity distribution of the selected luminaire is placed at the same point as the theoretical luminous intensity distribution. The luminaire is tilted more or less to increase the similarity with the theoretical luminous intensity distribution. Then, the inclination angle is specified precisely with minor alterations.

3.5 Control of glare by reflection

On the surface of non-matte objects or the works displayed in a glass frame, the reflected image of the luminaire may occur. Possible glare by reflection may cause difficulty in visual perception and should be avoided in lighting design. Hence, four ceiling- and four display surface heights (16 conditions) are analysed for glare by reflection. The shortest possible distance that a visitor can come close to the display surface without being affected by reflected glare is calculated for each situation. For the case where the ceiling height is 3.2 m and the display surface height is 1.5 m, the shortest possible distance between the visitor and the wall should be 0.82 m (d_{min}) as shown in Figure 3. If the allowed remoteness to avoid glare by reflection is smaller than the distance between the luminaire and the wall (x: 0.92 m), the latter should be taken as d_{min} (d_{min}=x). Nevertheless, this issue can be neglected if the luminaire's characteristics, such as location, beam- and tilt angle prevent the visitor's shadow from being cast on the display surface. Since the angle of inclination shall not be towards the visitor, there is no need to assess direct glare.

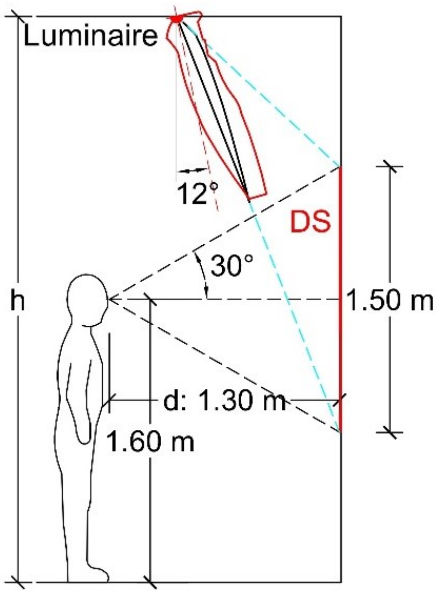


Figure 2. Size and location of the display surface

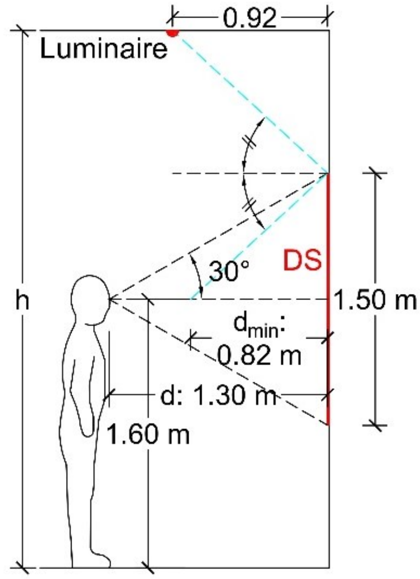


Figure 3. Control of glare by reflection

3.6 Determination of the calculation method

The control of vertical illumination differs depending on the number of luminaires used. Locating the luminaire (x) according to the ceiling height (h) and adjusting the tilt angle to obtain the desired uniformity shall be adequate when using a single luminaire. Illuminance distribution in the horizontal direction along the width of the display surface should be examined besides the control in the vertical direction along the height of the surface when using multiple luminaires. Since this study employed an array of luminaires, the uniformity of illuminance was controlled in both directions simultaneously in 16 conditions. First, the location of the luminaire (x) is determined. Afterwards, the appropriate tilt angle and the spacing of luminaires are analysed simultaneously to provide the desired uniformity in both vertical and horizontal directions. The dimension of the longer wall identifies the required number of luminaires. The span of the display surface starts with the centre of the first luminaire and ends with the last one. Luminaire spacing and the corresponded number of luminaires vary depending on the type (small, linear) and luminous intensity distribution (symmetrical, asymmetrical) of the luminaire, ceiling height and display surface height.

The decision on the optimal outcome of a specific condition relied on a two-phase evaluation. In the first phase, the mean illuminance ($\bar{E}$) and the illuminance uniformity (U_o) are taken into consideration. In general, when $\bar{E}$ increases, U_o decreases and vice versa. The targeted illuminance uniformity was 0.65 in this phase, which was performed in a black room. In grey rooms, a uniformity of 0.70 could be achieved through the contribution of reflected light. In some cases, the target uniformity (U_o=0.65) could not be acquired, as a matter of course. The attained maximum U_o is accepted as the best result in these cases. The desired uniformity of illuminance (or the maximum possible U_o) was yielded with different luminaire spacings and tilt angles. In other words, there were several positive results.

In the second phase of the study, the optimum one among these positive results was inquired. For this purpose, two additional criteria are considered. The first criterion is the 'total luminous flux (Φ) required for 200 lx illuminance, recommended for the artworks categorised as low sensitivity. The second criterion is the proportion of this luminous flux received by the display surface (Φ_{DS}). Thus, a comparison based on the luminous flux emitted from the luminaire regardless of the power and luminous efficacy of the light source and the luminaire efficiency could be conducted (Çelikmez & Dokuzer Öztürk, 2020). Providing the considered illuminance with a low amount of luminous flux and that this luminous flux falls on the display surface to a large extent have been positive outcomes in determining the optimum result. So, the energy efficiency is taken into account in determining the optimum result.

4. Calculation Results

For 16 black room conditions, the total luminous flux (Φ) required for the mean illuminance of 200 lx, the ratio of this luminous flux received by the display surface (Φ_{DS}), and the uniformity of illuminance (U_o) are calculated. For each display surface (16 conditions), the results of four luminaires are compared and rated between 1 and 4, with (4) being the most positive and (1) the least one. The result for the case where the ceiling height is 2.8 m and the display height is 1.15 m is presented as an example in Table 2. The values of grey rooms 3 and 4 in table 2 belong to the longer walls. As apparent in Table 2, luminaire B delivered the most positive while luminaire D supplied the least satisfactory result. Luminaire's ranking from the most positive to the least is based on U_o, Φ_{DS} and Φ values in black and grey rooms. Luminaires B and C provided higher uniformity in illuminance. As in practice, the uniformity of illuminance being below 0.70 in black rooms increases in grey rooms with the contribution of inter-reflected light. When these two luminaries, whose uniformity is close to each other, are compared in terms of energy consumption, the luminous flux required for 200 lx illuminance on the display surface is higher in luminaire C. In other words, luminaire B is more economical. In addition, the ratio of luminous flux (Φ_{DS}) received by the display surface is higher for luminaire B, which is more affirmative. Lower Φ_{DS} means that more luminous flux falls on the wall or/and floor outside the boundaries of the display surface. The ranking for luminaires A and D is based on the same reasoning.

Table 2. Calculation results; h: 2.8 m, DS: 1.15 m

Rank/	Black room			Grey room 1			Grey room 2			Grey room 3			Grey room 4		
Lum.	U_o	Φ	Φ_{DS}	U_o	Φ	Φ_{DS}	U_o	Φ	Φ_{DS}	U_o	Φ	Φ_{DS}	U_o	Φ	Φ_{DS}
1 / B	0.63	10505	31%	0.68	9605	34%	0.68	9736	33%	0.69	9270	35%	0.71	8396	36%
2 / C	0.64	15256	20%	0.68	13677	22%	0.68	13922	21%	0.69	13113	23%	0.69	12438	24%
3 / A	0.55	9613	34%	0.58	8881	37%	0.57	8986	37%	0.59	8616	38%	0.57	7777	39%
4 / D	0.54	9835	28%	0.57	9084	30%	0.57	9207	30%	0.59	8815	31%	0.58	8546	32%

Rankings per display surface based on the evaluations for each ceiling height and display surface are presented in Table 3. The comparison of all conditions revealed that the uniformity of illuminance generally decreases when the ceiling height decreases and the display surface height increases. The illuminance uniformities (U_o) related to black rooms are given in Table 4. U_o increases approximately 5% in grey rooms.

Table 3. Ranking of luminaires

Ceiling height (h); m		Height of display surface; m 1.15	1.5	1.85	h-1
4		3	4	4	1
		4	3	3	4
		2	2	2	3
		1	1	1	2
3.6		4	4	3	1
		3	3	4	4
		2	2	2	3
		1	1	1	2
3.2		4	3	1	1
		2	4	4	4
		3	2	3	3
		1	1	2	2
2.8		2	1	1	2
		4	4	4	4
		3	3	3	3
		1	2	2	1

Luminaire type: A B C D

Table 4. Illuminance uniformity

Ceiling height (h); m		Height of display surface; m 1.15	1.5	1.85	h-1
4		0.65	0.65	0.57	0.23
		0.63	0.63	0.65	0.63
		0.65	0.64	0.64	0.64
		0.65	0.56	0.49	0.39
3.6		0.65	0.60	0.51	0.27
		0.64	0.62	0.63	0.65
		0.64	0.62	0.53	0.64
		0.64	0.56	0.48	0.39
3.2		0.65	0.53	0.37	0.27
		0.64	0.65	0.62	0.65
		0.65	0.54	0.65	0.65
		0.60	0.53	0.45	0.38
2.8		0.55	0.37	0.21	0.32
		0.63	0.62	0.63	0.64
		0.64	0.65	0.65	0.65
		0.54	0.44	0.29	0.34

The results in Table 3 can be evaluated as below:

- Considering all cases, the small luminaire (B) with asymmetrical luminous intensity distribution received the highest score (58), followed by luminaires C, A and D with 41, 39 and 22 points, respectively. Despite its asymmetrical luminous intensity distribution, the linear luminaire D took the last place in the ranking.
- The two small luminaires, one with symmetrical (A) and the other with asymmetrical (B) luminous intensity distribution, delivered better results for display surfaces 1.15 m and 1.5 m. The luminaires B and C were more successful for the other display surfaces (1.85 m and h-1 m).
- The results provided by the luminaires B and A in high rooms (4 m and 3.6 m) were most satisfactory. On the contrary, luminaires B and C supplied better results at lower ceiling heights (3.2 m and 2.8 m).

5. Analysis of Glare by Reflection

The visitor's comfortable viewing angle is accepted as ±30° for each calculation surface. Accordingly, the visitor's viewing distance (d) to the display surfaces with the height of '1.15 m, 1.5 m, and 1.85 m' are '1 m, 1.3 m, and 1.6 m', respectively. The size of the fourth calculation surface (h-1) varies depending on the ceiling height and is 3 m, 2.6 m, 2.2 m, and 1.8 m for the ceiling heights of 4 m, 3.6 m, 3.2 m, and 2.8 m, respectively. For this calculation surface, the distance (d) between the visitor and the display surface should be 3.29 m, 2.6 m, 1.905 m, and 1.905 m for the ceiling heights of 4 m, 3.6 m, 3.2 m, and 2.8 m, respectively. Based on this data, the analysis results regarding glare by reflection for the four ceiling heights and four display surfaces are submitted in Table 5. This table presents the minimum distance (d_{min}) that the visitor can approach the exhibition surface without the risk of glare by reflection and the relevant viewing angle at this distance. The cases in which the observer is affected by glare are indicated by darkened cells in the table. Actually, under the condition h: 2.8 m, DS: 1.85 m, glare by reflection occurs at the defined distance (1.905 m) based on the visual angle of ±30°. To avoid this, the distance between the visitor and the display surface must be ≥2.36 m. Likewise, at ceiling heights of 4 m, 3.6 m and 3.2 m, the visitor must view the display surface at an angle of less than ±30°, which means moving farther from the surface.

Table 5. Control of glare by reflection

		Height of display surface; m							
		1.15		1.50		1.85		h-1	
		d_{min}	view angle	d_{min}	view angle	d_{min}	view angle	d_{min}	view angle
h (m)	4	0.44	±53°	0.63	±50°	0.87	±47°	5.27	+27°, -12°
	3.6	0.47	±51°	0.70	±47°	1.00	±43°	3.46	+23°, -18°
	3.2	0.52	±48°	0.82	±43°	1.27	±36°	2.03	±28°
	2.8	0.64	±42°	1.16	±33°	2.36	±21°	0.97	+36°, -49°

6. Comparison in Terms of Energy Consumption

Today, energy scarcity and carbon emissions are significant issues facing many countries (Lukosa, 2017). Lighting accounts for a large part of the energy consumption of buildings. Therefore, lighting energy savings in all sectors are essential to reduce CO_2 emissions and global warming (Lee & Cheng, 2016). The use of high efficacy lamps and lighting control systems are some of the measures to reduce energy consumption (Xu et al, 2017; Haq et al, 2014; Pandharipande & Caicedo, 2015; Hag et al, 2014).

Total luminous flux (Φ) required for an average of 200 lx illuminance is considered to compare the results of this study in terms of energy consumption. For this purpose, the results of 320 situations were compared, depending on four ceiling heights, four display dimensions, four luminaires, and five rooms (four grey+ one black). Among the mentioned 320 situations, the case requiring the highest luminous flux (100%) was determined and accordingly, the needed luminous flux for the rest of the situations is found separately in percentage. Table 6 shows the results of an example based on a ceiling height of 2.8 m and a display surface of 1.15 m. Regarding grey rooms 3 and 4, which have more than one wall allocated for exhibition, the result of a single long wall is in this table. The results in Table 6 show that the luminous flux required to provide the aimed illuminance on the display surface is minimum in luminaire A and maximum in luminaire C. Put another way: luminaire A is the most economical one, followed by luminaires D, B and C. By contrast, in terms of illuminance uniformity (U_o), the rank order of the luminaires is different. Because luminaire B provides the most uniform illuminance, followed by luminaires C, A and D. Another comparison was between black and grey rooms and the effect of the reflectance of inner surfaces on energy consumption is observed. The energy requirement in grey rooms is lower than in black rooms (Table 6). The number of luminaires employed in grey room 1 (GR1) and grey room 2 (GR2) is the same. However, the increase in the room size without changing the number of used luminaires reduces the contribution of reflected light from the interior surfaces to the illuminance on the display surface (GR2/BR>GR1/BR). As the number of display walls increases in the same size of rooms, the contribution of the reflected light to the illuminance on the display surface increases (GR4/BR< GR3/BR<GR2/BR). The effect of reflected light on energy consumption is parallel in all considered cases.

Table 6. Comparison of energy consumption; h: 2.8 m, DS: 1.15 m

Rank/ Lum.	Black room			Grey room 1			Grey room 2			Grey room 3			Grey room 4		
	U_o	Φ	BR	U_o	Φ	GR1/ BR	U_o	Φ	GR2/ BR	U_o	Φ	GR3/ BR	U_o	Φ	GR4/ BR
1 / A	0.55	25.7%	1	0.58	23.7%	92%	0.57	24.0%	93%	0.59	23.0%	90%	0.57	20.7%	81%
2 / D	0.54	26.3%	1	0.57	24.3%	92%	0.57	24.6%	94%	0.59	23.5%	90%	0.58	22.8%	87%
3 / B	0.63	28.1%	1	0.68	25.6%	91%	0.68	26.0%	93%	0.69	24.8%	88%	0.71	22.4%	80%
4 / C	0.64	40.7%	1	0.68	36.5%	90%	0.68	37.2%	91%	0.69	35.0%	86%	0.69	33.2%	82%

The energy consumption of four luminaires is compared with each other on the scale of the display surface. The luminaire that requires the lowest luminous flux has the best score (4 points), while the luminaire that requires the highest amount has the worst score (1 point). This comparison was conducted in two ways, considering only 'black rooms' and 'all black and grey rooms'. The results obtained in both conditions were significantly parallel to each other. Table 7 presents the ranking in energy consumption for each display surface.

Table 7. Ranking of energy consumption

		Height of display surface; m			
		1.15	1.5	1.85	h-1
Ceiling height (h); m	4	2	4	4	4
		4	1	1	2
		3	3	2	1
		1	2	3	3
	3.6	2	4	4	4
		3	2	1	2
		4	3	3	1
		1	1	2	3
	3.2	2	4	4	4
		1	1	2	2
		4	2	1	1
		3	3	3	3
	2.8	4	4	4	4
		2	2	2	2
		1	1	1	1
		3	3	3	3
Luminaire type:		A □	B □	C □	D □

The evaluation of the energy consumption comparison is as follows:

- As the ceiling height increases, the energy consumption required for the same display surface increases.
- While the ceiling height is constant, the larger the display surface, the more energy consumption.
- Considering all cases, the order of the luminaires from the lowest energy consumption to the highest is A, D, B, and C. When the energy requirement is minimum, i.e. minimum luminous flux emitted from the luminaire (luminaire A), the level of reflected light is also less. As the luminous flux emitted from the luminaire increases, the contribution of the reflected light to the illuminance on the display surface increases, in general.
- Considering all cases, luminaire B delivers the highest average uniformity of illuminance (U_o), followed by luminaires C, D and A. In other words, the energy consumption and the uniformity of illuminance change in the opposite direction.

7. Discussions

It is essential to provide the recommended illuminance and uniformity in the task area. In museums and art galleries where the exhibition is vertical, the task area is the vertical display surface. The illuminance should be uniform and not exceed the allowed level to properly and fully appreciate the artworks exhibited. In practice, however, high luminance contrasts are often encountered. The zone of highest luminance will be on the work of art or the background surface, depending on the conditions. The limited knowledge of the vertical control of illumination also plays a role in the low success in practice.

This study considered the literature data to determine the location and size of the display surface (Dean, 2002; FGL, 2000; Panero & Zelnik, 1979). The distance (x) of the luminaire from the wall corresponding to the ceiling height (h) was also determined using the literature (FGL, 2000; IESNA, 2000). Another commonly used specification relates to the angle of inclination of the luminaire to the vertical (30°) (FGL, 2000; IESNA, 2000). However, in 64 cases examined, only one positive result was (h: 4 m, DS: 1.15 m, luminaire A) with an inclination angle of 30°. Thus the uniformity of the illuminance not only depends on the inclination but also on the luminous intensity distribution of the luminaire (narrow/broad, symmetrical/asymmetrical).

Firstly, the tilt angle providing the desired uniformity in the vertical direction of the display surface is determined; afterwards, the spacing of luminaires ensuring the same uniformity in the horizontal course of this surface is analysed. However, the desired uniformity could not be acquired when using multiple devices. This observation revealed the importance of simultaneous consideration of the inclination angle and the luminaire spacing. Given this data, various luminaire spacings are taken into account, and the most suitable tilt angle for each spacing is defined. This approach delivered multiple states that yield the target uniformity in illuminance distribution. The decision on the optimum one among these states ensued under consideration of; 'uniformity of illuminance (U_o)', 'total luminous flux (Φ) required for an average of 200 lx illuminance and the proportion of this luminous flux received by the display surface (Φ_{DS})', and the required number of luminaires. The selected optimal condition provided the desired illuminance and uniformity by using minimum energy and prevented the background illuminance from being higher than the display illuminance. Optimizing the inclination and spacing of the luminaires is a significant and original result of this research. Regarding any level different from 200 lx or respecting the maximum illuminance instead of the mean illuminance will not affect the obtained results.

The first step in illuminance control is to select the luminaire's luminous intensity distribution. Therefore, the theoretical luminous intensity distribution (Figure 1) should be defined that enables homogeneous illumination depending on the room height, display area and luminaire position. The ideal approach is to design a reflector that provides the required theoretical luminous intensity distribution (Özmen & Dokuzer Öztürk, 2009). However, selecting the most suitable one among the available luminaires is preferred usually. Using the theoretical luminous intensity distribution as a reference in luminaire selection and tilt adjustment speeds up the lighting design process and enables positive results. This perspective of the lighting designer will increase the number of competent applications. Drawing attention to this phenomenon is believed to fill a crucial deficiency in the literature.

It is a general opinion that an asymmetric luminous intensity distribution provides positive results for a uniform illumination (FGL, 2016). However, 'asymmetric luminous intensity distribution' alone is not enough for a competent result. Intrinsically, both the best and the worst results supplied the luminaires with asymmetrical light distribution in this study. Besides being symmetric/asymmetric, the shape of the luminous intensity distribution is decisive. It is unrealistic to assume that a luminous intensity distribution delivers positive results for all room heights (h) and display sizes (DS). The results of this study also changed according to the dimensions h and DS. The luminaires A and B provided successful results for small display surfaces (1.15 m, 1.5 m) and high rooms (4 m, 3.6 m). On the contrary, the luminaires C and B submitted satisfactory results for larger display surfaces (1.85 m, h -1 m) and lower rooms (3.2 m, 2.8 m). Some opinions argue that the entire wall should be lit and accordingly perceived as equivalent (FGL, 2016). It is meaningful for the conditions in which the objects cover a large portion of a wall. However, for circumstances in which the exhibited objects are placed on a particular part of the wall, trying to provide uniform lighting over the entire wall, regardless of the area reserved for the works, does not seem sensible due to energy saving. In most cases, the illumination created by the reflected light is sufficient to ensure the visibility of the interior surfaces of the room. In addition, as the area illuminated by direct light from the luminaires increases, the uniform distribution of the illuminance becomes difficult.

The amount of luminous flux required to generate the target illuminance increases as room height and display area size increase. Comparing the energy consumption of the handled luminaires supported this conclusion. On the other hand, the uniformity of illuminance and the energy consumption contradict each other. Evaluations based on various criteria revealed that the luminaires B and C are superior to the others (A and D). On the other hand, the luminaires A and D, whose U_o values were generally below the target, proved to be more economical when compared just in terms of energy consumed. The goal of lighting design should be to offer visual comfort with the lowest possible energy consumption. In cases where these two contradict each other, it is apparent that the preference should favour visual comfort.

8. Conclusions

The principal purposes of electric lighting in museums are to ensure that the exhibited objects are perceived fully and comfortably, prevent these objects from being damaged and use energy efficiently. Providing illuminance uniformity on vertical display surfaces is one of the significant tasks of lighting design. If the illumination is not homogeneous, the perceived colours of the artefact may differ from the original, and the meaning and effect of the work may deviate from the artist's intention. This study presents an approach to distributing illuminance uniformly on vertical display surfaces using minimal energy consumption. According to this approach, the luminous intensity distribution of the luminaire shall be appropriate for the location and size of the display surface. It also emphasizes that the angle of inclination and luminaire spacing shall adjust simultaneously.

This approach is applied to assess the results conveyed by four luminaires with different luminous intensity distributions. The evaluation takes into account the luminous flux required to produce a certain level of illuminance, the targeted illuminance uniformity, and the ratio of the luminous flux received by the display surface. For each display surface (16 conditions), the four luminaires are rated between 1 and 4, being (4) the most positive and (1) the least one. The most positive results delivered the small luminaire (B) with asymmetrical luminous intensity distribution considering all cases. The linear (C) and small (A) luminaires with symmetrical luminous intensity distributions followed luminaire B. The linear luminaire (D) with asymmetrical luminous intensity distribution supplied the worst results under the conditions of this study. If one compares these luminaires only to energy consumption, the most economical is A, followed by D, B and C. However, it was not possible to achieve the desired illuminance distribution with the more economical A and D luminaires in most cases. In addition to the visual discomfort, the non-uniform illuminance also causes the annual luminous exposure will not be the same for the whole surface of the artwork. Efficient use of energy is undoubtedly critical. However, in museum lighting design, priority should be given to maintaining visual comfort and preserving artefacts.

Interior, lighting and exhibition design in museums should be conducted simultaneously. If this is not the case, it is inevitable to compromise at least one of the subjects, namely the preservation of objects, the provision of visual comfort and energy efficiency. For example, necessary analyses should be carried out to avoid glare by reflection that can occur on the surface of non-matte objects or works displayed in a glass frame. When setting up the exhibition layout, the shortest possible distance that which the visitor can approach the work should be taken into consideration.

The acquired results revealed that a single luminaire does not deliver positive results in all 16 cases. The choice of the luminaire shall regard the geometry of the room and the properties of the presentation area. The lighting designer can benefit from the outcomes of this research based on four luminaires in museum lighting. Assessing any luminaire using the approach presented in this study will provide optimal results in many respects.

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Conflict of Interests

The authors declare no conflict of interest.

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