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Original article

An evaluation of daylight distribution as an initial preventive conservation measure at two Smithsonian Institution Museums, Washington DC, USA

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ABSTRACT

This paper presents the results of a light levels survey conducted at the Donald W. Reynolds Center for American Art and Portraiture in Washington DC. The museum space is shared by the National Portrait Gallery and the Smithsonian American Art Museum. After six years of extensive renovations, the building reopened to the public in July 1, 2006. The structure was not originally designed to house a museum collection since it contains numerous openings such as windows, doors and skylights, which provide a path for natural radiation to enter the building and come in contact with the artworks. From a preventive conservation standpoint, this is an important problem since sensitive works of art in the collection may be subjected to damage caused by light exposure. Environmental data loggers installed throughout the museum were programmed to take successive measurements every 10 min for 24 h a day, 7 days a week and 52 weeks a year. This light levels assessment started in November 1, 2007 and finished in October 31, 2008. This study presents a new method for determining natural radiation exposures registered in exhibition spaces that rely on both electric lighting and natural lighting, considering the growing trend of using daylight illumination in museums.

1. Research aims

The main objective of the study was to evaluate the relative distribution of light throughout different exhibition areas of the Donald W. Reynolds Center for American Art and Portraiture, during a light levels survey of one year. The initial goal of the research was to establish and develop a measurement methodology that helped to assess natural and artificial lighting contributions in spaces where both types of radiation are employed. The investigations also had the intention of verifying the effectiveness of current preventive conservation measures used to minimize the solar illumination reaching the interior spaces of the building.

This study forms part of a comprehensive preventive conservation program, which includes various lines of research. First, light-fastness surveys of museum materials using micro-fading spectrometry have been conducted jointly with the aim of investigating the exposures capable of inducing noticeable color changes. Second, an investigation of the reciprocity principle of light exposures has also been performed with the objective of identifying deviations, which are dependent on light-stability of the material. Third, different illumination ratios employed throughout the museum have allowed devising a method for estimating the photometric exposures received by objects on display. This procedure takes into account the higher illuminance levels experienced by the object due to the use of direct light sources in addition to indirect sources. The final goal is the establishment of lighting exhibition guidelines at the two museums based on results gathered during the previously described research campaigns.

2. Introduction

Museum personnel often face the challenge of lighting and preserving objects on display since there should be a balance between pleasing viewers with adequate light levels that permit correct appreciation of artifacts, while addressing the possible amount of energy striking the object's surface. Natural lighting is often preferred over electric lighting when illuminating works of art, because the first one provides a more pleasing rendering effect due to its spectral power distribution. However, natural lighting has a large component of UV radiation, which is known for its detrimental effects to the artwork. Therefore, this type of radiation needs to be minimized. Museums worldwide have traditionally used the maximum recommended levels of illumination proposed by Thomson [1]. The difficulty relies on applying these guidelines without conducting a systematic light monitoring program, which helps to

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Table 1
Summary of various recommended annual exposure limits for susceptible museum artifacts.

Recommending organization	Low sensitivity (klx h/y)	Moderate sensitivity (klx h/y)	High sensitivity (klx h/y)
Illuminating Engineering Society of North America	Variable	480	50
Heritage Collections Council, Australia	–	507–650	127–200
Canadian Conservation Institute	–	1000 (ISO 4)[a]	100 (ISO 2)
Commission Internationale de l'Éclairage	600	150	15

[a] These values are based on light-fastness ratings established by the International Standard Organization (ISO).

qualitatively and quantitatively evaluate the visible light and UV radiation present in museum exhibition spaces. The spectral distribution of the light source is an important aspect of this kind of study since similar illuminance levels may contain different amounts of UV radiation depending on the source. The source with a higher UV component, usually natural lighting, is more damaging than its equivalent electric source. Current accepted levels of UV radiation are 35 and 75 microwatts per lumen ($\mu W\, lm^{-1}$) for highly sensitive and moderately sensitive objects, respectively [2]. Every museum preventive conservation policy must take into account the sensitivity to light of artists' materials found in their collections before establishing adequate light levels for their objects.

The importance of measuring the light levels in museum buildings due to potential detrimental effects to sensitive works of art on display has been indicated by several authors [3–5]. Some researchers [6,7] have incorporated annual photometric exposure limits, for works of art on paper, which are based on the maximum recommended levels published earlier by Thomson. Various authorities in the museum lighting research field have published a series of guidelines which include annual exposure limits for susceptible artifacts [8–11]. A summary of these recommendations is presented in Table 1. These maximum recommended values are based on International Standard Organization (ISO) light-fastness classifications. These ratings are then converted to exposures based on available data on the fading of typical museum materials. Moreover, annual exposures can be extrapolated to determine the approximate number of years that a material would require to experience a perceptible color change. The differences in maximum allowable exposures observed in Table 1 are mainly due to the number of hours per day and days per year in which these values are based. For example, a maximum annual exposure of 50 klx h for high sensitive materials recommended by the Illuminating and Engineering Society of North America (IESNA) is based on illumination at 50 lx, for 8 h in a day over a period of 125 days in a year. In contrast, the Canadian Conservation Institute (CCI) recommends a limit of 100 $klx\, h\, y^{-1}$ for a fugitive material that belongs to the ISO 2 class. This value is based on 8 h per day and 250 days per year, at the same illumination level. In the CCI scale, an ISO 2 material displayed for 250 days per year is expected to experience a perceptible color change after 10 years (1.0 Mlx h exposure). The same type of material exhibited for 125 days per year, as specified in the IESNA guideline, would take twice as long to reach the same degree of damage. A guideline proposed by the Commission Internationale de l'Eclairage (CIE) in 2004 divides the materials into four categories based on their responsiveness to visible light. Although initially the CIE standard may seem too restrictive, the scales become equivalent after carefully examining the types of materials belonging to each category. For example, materials such as oil paintings classified as moderately sensitive in the three other scales belong to the low responsivity group in the CIE system. Therefore, a comparison of the CIE and IESNA guidelines reveals that the maximum recommended exposures for oil paintings are 600 and 480 $klx\, h\, y^{-1}$, respectively.

Numerous investigations on the interaction of light with museum materials [12–14] and the use of dosimeters to estimate photometric exposures in museums [15,16] have been conducted. Bacci et al. have developed a new kind of light dosimeter, which consisted of a mixture of photosensitive dyes and a polymer applied on a paper substrate [16]. In this paper, the authors accurately mention some of the problems related to measuring light levels in the museum, which can be divided into three principal areas. First, the difficulty of measuring radiation coming from mixed sources (natural and artificial) and subjected to seasonal changes. Second, extrapolations of point measurements often provide uncertain cumulative photometric exposures. Third, placement of an illuminance meter next to each object is unmanageable and results in elevated costs for the institution. Despite all of these aspects, a few studies concentrate on proposing a systematic methodology for evaluating natural and artificial radiation levels and presenting results derived from field measurements [17,18].

For all the above-mentioned reasons, this work presents a new promising methodology for cultural institutions interested in quantifying the distribution of natural radiation in their exhibition spaces. This study includes three major innovative aspects. First, photometric and UV radiation readings were recorded continuously every 10 min for an entire year. This has provided the opportunity of examining separately the data from any desired interval of a day, month or year. Second, the illuminance data presented parallel with the cumulative exposure curves offers an original way of evaluating the results, since daylight behaviors can be easily inferred from the combination charts. Third, this new method offers the possibility of separating the radiation into its natural and artificial components. This separation is based on the assumption of a constant artificial lighting baseline in illuminance and a discernable natural radiation signal at specific times of the day. Continuous measurements are important since they permit to evaluate changes throughout the day and those taking place at different times of the year. Comparable exhibition areas can be evaluated by determining the natural lighting distribution of one area, which then allows extrapolating the results to similar locations within the building. Finally, data loggers provide a more accurate method for calculating total photometric exposures when compared to estimations obtained from light dosimeters.

2.1. The Old Patent Office Building

The Old Patent Office Building is the third public structure constructed in early Washington DC after the White House and the United States Capitol. It was designed by American architect Robert Mills in the Greek Revival style characteristic of the 19th century in the United States [19]. The construction of the building begun in 1836 and it was completed in 1868. The Old Patent Office Building has witnessed many important historical events throughout its history and it was employed by several government agencies before it was converted into a national museum. The building is a National Historic Landmark and was included in the National Register of Historic Places of the United States of America in 1966. Two major renovations took place during the 20th century, resulting in a transformation of the space from office spaces into exhibition galleries. After the most recent six-year renovation, the building reopened to the public in July 1, 2006, and was renamed The Donald W. Reynolds Center for American Art and Portraiture. This historical

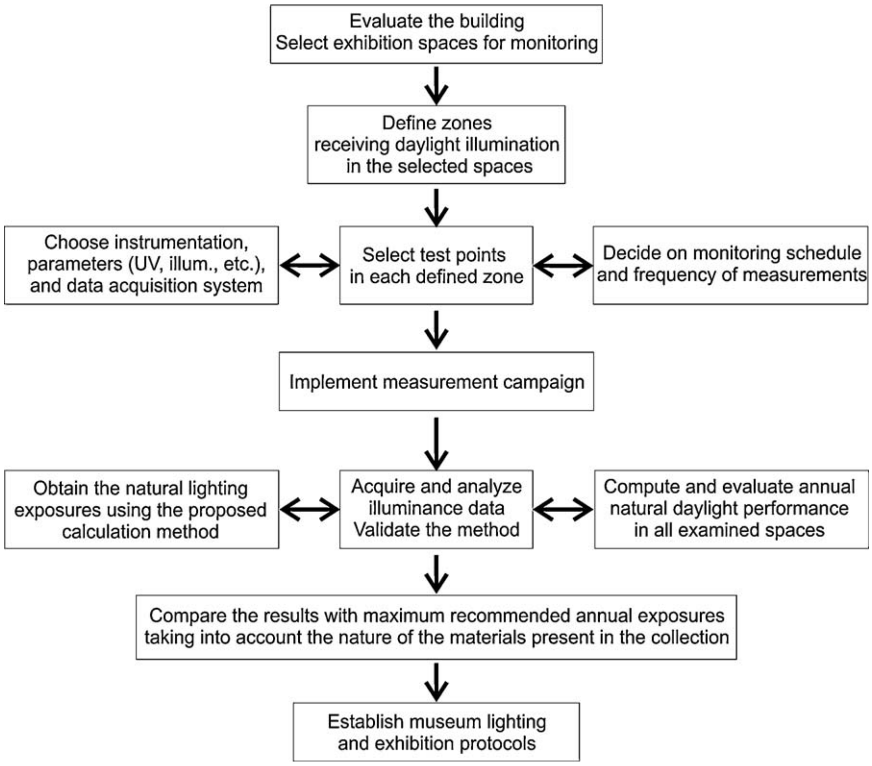

Fig. 1. Schematic description of the proposed method.

structure covers an entire city block demarcated by F and G Streets and 7th and 9th Streets NW in Chinatown, Washington DC. The building consists of four wings, which surround a central courtyard that has an undulating glass roof. Every wing has an external portico and a central corridor, with galleries distributed along both sides. The galleries are either adjacent to the street or next to the central courtyard and have been defined as external and internal, respectively.

3. Methodology

An overview of the methodology employed in this study is shown in Fig. 1. Potential users should follow this outlined procedure if interested in implementing the methodology in other museums or cultural institutions around the world. Initially, it is necessary to conduct an evaluation of the building and its exhibition spaces. The building site in terms of its geographic location, climatic zone and weather patterns needs to be investigated. A representative number of areas must be selected taking into account the different display areas within the building. Some of the aspects that need to be considered regarding the monitoring zones include: floor area, fenestration, ceiling height, construction materials, outdoor obstructions and type of works exhibited in the space. The different zones illuminated with natural daylight within a selected space must be defined next. For example, various orientations such as south-facing versus east-facing walls or horizontal in opposition to vertical surfaces are specified at this stage. Afterward, the test points are chosen for each defined zone. In the present study, the selection of light monitor locations took into consideration several architectural aspects such as four building wings, three different floors, internal and external galleries, horizontal and vertical surfaces and various window treatments, among others. The objective was to assure that these measuring points would be representative of several lighting situations encountered throughout the building. At this point, various aspects such as measuring devices, data acquisition system, monitoring schedule and frequency of measurements are selected. For example, the sampling interval selected for this study was one reading every 10 minutes; measurements were then logged automatically and saved into a single file. A total of 24 monitors were installed with various positions towards the sun. The distribution included 19 monitors mounted to walls next to the artwork. Three meters were horizontally positioned near three-dimensional works of art located under skylights or near windows. Two meters were placed inside display cases that were directly below skylights on the west wing. A building plan that includes the location and orientation of 12 meters installed on the second floor is shown in Fig. 2. Data loggers were named using the following format: building wing initial, floor number and a two-digit gallery number. In special cases where two meters were employed in the same gallery, initials such as EFW, WFW, SFW or H were added to designate an east-facing wall, a west-facing wall, a south-facing wall or a horizontal surface, respectively. For example, meter E112_EFW was located in the east wing, first floor, gallery 12 and was mounted to an east-facing wall.

After all these aspects were considered, the measurement campaign was implemented. The data was then downloaded, evaluated and presented to staff from both museums on a monthly basis in order to identify problematic areas and to provide an opportunity for making adjustments during the course of the study. Validation of the method is performed using a computer simulation program, which has already been validated. This allows comparing simulated and measured illuminance data from winter and summer months acquired for various museum locations. This computer simulation program allows estimating the amount of daylight reaching an exhibition space taking into account the geographic location of the building, the various seasons of the year and different sky illuminance models. If there is good agreement between calculated and measured data, the method is validated and further treatment of the illuminance data is possible. Numerical integration is employed for obtaining cumulative photometric exposure curves

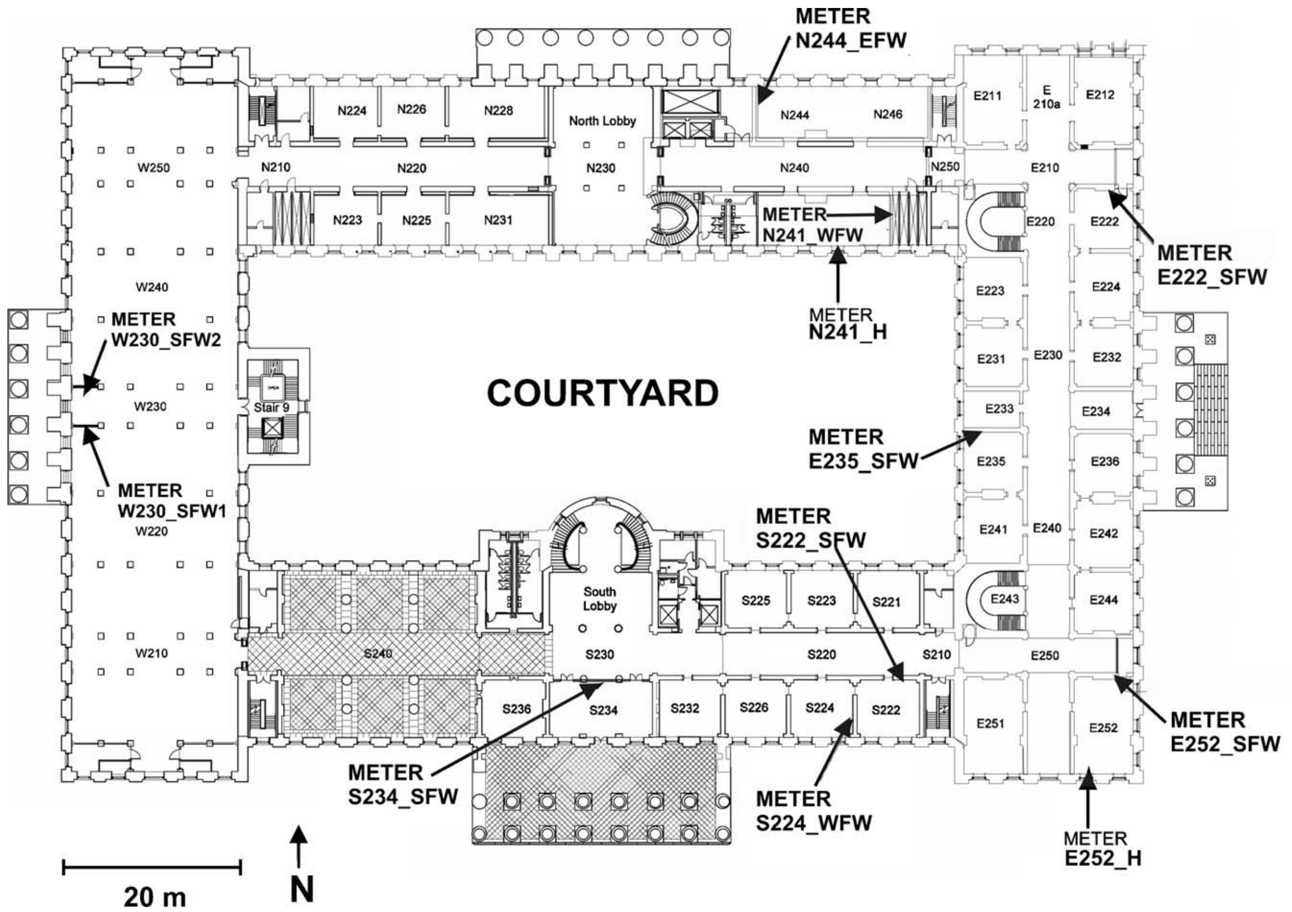

Fig. 2. Second floor plan of the museum showing approximate locations and orientations of 12 light monitors (image courtesy of Smithsonian Institution).

and consequently calculating the total exposure. Even though contributions from both natural and artificial radiation during most of the day are evident, the average artificial lighting baseline of each gallery provides a way for estimating the artificial lighting exposure, since this type of radiation is easier to be controlled than its natural counterpart and its intensity is roughly constant. Hence, the artificial radiation exposure is obtained by multiplying the number of electric lighting hours times the artificial lighting baseline in illuminance. The assessment of illuminance data permits to accurately establish the lighting schedule and the average baseline produced by electric lights. In the present study, an additive effect of natural radiation to the artificial lighting component was noticed after inspecting the illuminance data. These high illuminance values of natural lighting resulted in daylight signals, which exceeded the artificial lighting baseline during a specific time interval. Therefore, the natural lighting exposure was obtained by calculating the area under the daylight curve, after subtracting the artificial lighting baseline from the data.

After concluding the measurement campaign, the annual natural daylight performance of the spaces is evaluated. The different annual trends in daylight distribution are identified at this stage and also the areas of high risk of damage for the objects. The results are then contrasted with maximum recommended museum exposures taking into consideration the light-sensitivity of the displayed works, the museum opening hours and the artificial lighting component registered in each space. The data can be eventually used towards the establishment of museum lighting and exhibition protocols. The results will have an influence on decisions such as the use of a larger or lower natural lighting component in a space and the frequency of rotation of exhibitions.

This method has repercussion on museum energy savings applications since it permits to identify exhibition areas where a lower artificial lighting baseline can be employed while introducing a higher natural lighting component; especially in spaces where objects with moderate or low light-sensitivity are displayed. The method also finds application in the museum lighting design field. The production of visually pleasing exhibits often requires illumination using a large natural lighting component, which permits better color rendering of the artworks. This methodology would allow assessing individual lighting scenarios in order to determine if an increment in natural lighting component is feasible. Nevertheless, the integration of the method in preventive conservation programs in museums is probably the most important application. Knowing the natural daylight distribution in a room throughout the year permits better control through the introduction of window treatments at specific locations during a particular season or by reducing unnecessary layers during the months when natural lighting poses a lower risk. This work also lays the foundation for future studies in other institutions located in different climatic zones with different solar radiation amounts and distribution.

3.1. The geographical location of the museum and its relationship to sun paths

As previously stated, it is important to get acquainted with the geographical coordinates of the museum site relative to the International Meridian. Geographic coordinates for the Donald W. Reynolds Center are latitude 38°53′52.5″ N and longitude 77°01′21.90″ W and were obtained using EZ-locate online geocoding software [20]. This information is essential when searching

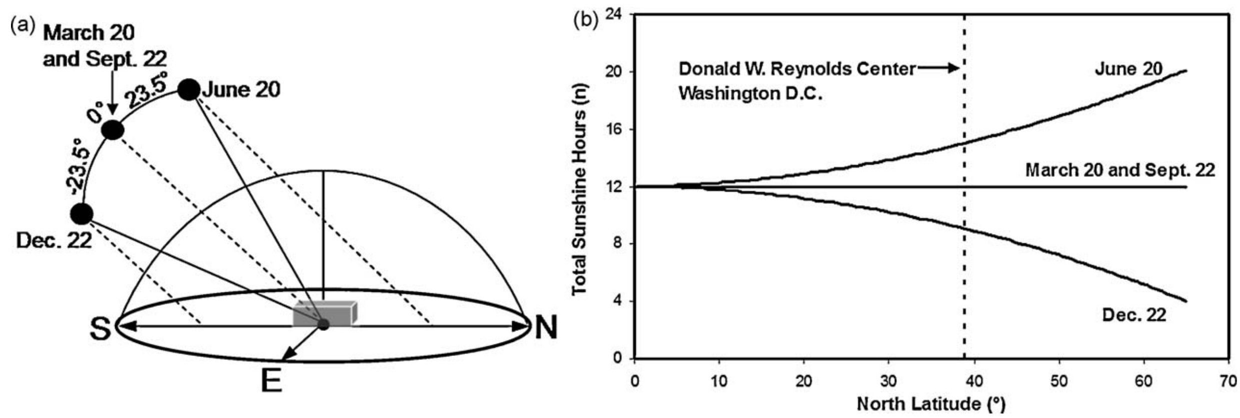

Fig. 3. Astronomy and geography related concepts: (a) the various sun's paths across the celestial sphere as experienced by an arbitrary building. The dashed lines represent the equinoxes and solstices (adapted from E.C. Boes [21]); (b) change in total sunshine hours with latitudes, the position of the museum site is indicated by a discontinuous line (adapted from G.N. Tiwari [22]).

for solar and meteorological information available at various web-based databases. The earth's inclination of 23.5° with respect to its rotational axis and its rotation around the sun give rise to the seasons, due to higher or lower proximity of the hemispheres to the sun. The pre-Copernican model of the sun rotating around the earth is typically used to simplify the discussion about sun paths [21]. An arbitrary building located in the Northern Hemisphere and covered by the celestial sphere has been used to describe sun paths at various times of the year. This model can be used to track incident sunrays on the sphere that can ultimately make their way into the building. As viewed from the earth, the sun is higher in the sky during the summer and it reaches its lowest altitude during the winter. In Fig. 3a are shown the resulting sun trajectories that give rise to four solar phases namely vernal equinox, summer solstice, autumnal equinox and winter solstice. The variation of total number of sunshine hours with latitudes is shown in Fig. 3b. The data shows that there are 12 h of natural daylight in March and September since declinations are approximately 0° at all latitudes [22]. It can also be observed that sunlight hours will increase or decrease at higher latitudes, depending on which solstice takes place. The 38°53′52.5″ north latitude of the Donald W. Reynolds Center is indicated by a discontinuous line that intersects the curves at approximately 9.5 h and 15 h of sunlight for December and June solstices, respectively. These sunshine hours have a clear effect on the monthly natural radiation exposures, confirming that this type of evaluation is essential prior to starting any monitoring program.

Natural daylight enters the museum through side windows, glass doors and skylights. Fig. 4a shows the museum's Great Hall viewed from the third floor showing skylights on the south wing. Two examples of meter set-ups are presented: the first case shows a monitor that was vertically installed (Fig. 4b) next to an oil painting. The second example shows a meter that was horizontally mounted (Fig. 4c) on a sculpture's pedestal. The method of reducing UV radiation and visible light levels is by using 3M™ Scotchtint™ NV-15 Night Vision window film, as well as either Thermoveil® shade cloth or Venetian blind window treatments employed by the Smithsonian American Art Museum and National Portrait Gallery, respectively.

3.2. Instrumentation

The meters used in this survey were ELSEC 764C environmental monitors manufactured by Littlemore Scientific Engineering (Dorset, United Kingdom). These monitors allowed to take periodic readings of the amount of visible light in lux ($\mathrm{lm\,m^{-2}}$) and the UV component in $\mu\mathrm{W\,lm^{-1}}$. The monitor is cosine corrected for angular response and the radiation is detected by a pair of silicon photodiodes connected to a single chip microprocessor. UV radiation and visible light wavelength ranges are 300–400 nm and 400–700 nm, respectively. The accuracy of the ELSEC 764C instrument for visible light and UV radiation readings is 5% and 15%, correspondingly. Monitors were installed on all three floors and distributed in the following manner: four on the first floor, 12 on the second floor and eight on the third floor. The meters were programmed to take measurements every 10 min, for 24 h a day, 7 days a week and 52 weeks a year. A USB2IR external wireless mini adapter from StarTech.com was employed for instantaneous transfer of files from the monitors to a portable computer. The data was downloaded using RView 3.8 for Loggers from Littlemore Scientific Engineering, then converted into a spreadsheet for data reduction and preparation of plots.

3.3. Calculation of total, artificial and natural photometric exposures

Light data was organized into a series of plots of change in illuminance with time. The total exposure, H_T, in lux-hours (lx h) was obtained by calculating the area under the illuminance curve using numerical integration. The integral was approximated by adding the areas of all rectangles obtained after dividing the total region into 10-minute intervals. The integral can be expressed by Eq. (1), where E_v is the illuminance integrated over the exposure time, t.

$$H_T = \int_0^t E_v dt = \frac{1}{2}\sum_{i=1}^{n-1}(E_{v_i} + E_{v_{i+1}})(t_{i+1} - t_i) \quad (1)$$

Each monitor recorded a set of n points: (t_1, E_{v1}), (t_2, E_{v2}),. . .,(t_n, E_{vn}), every 10 min. These points define $n-1$ rectangular intervals, where the width of the i-th interval is given by the difference between two successive measurements, as shown in Eq. (2).

$$\Delta t_i = t_{i+1} - t_i \quad (2)$$

The height of the rectangle associated with this i-th interval is the average illuminance at that specific interval shown in Eq. (3).

$$\overline{E_{v_i}} = \frac{E_{v_i} + E_{v_{i+1}}}{2} \quad (3)$$

Assuming a constant artificial lighting baseline in illuminance and absence of natural radiation, the artificial lighting exposure, H_A, was obtained by multiplying the average artificial lighting value times the duration of exposure, as shown in Eq. (4).

$$H_A = \overline{E_v} \times t \quad (4)$$

Afterward, the natural lighting exposure, H_N, was obtained by subtracting the artificial lighting exposure from the total exposure as shown in Eq. (5).

$$H_N = H_T - H_A \quad (5)$$

Monthly natural lighting exposures and cumulative exposure curves were plotted on a single graph using a primary and a secondary y-axis, respectively. Furthermore, the generated cumulative exposure curves served to evaluate the resulting daylight illumination trends.

3.4. Method validation

The method has been validated using Superlite 2.0 [23]. This software allows simulating the natural daylight distribution in a room by calculating hourly values of illuminance on any given plane that describes the space. The calculation technique used is based on the radiation flux exchange between surfaces by dividing the examined space into a mesh of small elements. Interior natural daylight levels for any sun and sky condition can be modeled for spaces having windows or skylights. The program takes into account the variation of the fenestration transmittance with the angle of incidence and also the effect of the direct solar radiation and the reflected light component. Some of the parameters considered include the dimensions of the space, the overall fenestration area, the reflectance and the transmittance of the construction materials, and the orientation of display surfaces. Hourly indoor illuminance levels were simulated from 9:00 h to 16:00 h in various display areas of the museum during winter and summer days with the aim of comparing expected and measured values.

Measured and Superlite-simulated indoor illuminance in a south-facing test-point of gallery S222 are shown in Fig. 5a. This room has a floor area of 64 m^2 and it is side-lighted by two windows located on the south wall, each one with an area of 2.4 m^2. In December 20, under clear sky conditions, the illuminance registered by meter S222_SFW varied between 2 and 47 lx while the simulated illuminance for an equivalent surface ranged from 15 to 44 lx. The same surface exhibited subtle changes throughout the day under overcast sky conditions observed in December 13, with measured and simulated values that ranged from 2 to 5 lx and 1 to 4 lx, respectively. Simulated and measured illuminance trends obtained for two summer days were fairly similar and remained within the 3 to 12 lx range. A reasonably low discrepancy was observed in June 13, which consisted of a slower increase in illuminance recorded between 10:00 h and 12:00 h relative to the predicted augment. Equivalent south-facing display areas located in the first, second and third floor also showed good agreement between simulated and measured data. Measured and simulated indoor illuminance values for a horizontal surface of gallery S321 are shown in Fig. 5b. This space has a floor area of 494 m^2 and it is mainly illuminated by a large skylight that has an area of 187 m^2. Simulated and measured illuminance data for December 20 (clear sky) showed similar natural daylight patterns which fluctuated from 49 to 183 lx and 39 to 243 lx, respectively. In contrast, overcast sky conditions observed in December 13 resulted in less variation in illuminance throughout the day, which ranged from 6 to 23 lx and 13 to 47 lx for simulated and measured data, respectively. For all examined cases, the differences in absolute illuminance values ranged from 5% to 25%. The data shows a fairly good agreement in both range and distribution pattern considering the difficulty of accurately simulating the daylight availability in the building. Simulated and measured illuminance data is consistent even under various sky conditions and at different times of the year.

4. Experimental data and results

An example showing visible light values recorded by one of the monitors on a single day is included to illustrate how the

Fig. 4. (a) the Great Hall viewed from the third floor mezzanine showing skylights on the south wing of the building; (b) light monitor E112_EFW vertically installed near an oil painting; (c) light monitor S321_H horizontally installed on a sculpture pedestal. (Photos: Julio M. del Hoyo-Meléndez).

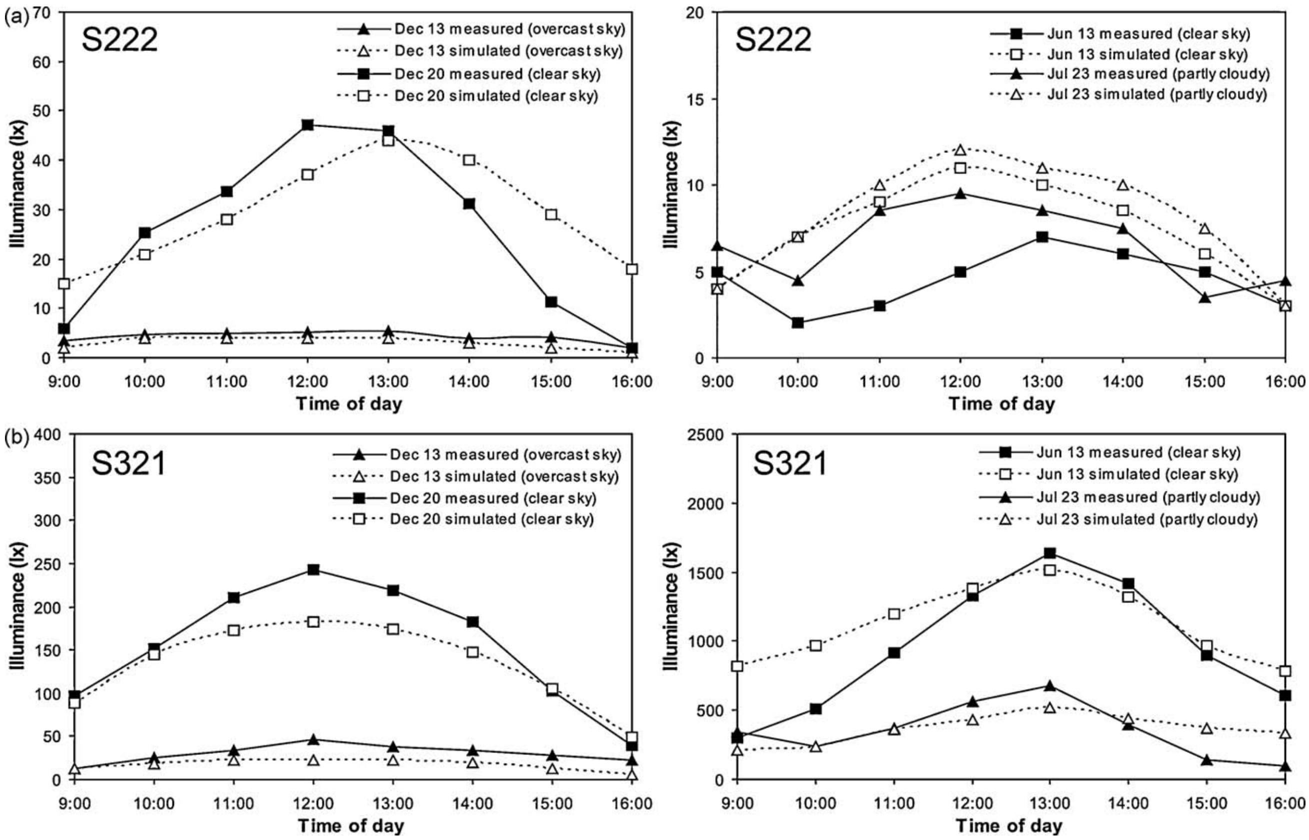

Fig. 5. Measured versus Superlite-simulated indoor illuminance in two of the exhibition spaces examined: (a) south-facing test-point of gallery S222; (b) horizontal test-point of gallery S321.

data was treated. An intense signal produced by natural lighting and a constant artificial lighting baseline can be deduced from the data. After acquiring the data, the calculations described in Section 3.3 were performed. The same procedure was used for determining monthly and yearly natural lighting exposures for every monitor.

4.1. Determination of the natural lighting exposure using the proposed model

Illuminance data recorded by monitor E252_SFW in September 7, 2008, is shown in Fig. 6. This meter was located in a southeast gallery on the second floor and was mounted to a south-facing wall. Sunrise and sunset times on that day were 5:43 h and 18:28 h, respectively. The data show a gradual increase in illuminance from about 6:30 h until 8:40 h, when gallery lights were switched on. This is indicated by an abrupt increase in illuminance pointed out by the arrow in Fig. 6. An illuminance maximum of 185 lx, primarily due to the effect of natural lighting, was observed at 9:10 h. This was followed by a decrease in illuminance observed from 9:20 h to 13:00 h. Artificial lighting clearly had a dominating effect from 13:00 h to 19:30 h, indicated by an average artificial lighting baseline of 9.3 lx. This was deduced from the data recorded between 18:40 h and 19:40 h, time when only artificial lighting was detected. The lights were then switched off from 19:50 h to 00:00 h, hence the gallery had an artificial lighting baseline of 9.3 lx for an 11-hour period. Assuming that the illuminance produced by the electric light sources was constant, an artificial lighting exposure of 0.1 klx h is obtained, by multiplying the average illuminance times the number of hours of electric lighting. The total exposure obtained for 11 h was 0.3 klx h, which gave an estimated natural lighting exposure of 0.2 klx h. This simple example helps to illustrate how natural and artificial lighting contributions to the total exposure can be quantified as 67% and 33%, respectively. Even though the two components of light were present from 8:40 h to 19:50 h, the data shows that natural lighting had a significant additive effect from 8:40 h until 18:30 h. This is characterized by daylight data with illuminance values higher than the 9.3 lx artificial lighting baseline. The effect of natural lighting was observed to a lower extent from 13:00 h until 18:30 h. This was indicated by a slightly higher average illuminance of 10.7 lx produced by subsequent positions of solar rays with increasing distance from the meter location.

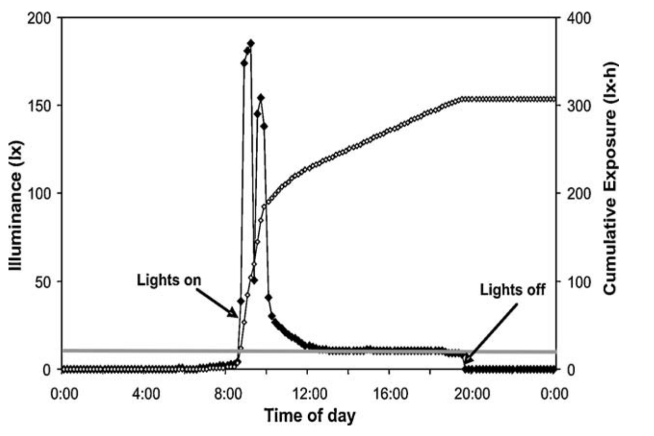

Fig. 6. Illuminance data (primary axis) recorded by monitor E252_SFW in September 7, 2008, and the cumulative exposure (secondary axis) obtained from numerical integration. A gray horizontal line is used to indicate the artificial lighting baseline in illuminance.

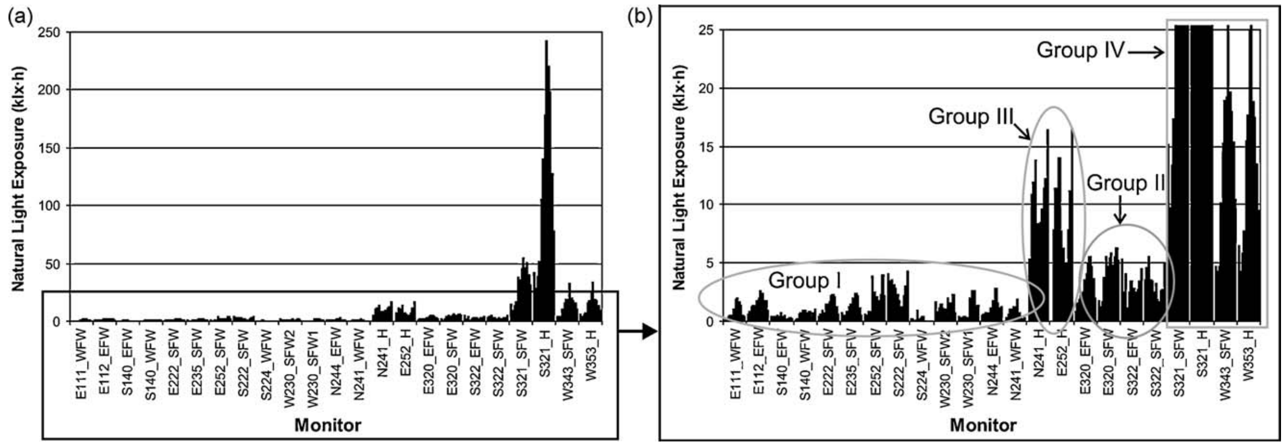

Fig. 7. (a) overall monthly natural lighting exposures obtained for 23 monitors; (b) detail of the 0–25 klx h range showing monitors divided into four groups according to their calculated exposures.

4.2. Monthly natural lighting exposures and cumulative exposure curves

Fig. 7a shows the monthly natural lighting exposures recorded by each monitor over the entire year. The same graph expanded along the 0–20 klx h exposure range is presented in Fig. 7b. It can be observed that 17 vertically installed monitors located in side-lighted spaces registered lower monthly natural lighting exposures, which were typically below 5 klx h. In this group, third floor monitors experienced natural lighting exposures that were approximately two times higher than the ones recorded in the first and second floor. Two horizontally installed meters located in the second floor registered natural lighting exposures, which were approximately three times higher than the ones recorded by their vertical counterparts. The highest monthly natural lighting exposures were registered by four monitors installed below skylights. The monitors were divided into four groups based on calculated annual natural lighting exposures. Group I consists of vertically installed monitors located in the first and second floor in side-lighted spaces. The natural lighting exposures registered by these 13 monitors ranged from 5 to 33 klx h y^{-1}. Four vertically installed monitors also located in side-lighted galleries in the third floor constitute the second group. These meters recorded natural lighting exposures that ranged from 38 to 52 klx h y^{-1}. Two horizontally installed monitors located in the second floor form the third group since they recorded natural lighting exposures of 104 and 116 klx h y^{-1}. Finally, four monitors installed directly under skylights located in the third floor comprise the fourth group. This later group can be further divided in two classes: fully exposed meters and monitors inside display cases. For instance, fully exposed monitors located in gallery S321 registered 398 and 1451 klx h y^{-1} and the differences were due to their placement in vertical and horizontal surfaces, respectively. In contrast, monitors placed inside display cases experienced similar annual exposures of 173 and 175 klx h.

The monitors belonging to groups I and II measured illuminance levels on vertical surfaces in which objects with moderate to high light-sensitivity are exhibited. The artifacts displayed in these galleries range from paper documents to oil paintings and their annual natural lighting exposures averaged 15 and 42 klx h y^{-1} for group I and II, respectively. Although these yearly exposures remain under the maximum recommended values, it is important to also take into account the electric lighting component detected in these galleries which was usually in the 90–150 klx h y^{-1} range. Thus, materials with moderate sensitivity would generally receive total annual exposures that are under the maximum recommended levels in all four scales described in Table 1. However, the exposure limits for highly sensitive materials proposed by the CCI and the Heritage Collections Council (HCC) of Australia seem more adequate for comparison with the present study since the two examined museums are open 10 h a day for 364 days per year. For instance, any object exhibiting high light-sensitivity located in an exhibition area that belongs to either group I or II could have experienced an exposure in the 105–165 or 130–170 klx h y^{-1} range, respectively. Group III monitors measured the amount of radiation striking two different horizontal surfaces adjacent to various wooden furniture pieces identified as moderately light-sensitive. The calculated total exposures for these two meters were in the 200–250 klx h y^{-1} range and therefore remained under the maximum recommended limits. According to the CCI scale, these two objects could experience a perceptible color difference within 40–50 years of continuous exhibition after reaching a total exposure of 10 Mlx h. Finally, objects exhibited in group IV zones have moderate to low light-sensitivity. Artifacts exhibited in gallery S321 and inside display cases located in the west wing consist of oil and acrylic paintings as well as inorganic-based objects such as stone and metal sculptures. The annual artificial lighting components registered in gallery S321 were approximately 22 and 225 klx h for a horizontal and a vertical surface, respectively. Therefore, the horizontal surfaces of the more permanent artifacts experienced total annual exposures, which were in the 1500 klx h vicinity. Although this value may seem relatively high, it is not of great concern since these objects are composed of permanent materials. In contrast, vertical surfaces in gallery S321 registered total exposures, which were approximately 600 klx h y^{-1}. This value remains within the annual exposure limits for oil paintings except for the IESNA guideline for moderately susceptible materials, which recommends 20% less. Finally, meters placed inside display cases located in the third floor recorded total annual exposures, which were in the 300–400 klx h range. Thus, materials exhibited in these areas remained within the maximum exposure limits for moderately sensitive materials according to the four-museum lighting guidelines used for comparison.

The procedure described in the previous section was applied to every meter at the end of each month. An example of monthly natural lighting exposure and cumulative exposure curve of one year obtained for meter E252_SFW is shown in Fig. 8. This meter registered an increase in natural lighting exposure from December 2007 until March 2008, when a maximum exposure of 3.8 klx was observed. A decrease in exposure was then observed from March 2008 until May 2008, followed by a new rapid increase from July 2008 until September 2008, when a new maximum

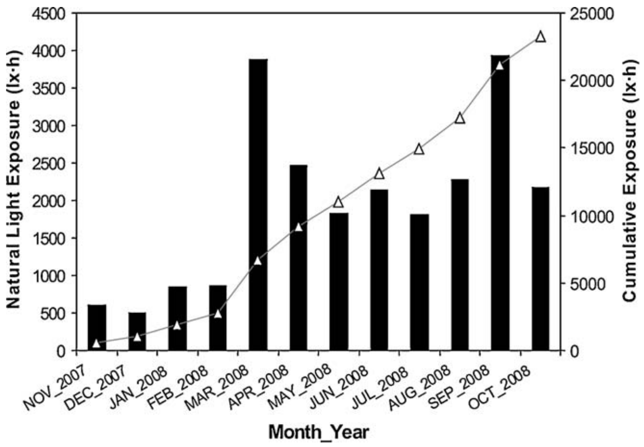

Fig. 8. Monthly natural lighting exposures and cumulative exposure curve obtained for meter E252_SFW showing exposure maxima in March 2008 and September 2008; therefore its cumulative exposure exhibits Type A behavior.

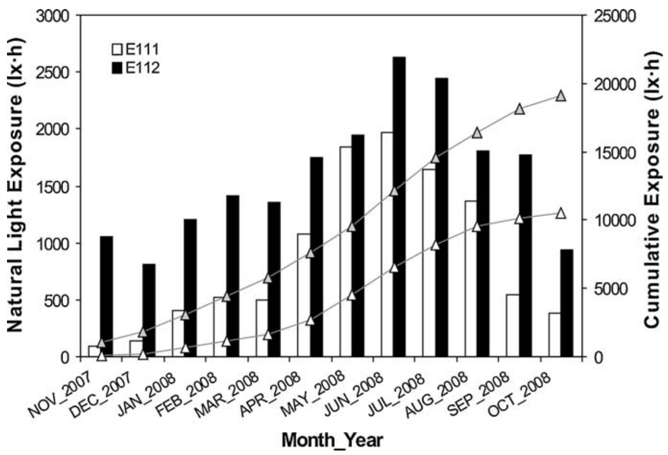

Fig. 9. Monthly natural lighting exposures and cumulative exposure curves obtained for meters E111_WFW and E112_EFW showing exposure maxima in June 2008; therefore their cumulative exposures exhibit Type B behavior.

exposure of 3.9 klx was registered. The natural radiation exposure for November 2007 was obtained using numerical integration. Afterward, the December 2007 exposure was determined similarly and added to the exposure obtained for the previous month to calculate the cumulative exposure for these two months. The same procedure was successively applied to obtain the cumulative exposure for the following months. A line connecting all cumulative exposure points permits to evaluate the annual trends in daylight illumination. Location and orientation of the meter gave rise to two exposure maxima observed during the months of vernal and autumnal equinoxes when solar declinations were −0.02°and 0.17°, respectively. All meters vertically installed in south- and west-wing galleries and two horizontally installed meters located on side-lighted spaces in the second floor exhibited a natural lighting behavior similar to the one described in Fig. 8, identified as type A for the purpose of this paper.

A different trend in cumulative exposure was observed for meters located in side-lighted vertical zones in the north and east wings as well as for the four meters located beneath skylights on the third floor. This behavior was identified as Type B just for differentiation purposes. For example, cumulative exposure curves obtained for meters E111_WFW and E112_EFW show gradual increases from December 2007 until June 2008, when maximum natural lighting exposures of 2.6 klx h and 1.9 klx h were registered (Fig. 9). This was followed by decreases in natural lighting amount, recorded from June 2008 until October 2008. For one year, the total natural lighting exposures recorded by meters E111_WFW and E112_EFW were 19 klx h and 10 klx h, respectively. This 9 klx h difference is explained by meter locations on external and internal east-wing galleries. The meter on an external gallery was mounted to an east-facing wall and therefore received a higher natural lighting amount than its counterpart, which was installed on a west-facing wall at an adjacent internal gallery.

These two natural lighting distributions can also be distinguished in Fig. 7b in which overall monthly exposures for all meters are shown. The two behaviors observed are consistent with data calculated for the city of Dublin by McVeigh [24]. Although Dublin is located at higher north latitude than Washington DC, it was also possible to identify two natural lighting behaviors, which were dependent on orientation and ratio of vertical to horizontal radiation. In the cited study, solar radiant exposure measurements were given in MJ m^{-2} but they can be somehow correlated to photometric measurements, since the two quantities are proportional. Solar radiant exposure is a radiometric quantity used to describe and quantify the irradiation level on a surface considering UV radiation, visible light and infrared radiation. In contrast, photometric exposure based on illuminance measurements exclusively indicates the amount of radiation spectrally weighted by the standard photometric visibility curve, which has a maximum at the wavelength of 555 nm for the human eye.

A summary of the results is presented in Table 2. Some of the general trends observed included higher exposures registered in external galleries relative to the internal ones and also higher exposures recorded by horizontal meters relative to the ones vertically installed. The data also indicated that natural lighting exposures increase as one moves up from the first floor to the third floor. East-wing galleries typically received higher exposures than those located on the south wing; this effect was noticeable after evaluating the data recorded by monitors located in the first floor and third floor. As discussed earlier, larger natural radiation values were recorded by meters located under skylights on the third floor. Therefore, objects with moderate to high light-stability exhibited in this area were recommended to be periodically rotated, taking into account that the highest natural lighting exposures are expected in June, around the summer solstice.

Table 2
Summary of natural lighting distributions observed for various museum locations.

Museum floor	Type A behavior (group[a])	Type B behavior (group)
First	Side-lighted vertical surfaces in the south wing (I)	Side-lighted vertical surfaces in the east wing (I)
Second	Side-lighted vertical surfaces in the west and south wings (I) Side-lighted horizontal surfaces in the north and south wings (III)	Side-lighted vertical surfaces in the north and east wings (I)
Third	Side-lighted vertical surfaces in the south wing (II)	Side-lighted vertical surfaces in the east wing (II) Top-lighted vertical and horizontal surfaces below skylights (IV)

[a] These numbers are used to classify the exhibition areas, which were divided into four groups based on annual natural lighting exposures obtained.

Table 3
Comparison of UV radiation data and total photometric exposures recorded by five monitors in December 2007.

Monitor	UV radiation (μW lm^{-1})	Total natural light exposure (klx h)
S234_SFW	338	18
E252_H	30	7.8
S321_SFW	28	9.7
S321_H	0	28
S222_SFW	0	3.4

4.3. UV radiation data

Small amounts of UV radiation, derived from solar illumination, were detected by four meters namely S234_SFW, E252_H, S321_SFW and S321_H. The meter located in gallery S234 was an exceptional case since it was used to measure unfiltered sunlight striking a south-facing wall of a south-wing gallery in December 2007. Architectural glass elements in this gallery had no treatment against natural radiation and this served to estimate how much protection the current window treatments provide. These results are presented in Table 3. Meters S234_SFW and S222_SFW registered UV radiation averages of 338 μW lm^{-1} and 0 μW lm^{-1}, respectively. These two meters were mounted to south-facing walls on south-wing galleries and recorded total natural radiation exposures of 18 and 3.4 klx h. This indicates that window treatments employed in gallery S222 were accountable for an 81% reduction in natural lighting exposure relative to the one registered in gallery S234. A 100% reduction in UV radiation was noticed after comparing the data from these two galleries. The two horizontal meters, E252_H and S321_H, registered a natural radiation exposure variation of approximately 20 klx h. This was most likely due to the location of the latter one in a space illuminated using a skylight. However, no UV radiation was registered by meter S321_H in December 2007 probably due to the low solar altitude observed near the winter solstice. Meters E252_H, S321_SFW and S321_H registered UV radiation yearly averages of 24, 23 and 7 μW lm^{-1}, respectively. These averages remain under the maximum recommended levels of 30 μW lm^{-1} and 75 μW lm^{-1}, for very sensitive and sensitive objects [2].

4.4. Action of natural and artificial lighting on the artworks

Illuminance measurements taken near the surface of the objects have revealed that artifacts may receive higher exposures due to the use of direct sources, which are sometimes employed as accent lights. In absence of natural radiation, it is possible to determine the direct to indirect artificial lighting ratio. These spot measurements can be used in conjunction with continuous readings recorded by a fixed monitor adjacent to the artwork, with the aim of evaluating the individual effects of natural and artificial lighting throughout the year. Preliminary results indicate that in cases where a direct artificial lighting source has a dominating effect over natural radiation, the annual exposure received by an object may be extrapolated from a spot measurement recorded near its surface, since the contribution from natural radiation is almost negligible. This effect has been observed in galleries in which the natural radiation component is significantly reduced, either by the use of window treatments or due to their location adjacent to tall evergreen trees planted on the exterior of the building. In contrast, increases in diffuse daylight signal observed at various times of the year may result in a significant contribution of natural radiation to the total exposure. As a consequence, a higher exposure than the one extrapolated from a single photometric measurement is generally obtained. This phenomenon has been identified in various museum exhibition spaces containing skylights. The results have allowed making more informed decisions on suitable locations and times of exhibiting the artworks. For example, light-sensitive objects can be safely exhibited nowadays in spaces where protection from natural radiation has been confirmed. In contrast, galleries illuminated with a significant component of natural radiation are now intended for works with moderate to low sensitivity. The data recorded in these areas has indicated the need for restricting the exhibition periods for objects with moderate light-sensitivity, with the aim of minimizing their exposure to natural radiation.

5. Conclusions

A light levels assessment of several exhibition spaces of the Donald W. Reynolds Center for American Art and Portraiture has been conducted. The proposed methodology has allowed quantifying and understanding the behavior of natural lighting inside the building. The method has been validated by comparing winter and summer data for various museum test-points. Simulated and measured illuminance data shows good correlation at different times of the year and under various sky illuminance conditions. This methodological approach allows separating the radiation into its natural and artificial lighting components. Cumulative exposures were calculated by determining the area under the illuminance curves using numerical integration. After evaluating the natural lighting data, four major zones of exposure were identified. The annual natural lighting exposures obtained have been correlated with maximum recommended values found in the museum lighting literature. With the exception of exhibition spaces located directly beneath skylights, it has been observed that the majority of areas evaluated received total exposures which were under the maximum allowable limits. Analysis of the cumulative exposure data also permitted to identify two different types of behavior, namely A and B, which were based on meter location within a gallery and their orientation towards the sun. Exhibition areas exhibiting type A behavior experienced two exposure maxima near the equinoxes while type B zones registered maximum exposures near the summer solstice. Small amounts of UV radiation were detected at four south-wing locations. Even though these UV radiation amounts remain under the 30 μW lm^{-1} recommended level for very sensitive objects, preventive measures are now being implemented in the museum to further reduce it.

This study has demonstrated the importance of conducting long-term systematic studies of daylight illumination distribution in museum buildings that make use of both electric and natural lighting in their exhibition spaces. It is necessary to quantify the sunlight since it shows a higher degree of variation throughout the year and it is more difficult to control than artificial illumination. Traditional museum light levels guidelines are based on correct perception of the objects and make little or no indication about their preservation implications. Other guidelines only provide recommended exposure limits that are based on known light-sensitivities of various standard materials. The placement of an illuminance meter next to each object is an unrealistic task and such an ambitious program presents evident elevated costs for any museum. However, once the distribution of natural lighting is known for a specific location and orientation one will expect similar behaviors in adjacent galleries with similar window sizes and floor areas. For instance, natural lighting exposures and trends similar to the ones described in this paper are expected for nearby museums in the Washington DC area. Spot measurements taken near the surface of objects at random times or days of the year only provide an overall view of a particular lighting scenario at a specific moment. These point measurements do not offer detailed information about continuous changes in natural lighting exposure, which take place throughout the year. Therefore, a qualitative and quantitative evaluation of natural lighting is essential in order to determine if there is a significant contribution that may result in high risk of damage for the artwork.

The proposed methodology can be applied to other cultural institutions around the world. From a qualitative point of view, daylight trends similar to the ones described in this paper are expected in museums and galleries located in the Northern Hemisphere. Based on the results, these annual daylight behaviors could be easily identified since they are mainly influenced by location and orientation of the area of interest with respect to various solar positions observed throughout the year. If the results presented in this study are used as a reference point, museums located in lower latitudes would experience less variation during the year due to sun paths, while institutions situated in the Southern Hemisphere would expect similar cumulative exposure trends during the equinoxes, accompanied by inverted natural radiation totals during the solstices. In the present study, the illuminance data and annual exposures recorded at various equivalent locations showed good correlation, indicating that a lower number of monitors could be employed when assessing natural radiation. This makes possible to extrapolate the results from representative galleries to other similar spaces, since the distribution of daylight should be similar for all equivalent areas. The results have also revealed that electric lighting adjustments take place throughout the year. As a consequence, variations in illuminance baselines or longer illumination periods than anticipated may be observed due to special events or gallery maintenance activities. Therefore, potential users must carefully evaluate the electric lighting component of the examined representative gallery since the amount of natural radiation is calculated by subtracting the artificial lighting component from the total exposure.

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