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# A dynamic performance analysis of passive sunlight control strategies in a neonatal intensive care unit

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Neonatal intensive care units are a special lighting design challenge. Although natural light is highly desirable, it should be carefully planned to maximise benefits and minimise the problems associated with uncontrolled sunlight. This paper discusses the performance of different passive sunlight control strategies in a neonatal intensive care unit at the Dr. Humberto Notti Children's Hospital in Mendoza, Argentina, analysing their annual daylight behaviour through dynamic daylight simulations. The aim of this work is to optimise the use of daylight in neonatal intensive care units, considering the special lighting conditions required. Results show that, in this case study, the adequate implementation of solar control systems and the appropriate layout of the space for different uses according to surrounding building design and the characteristics of the local luminous climate can increase the useful daylight illuminance by up to 13%, while avoiding the incidence of direct sunlight at all times.

## 1. Introduction

This paper discusses the performance of different daylighting strategies in three hospital therapy rooms of a neonatal intensive care unit (NICU) at the Dr Humberto Notti Children's Hospital in Mendoza, Argentina. The paper analyses their annual dynamic daylight behaviour in order to provide more useful daylight within these spaces. This research was done at the request of the hospital with the purpose of remodelling the neonatology sector. The project aims to improve the positioning of the medical equipment, incorporate a nursing monitor station and increase the size of the patient rooms. According to the remodelling design presented by the hospital, the daylight performance of the space with four different façade settings was analysed: (a) east and south horizontal louvres – the original solar control system; (b) no solar control system; (c) east roller blind and south fixed vertical louvred microblinds; (d) east adjustable vertical louvred microblinds and south vertical fixed louvred microblinds.

Lighting has an important influence on the daily human environment contributing to health, wealth and safety.[1] A fast growing body of knowledge suggests that light has beneficial effects on human health and well-being; in particular, the presence of daylight and contact with nature.[2] The implementation and the conscious use of innovative systems of daylighting can reduce energy consumption and improve the quality of use of interior spaces. Controlled daylight has a positive impact on human health and performance, as well as on the thermal and

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luminous efficiency of built spaces.[3] It is a preferred light source[4] and the presence of windows opens a view to the outside.[5] It is for these reasons that daylight plays an essential role in indoor spaces such as NICUs and developmental care units.[6–8] In these spaces, daylighting strategy designs must overcome significant challenges due to the coexistence of different user groups – newborns, health professionals and families.[9] This scenario often reduces the use of daylight as a source of illumination in environments with special uses. Therefore, this resource is effectively squandered[10] especially in cities with predominantly clear skies, e.g. Mendoza, Argentina and many others.

In terms of NICU visual tasks, daylight is a desirable light source: it has excellent colour rendering index (CRI) properties[11] and is highly intense in the spectral region that promotes the activation of the circadian system. The presence of at least one source of daylight is recommended.[9] As for neonates, lighting influences the postnatal development of vision and visual processes,[12–15] affects the developmental outcomes[16,17] and regulates the circadian rhythm of children.[11,18–20] This is why, in 1997, the American Academy of Pediatrics recommended introducing regular day–night cycles of illumination in the NICU.[19]

Although daylight is highly desirable in the NICU, it should be carefully planned according to the differing amounts of incident solar radiation throughout the year to maximise its benefits and minimise the problems associated with uncontrolled sunlight. Neonates should be kept away from direct light exposure. Glare for the staff should be avoided.[21] High light levels have also been associated with negative clinical outcomes: lower weight gain,[22] delays in the development of sleep patterns,[23] changes in oxygen saturation[24] along with stress and discomfort in preterm or critically ill patients.[25,26]

Current regulations have been reviewed.[14,27,28] The latest lighting American recommendations for a NICU indicate a range of 10–600 lx[28] in order to allow the assessment of the children, to examine skin colour and perfusion anywhere in the room. Considering the benefits of cycled lighting during the day, the lighting levels should range between 100 and 200 lx, preferably from daylight. At night, the illuminance from electric lighting with a spectral power distribution similar to daylight should be less than 50 lx with an allowed range of up to 600 lx, if required. Independent control of the lighting fixture must be provided.[27] When using individual procedure lights, which are capable of reaching 2000 lx,[14] care should be taken to avoid the exposure of high light levels at the neonate's eyes.

Regarding windows, the following issues should be considered: windows should be treated to minimise heat gain/loss and glare. Direct sunlight should be directed away from patients, IV lines and VDTs at all times. Cots and incubators should be located at least 60 cm from windows, which must have solar control elements of neutral finish to minimise color perception distortion.[29] Those control elements must be easily adjustable and they must be easily accessible for cleaning.

The NICU is a special lighting design challenge because there are heterogeneous needs that must be met. The different biological necessities of the infants and the health care providers must be considered along with the traditional issues such as visual performance, cost, energy and aesthetics.[25] However, the analysis should always focus on newborns.

The aim of this paper is to analyse the behaviour of daylighting in three different areas of the NICU: (i) intermediate therapy, (ii) intensive care and (iii) isolated therapy, to apply various daylighting strategies, and to assess their impact on indoor daylighting annual conditions. The hypothesis of this paper argues that, implementing appropriate sunlight control systems can improve the use of daylight in indoor spaces with demanding requirements such as a NICU. The challenge of this work consists in optimising the use of daylight in care units, considering the special lighting conditions that this type of space demands; as well as for the benefits that the daylight provides to patients.[2,27] It aims to provide new studies and analysis methodologies that encourage the use of daylight in these types of spaces.

## 2. Methodology

The methodology of this work is divided into four main stages: (1) NICU setting: intermediate therapy, intensive care and isolation therapy, (2) Description of the solar control systems tested, (3) Daylight simulation and (4) Dynamic daylight performance metrics.

### 2.1. NICU setting

The indoor space studied for the implementation of daylighting strategies is located in the NICU of the Dr Humberto Notti Hospital, Mendoza (32° 53' 51'' S – 68° 48' 15'' W). The metropolitan area of Mendoza is located in a semi-arid region of western Argentina. The sky is predominantly sunny; 83% of the year is sunny or partly cloudy with solar presence (Argentine National Weather Service for the period 1981–1990). There is an annual average of 2850 hours of sunlight. From the point of view of daylighting, Mendoza has a luminous climate that is predominantly 'clear sky'.[30] The mean maximum global horizontal illuminance values are 90,000 lx in the summer and 30,000 lx in the winter.[31,32]

As mentioned before, the remodelling design aims to improve the location of the medical equipment in order to incorporate a nursing monitor station and increase the size of the patient rooms. According to the proposed remodelling, the internment area of the NICU studied has an area of 121 $m^2$, which is divided into three different rooms by type of care required: intermediate therapy (E1) (28 $m^2$), intensive care (E2) (78 $m^2$) and isolation therapy (E3) (15 $m^2$) (Figures 1 and 2). The windows (double glazed hermetically sealed units) in the NICU are oriented toward the east and south and the building is offset

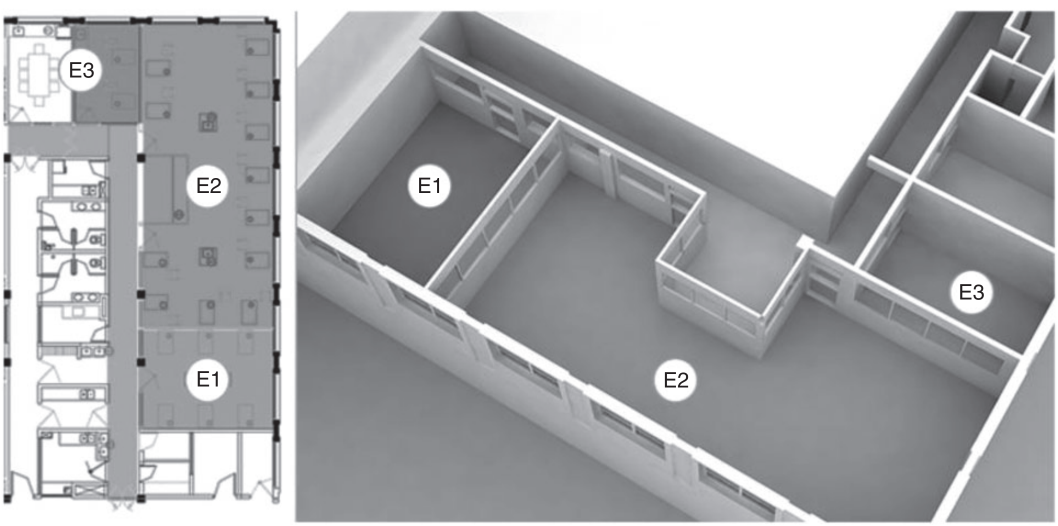


**Figure 1** Map of the zones analysed at the Humberto Notti Pediatric Hospital (E1, E2 and E3)

**Figure 2** Interior views of the NICU at the Humberto Notti Pediatric Hospital (E1, E2 and E3)

from the north by about 22° toward the east (Figure 3). The windows have solar control systems, horizontal movable aluminium louvres, which are never adjusted and mostly remain closed. Walls with glassed surfaces at eye level divide the different rooms generating partially opaque internal divisions. For a complete analysis, each of the rooms is studied individually.

## 2.2. Description of solar control systems tested

The most suitable solar control devices (SCD) for window bays facing east are those that are adjustable because of the variation of incident solar radiation, direct in the early hours of the morning and diffuse throughout the rest of the day.[33] In agreement with what was written above and along with the necessary conditions of strict hygiene of the NICU, an analysis of the luminous behaviour was proposed for spaces with an easterly orientation under the following conditions: (a) integrated vertical louvred microblinds[34] (diffuse white) and (b) integrated roller blinds (visible transmittance: 0.2). Both systems are adjustable. In the east and west, incident solar radiation has principally one direction (northeast-northwest in the southern hemisphere) and this is why the use of vertical louvre systems is recommended.[34] By saying that the are integrated, we mean that they are placed between two glass layers of the hermetically sealed double glass window system.

While the south façade receives only diffuse solar radiation during most of the year in the southern hemisphere, in the early hours of the morning and afternoon in the summer, this façade is exposed to direct solar radiation because of the relative position of the sun. This situation must be taken into consideration because this space is in continuous use being occupied throughout the day. It is important that the hospital has a deviation from the north of 22° to the east which causes the incidence of direct solar radiation to be zero on the south façade during the morning hours. However, this condition, which is relative to orientation, generates periods of incident solar radiation on the south façade during the last hours of the day, which extends to April. Accordingly, an integrated system of fixed vertical louvred microblinds (diffuse white) was implemented. The use of this system as a blockade against direct solar radiation is only for a limited amount of time throughout the year (December to April), as well as a short period of the day, which is no longer than 4 hours (afternoon).

The daylight behaviour of the selected spaces was evaluated with the following four conditions: (a) east and south horizontal louvres – the original solar control system; (b) no solar control systems; (c) east roller

**Figure 3.** East façade of the area of analysis

blind and south fixed integrated vertical louvred microblinds; (d) east integrated adjustable vertical louvred microblinds and south integrated vertical fixed louvred microblinds.

Louvered microblinds are within the category of discrete systems; they cover the entire aperture protecting the interior through the regulation of the entry of direct sunlight. The dimensions (units in mm) of the radius of the curvature R, the slat thickness, slat width and amplitude of the curvature of the slat of the louvred microblinds are given in Figure 4. The distance between each centre of the slats is 13 mm.

Integrated roller blinds are homogenous solar control systems, exhibiting a uniformly decreased transmittance. The optical data that characterise the behaviour of surface shading systems and the glass used in this investigation are given in Table 1.

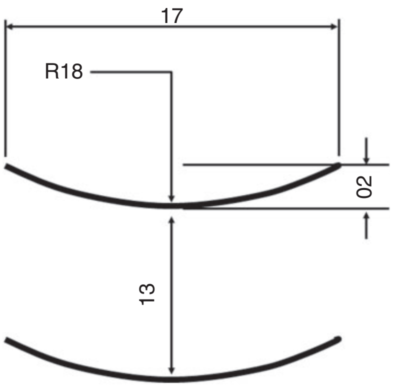


**Figure 4** Geometric properties of individual louvered microblind slat (units in mm)

**Table 1** Photometric properties of materials (solar transmittance (*Ts*), solar reflectance (*Rs*), visible transmittance (*Tv*), visible reflectance (*Rv*)).

| Material | *Ts* | *Rs* | *Tv* | *Rv* |
|---|---|---|---|---|
| White textile (10% open) | 0.23 | 0.63 | 0.18 | 0.45 |
| Single pane clear glass | 0.83 | 0.07 | 0.89 | 0.08 |
| Double pane 4 + 20 + 4 | 0.60 | 0.11 | 0.78 | 0.14 |
| Opaque white coloured aluminium | 0.00 | 0.70 | 0.00 | 0.70 |

### 2.3. Daylight simulation

The CAD model of the NICU was generated with Rhinoceros 4[35] (Figure 5). Daylight simulations were developed using the Design Iterate Validate Adapt (DIVA) tool.[36] DIVA is a highly optimised daylighting and energy modelling plugin for Rhinoceros 4, developed at the Graduate School of Design at Harvard University. This software employs optimisation methods for the calculation and distribution of luminance under different annual weather conditions – the site's annual climate information – under the Perez sky model.[37] DIVA integrates Radiance and DAYSIM for daylight

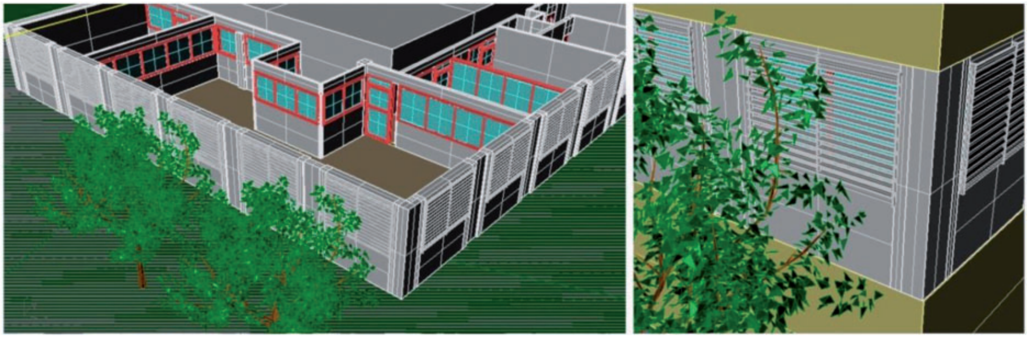

**Figure 5** Virtual image of the modelled area under analysis of the NICU (*.3dm)

simulations. Radiance is a highly accurate ray-tracing software, considered to be one of the most powerful and popular forms of lighting simulation software, it has been extensively validated in the last 20 years.[38–41]

The photometric characterisation of the interior materials of the rooms was entered according to typical reflectance values: wall 60%, ceiling 80%, floor 30%. In addition, materials that make up the solar control systems and glass surfaces were characterised as follows: (i) clear glass (4 mm), the optical characteristics (0.89 visible transmittance, 0.08 reflectance) were imported from a (*.rad) file generated by the OPTICS software. In this computer program, a specific description of the materials can be found according to the parameters required by the Radiance environment. (ii) Integrated vertical louvered microblinds (white matte), were characterised as plastic, although the interior is aluminium and the surface finish is polyester enamel. Because this research focuses on the analysis of daylight, not heat transfer, this change does not affect system performance. Values for its characterisation in the simulation environment were: diffuse reflectance 0.7; specular reflectance 0; specular transmittance (not applicable); transmissivity (not applicable) and roughness 0. (iii) Integrated roller blind. Surface photometric characterisation in the simulation environment was made according to translucent material criteria: diffuse reflectance 0.45; specular reflectance 0; specular transmittance 0.1; diffuse transmittance 0.08.

The dynamic solar control systems were regulated with automated controls. These enable the adjustment of the dynamic shading/glazing system avoiding excessive interior daylighting levels. For the study case, it was assumed that the reference sensor faces the east facade and is mounted on the outer surface of the window. When the illuminance at the control sensor rises beyond the specified threshold (1000 lx), the system automatically adjusts the shading system to the next lower setting.

For weather data, the climate database ARG_MendozaCCT, which corresponds to the city of Mendoza was used. This database was generated from information provided by measuring stations of natural light at the Institute of Environment, Housing and Energy (INAHE), located in the Science and Technology Center Mendoza (32° 52' S and 68°51' W).[42,43] An illuminance range of 200–600 lx was selected following design suggestions from the studies previously mentioned in this paper. To measure illuminance values, three grids of sensors were arranged at the height of the infant incubator ($h = 80$ cm), in a homogenous distribution (the distance between the sensors was 1 m): Intermediate therapy (42 sensor grid); Intensive care (93 sensor grid) and Isolation therapy (24 sensor grid). An occupation file (*.cvs) for calculating dynamic daylight metrics was created focusing on the use of the space every day of the week including weekends from 6:00 am to 8:00 pm (solar time). The selected time period of occupancy was defined according to the availability of sunlight in the region in summer – the maximum number of hours with solar radiation. The simulation parameters used are: (i) simple scene, conditions without solar control systems (ab) 5; (ad) 1000; (as) 20; (aa) 0,1; (ar) 300; (dt) 0; (ds) 0; (ii) complex scene, conditions with horizontal louvres/integrated vertical louvred micro-blinds/integrated roller blinds (ab) 7; (ad) 1500; (as) 100; (aa) 0.1; (ar) 300; (dt) 0; (ds) 0.[44]

## 2.4. Dynamic daylight performance metrics

When dynamic daylight performance metrics are considered as an analytic parameter of daylight behaviour for the illumination of interior spaces, one of the first questions to appear is: how to assess with *general* metrics *particular* situations? Beyond the important advances produced by dynamic metrics over the last decade, it is still necessary to contemplate the new requirements that appear in the practice, the particular specifications of the spaces and the different climactic conditions of each region. This can be appreciated in the case study selected in this investigation, where specific requirements exceed pre-established parameters of analysis. Accordingly, a great amount of flexibility in daylight analysis is necessary as well as in the selection of useful daylight ranges (UDI), generating new ranges that are adjustable (aUDI). In practice, we can see how the upper limit employed by UDI (>2000 lx) for identifying glare risk is not appropriate in specific situations like a NICU, where the established requirements for the upper limits should not exceed 600 lx. This aspect can cause misunderstandings of the data obtained and as a result the design of spaces may not meet the visual needs of users. In this study the following dynamic daylighting metrics are analysed.

*Adjustable useful daylight illuminance (aUDI)*.[42,44,45,46] This proposed metric is based on the useful daylight illuminance (UDI) and its limitation in the adjustment of the lower and higher limits of the illuminance range. The percentage of space with an $aUDI_{200–600\,lx}$ larger than 50% is analysed ($aUDI_{200–600\,lx,50\%}$).

*Spatial daylight autonomy (sDA)*.[45-47] This metric describes the adequacy of ambient daylight levels within interior environments, annually. It is defined through a percentage of an area of analysis that meets minimum daylight illuminance levels for a specified fraction of the hours of the year that the space is occupied. The illuminance level and time fraction is included as subscripts, as in $sDA_{500,50\%}$. The sDA value is expressed as a percentage of area, as proposed by the IES LM-82-12.

The selection of these metrics enables, on the one hand, the detection of sufficient daylight; and, on the other, the identification of the percentage of occurrence of illuminance within a given range. While today, much emphasis is given to luminance values as glare metrics, this study considers it essential to focus on illuminance values surrounding the incubators in order to avoid high levels of solar radiation exposure to infants. Furthermore, as is asserted in other studies,[41] the lack of established methodologies for evaluating the multitude of glare situations in these types of spaces generates an uncertainty about this type of analysis.

## 3. Results

Following are the results obtained in the different rooms analysed (E1, E2 and E3), according to different shading conditions: (a) east and south horizontal louvres – original solar control system; (b) no solar control systems; (c) east roller blind and south fixed integrated vertical louvred microblinds; and (d) east integrated adjustable vertical louvred microblinds and south integrated vertical fixed louvred microblinds.

### 3.1. Intermediate therapy (E1)

Table 2 shows the results obtained for the Intermediate therapy room (E1). At first, it can be seen that the system currently employed – condition (a) – does not promote the entry of daylight inside the space. This condition blocks most daylight, unlike the rest of the analysed conditions (b), (c) and (d). The $sDA_{200,50\%}$ analysis shows that the best conditioning for this area is given under setting (b) without solar control systems, with a $sDA_{200,50\%} = 52\%$; while conditions (c) and (d) do not exceed 31%. When we focus on $aUDI_{200\text{–}600\,lx,50\%}$, similar results were observed. That is, condition (b) is the one with a greater availability of useful daylight ($aUDI_{200\text{–}600\,lx,50\%} = 24\%$); while conditions (c) and (d) reach 21% and 19% respectively. Results achieved in this sector of the NICU, are due to the orientation of the windows (south) and the morphology of the adjacent area of the building that blocks direct solar radiation that may enter the space in the afternoon during the summer. Therefore this sector has mainly diffuse solar radiation, with a percentage of hours where illuminance values exceed 600 lx ($DA_{600}$) being less than 10%. Nodes with illuminance values over 600 lx are located in the area close to the window.

### 3.2. Intensive care (E2)

Table 3 shows the simulation results obtained in the intensive care therapy (E2). It can be observed in the first instance, that condition (a) – the system currently employed – does not allow the entry of daylight. However, the absence of solar control in this area causes the existence of a high percentage of hours with illuminance levels above 600 lx ($DA_{600} = 28\%$). This reveals that although this space requires solar control, inadequate implementation of strategies (horizontal louvres in east and south orientations) obstruct the available daylight in the interior space. According to $sDA_{200,\ 50\%}$, as in intermediate therapy (E1), the best conditions are provided in condition (b): $sDA_{200,50\%} = 85\%$. The remaining conditions are below 80%, the $sDA_{200,\ 50\%}$ for scenario (c) is 77% and for (d) of 73%. However, according to $aUDI_{200\text{–}600\,lx,50\%}$ increased availability of useful daylight is given under condition (d) (35%), followed by (c) with a 30%. The remaining conditions – (a) and (b) – do not exceed 25% of $aUDI_{200\text{–}600\,lx,50\%}$, due to an excess or absence of daylight availability. Of the

**Table 2** Dynamic daylight metrics results for the intermediate therapy (E1)

| | Intermediate therapy *(E1)* | | | |
|---|---|---|---|---|
| | *(a)* | *(b)* | *(c)* | *(d)* |
| $sDA_{200,\ 50\%}$ | 0 | 52.38 | 30.95 | 28.57 |
| $aUDI_{200\text{–}600\,lx,\ 50\%}$ | 0 | 23.8 | 21.43 | 19.05 |
| % of hours with illuminance > 600 lx ($DA_{600}$) | 0.06 | 9.56 | 2.95 | 2.33 |
| % of hours with illuminance > 2000 lx ($DA_{2000}$) | 0 | 0.02 | 0.00 | 0.00 |

**Table 3** Dynamic daylight metrics results for the intensive care therapy (E2)

| | Intensive care therapy *(E2)* | | | |
|---|---|---|---|---|
| | *(a)* | *(b)* | *(c)* | *(d)* |
| $sDA_{200,\ 50\%}$ | 3.22 | 84.94 | 77.42 | 73.12 |
| $aUDI_{200\text{–}600\,lx,\ 50\%}$ | 2.15 | 24.73 | 30.11 | 35.48 |
| % of hours with illuminance > 600 lx ($DA_{600}$) | 0.08 | 28.01 | 19.82 | 14.08 |
| % of hours with illuminance > 2000 lx ($DA_{2000}$) | 0 | 3.27 | 2.85 | 1.32 |

proposed strategies, the intensive care therapy presented as the most useful state (d), with a $aUDI_{200-600\,lx,50\%}$ of 35% and the lowest percentage of illuminance values above 600 lx ($DA_{600} = 14\%$). It is noteworthy that although there are a 14% of illuminance values above 600 lx, only 1% of the values are above 2000 lx ($DA_{2000}$). Like the results achieved in (E1), the location of illuminance values above 600 lx is at the peripheral zone of (E2).

### 3.3. Isolation therapy (E3)

Before analysing this room, the particularities of the space are worth mentioning. The isolation therapy room is a smaller space (14.73 $m^2$) with unilateral windows facing east. These features do not allow the illuminance values of this space to meet the range established as useful under any of the conditions tested ($aUDI_{200-600\,lx,50\%} = 0\%$). In addition, it shows the highest percentage of values above 600 lx (27%) and above 2000 lx (5%) (Table 4).

It is worth mentioning that, despite the high availability of solar radiation ($sDA_{200,50\%}$) found in conditions b, c and d values of $aUDI_{200-600\,lx,50\%}$ are equal to 0%, this is because none of the analysed nodes show illuminance values between 200 and 600 lx more than 50% of the time the study is performed (every day of the week from 6:00 am, including weekends, to 8:00 pm). The results highlight the low efficiency in the use of daylight achieved by the solar control systems currently employed – condition (a). Furthermore, the results show, in some areas of the NICU analysed, that this condition – horizontal louvres with east and south orientation – is the least favorable within the daylighting strategies analysed in this study.

**Table 4** Dynamic daylight metrics results for the isolation therapy (E3)

| | Isolation therapy *(E3)* | | | |
|---|---|---|---|---|
| | *(a)* | *(b)* | *(c)* | *(d)* |
| $sDA_{200,\ 50\%}$ | 0 | 95.83 | 79.17 | 54.17 |
| $aUDI_{200-600\,lx,\ 50\%}$ | 0 | 0 | 0 | 0 |
| % of hours with illuminance > 600 lx ($DA_{600}$) | 0.13 | 26.62 | 27.08 | 17.04 |
| % of hours with illuminance > 2000 lx ($DA_{2000}$) | 0.09 | 5.26 | 5.51 | 2.48 |

In summary, the results show that it is more appropriate not to place solar control elements in the windows of the intermediate therapy room. For the intensive care therapy room, the most appropriate strategy is (d) east integrated vertically adjustable louvred microblinds and south vertically integrated fixed louvred microblinds. For the isolation therapy room, the most appropriate solution is the use of an artificial lighting system that suits the needs of the users: cycled lighting (day/night) and controlled lighting levels. This highlights the importance of proper selection and the application of solar control systems.

## 4. Discussion

Concerning the solar control systems analysed, the results demonstrate that adjustable solar control elements should be implemented for the east orientation due to the fluctuation of incident solar radiation on this façade (seasonal – daily). However, the south orientation supports the use of fixed shading systems. This highlights the importance of considering the type of luminous climate and the orientation of windows in the building envelope, as some of the determinants of the luminous performance of solar control systems. The need to individualise the treatment of the facades is emphasised.

Based on the results of this study, a change of the layout of the spaces in the NICU is proposed, considering re-locating the halls to the periphery of the area, which is currently a storage area, and enlarging the internment areas toward the interior of the building, the interior circulation. This avoids the risk of overexposing neonates to direct incident solar radiation (Figure 12). It is relevant to have in mind that in the original architectural project the area currently used as storage space was a corridor. As for the spatial layout of the therapy rooms of the NICU, it can be seen that the proposed modifications of space layout can improve its daylighting behaviour, by utilising more appropriate amounts of daylight in circulation and internment areas with controlled illuminance levels, below 600 lx. This reorganisation will favour the day–night cycle with natural light, which is a priority in this kind of space, and avoid the exposure of infants to high illuminance levels at all times. It should be noted that the interior walls that separate the NICU internment area from circulation must be transparent for the daylight strategies identified in this study to work properly.

The daylight performance results following the proposed remodeling are given in Table 5. With respect to the intermediate therapy room, although the value of $aUDI_{200–600\,lx,50\%}$ decreases from 24% – absence of sunlight control (b) – to 13% in the proposed design, illuminance values over 600 lx decline from 10% to 1%. In addition, there is a 13% improvement in the performance of daylight compared to the original condition. In the intensive care therapy room an $aUDI_{200–600\,lx,50\%}$ of 15% is obtained, although this value is lower than that detected in the condition (d) ($aUDI_{200–600\,lx,50\%} = 35\%$), illuminance over 600 lx decreases to 13%. The recommended change shows an improvement in the use of daylight with respect to the current condition of 13%. Daylight performance analysis of the suggested design shows an improvement in fundamental issues regarding lighting in this type of space: use of daylight as a light source, focusing on avoiding the incidence of direct sunlight in the internment area.

This study puts forward that in NICUs, achieving the required lighting conditions is not simple only using daylight. The characteristics for the care and wellbeing of recently born babies involves strict lighting conditions, owing to the fragility of the users, and therefore the establishment of a relatively limited range of illuminance, between 200 and 600 lx ($aUDI_{200–600\,lx}$). This type of space offers considerable challenges for the design and implementation of daylighting strategies. This study proves that none of the rooms analysed reached a luminous behaviour ($aUDI_{200–600\,lx,50\%} > 50\%$) that would turn it into an adequately daylit space under the daylighting strategies being analysed. These data demonstrate that for this type of space hybrid systems are necessary – artificial/natural illumination – for adequate lighting conditions during the day.

Spaces with critical demands for lighting conditions, like NICUs, present important challenges, not only for the strict requirements for the lighting conditions, but also because the architectural design and the layout need to be taken into account, e.g. orientation, size of apertures, the depth of the space. Here, we can mention the two different situations that project professionals face: (i) spaces that permit the optimisation of the use of daylight as the principle source of illumination; (ii) spaces that must resort to the use of electric lighting. The space studied has both conditions, as with many other case studies, where a design needs the coexistence of controlled daylight (in accord with the specific requirements) and complementary electric illumination systems.

## 5. Conclusions

This study analyses daylight performance in an indoor space with special requirements, a NICU, according to the proposed remodelling design of a real space in the Dr Humberto Notti Children's Hospital (Mendoza, Argentina). Different solar control strategies that favour the entry of controlled daylight into the space (conditions c and d) were evaluated to optimise the use of daylight in these types of spaces. The daylight behaviour of the different rooms in the NICU under these settings – (c) and (d) – was compared with the one obtained with the original façade – east and south horizontal louvres (a) – and the absence of solar control devices (b). In this context, and according to the particular characteristics of the space, some specific criteria for dynamic daylight analysis were accomplished: (i) adjustment of upper and lower ranges of useful illuminance in order to optimise dynamic daylight metrics ($aUDI_{200–600\,lx}$); (ii) location of the illuminance measurement grid at the height of neonates in the incubator ($h = 85$ cm); (iii) differential analyses by sector of the NICU (intermediate therapy (E1), intensive care (E2) and isolation therapy (E3)). Based on these criteria, the study focuses on the care of the most sensitive user of this space, neonates.

From the point of view of daylight performance, this study highlights three issues: solar control system selection, space layout and dynamic simulation applied to daylight performance analysis. With respect to the first issue, none of the therapy rooms of the studied NICU managed to be a daylit space under the proposed strategies because of the narrow illuminance range suitable for these types of spaces (200–600 lx). Nevertheless, results show an increase in the availability of controlled daylight within the space through the proper implementation of solar control systems. The appropriate choice of solar control systems not only depends on their type or the orientation of the windows – two issues quite known – but also on their location within the façade in relation to the blockage of solar radiation caused by the building morphology. This suggests that the same shading strategy should not be implemented in a general way on the whole façade, especially in spaces with special lighting requirements. It is also necessary to consider the type of solar control device use (manual or automatic) and its maintenance over time. Otherwise, the benefits provided by solar control devices can be affected by incorrect use or lack of maintenance. Regarding the use of shading devices, the use of automated systems seems to be the correct choice for these types of spaces where doctors and nurses focus on patient care and not on lighting requirements. Yet, there are many studies that demonstrate that automated shading systems do not always generate the expected beneficial results concerning their impact on daylighting quality and the reduction of electricity consumption.[48,49] Therefore, automation should be more deeply studied in the future for the type of space, a NICU, analysed in this study.

Concerning the layout of the NICU, two important factors should be considered. First, the recommendations for NICUs state that incubators should be located away from the windows, at a minimum distance of 60 cm. This recommendation is very consistent with the results obtained in this study, which show that higher illuminance values are detected in the peripheral area of the space, the proposed enlargement area. However, this approach is not consistent with the proposed remodelling submitted by the hospital, which aims to enlarge the NICU sector towards the window area.

Furthermore, it is important to consider the original layout for the spaces and that which the users will eventually give them. The area, which at present is the storage sector, at first, was conceived as a hall area, which seems to be an appropriate use for this area according to the lighting requirements of the NICU. The use of this sector as a circulation corridor will allow doctors and assistants exposure to higher but controlled illuminance values (<2000 lx). This will also protect infants from excessive illuminance (>600 lx) while still taking advantage of the available daylight and its benefits.

Finally, it is important to emphasise the value of a dynamic daylight performance analysis in the design or redesign of daylighting strategies for an indoor space, particularly when it has special requirements. The adaptability to different ranges of illuminance is important and dynamic daylight performance metrics must reflect this versatility in order to provide an adequate analysis of indoor spaces with special requirements, such as NICUs.

The results obtained in this study show that the remodelling proposed by the hospital should be adjusted. In this paper, a new spatial layout (Figure 12) is suggested. This new design recommends enlarging the interment area towards the interior hall of the NICU and using the storage sector as a corridor.

In the future, studies like this one should be correlated with health outcome evaluations in order to encourage the use of daylight in these types of spaces.

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## References

1 Boyce PR. Lighting research for interiors: the beginning of the end or the end of the beginning. *Lighting Research and Technology* 2004; 36: 283–293.
2 Beute F, Kort YA. Salutogenic effects of the environment: Review of health protective effects of nature and daylight. *Applied Psychology: Health and Well Being* 2014; 6: 67–95.
3 Boyce P, Hunter C, Howlett O. *The Benefits of Daylight through Windows*. Troy, NY: Lighting Research Center, 2003.
4 Galasiu AD, Veitch JA. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings* 2006; 7: 728–742.
5 Tuaycharoen N, Tregenza PR. View and discomfort glare from windows. *Lighting Research and Technology* 2007; 39: 185–200.
6 Joseph A. *The Impact of Light on Outcomes in Healthcare Settings*. Issue Paper 2. Concord, CA: The Center for Health Design, 2006.
7 Alzoubi H, Al-Rqaibat S, Bataineh RF. Pre-versus post-occupancy evaluation of daylight quality in hospitals. *Building and Environment* 2010; 45: 2652–2665.
8 Iyendo TO, Alibaba HZ. Enhancing the hospital healing environment through art and day-lighting for user's therapeutic process. *International Journal of Arts and Commerce* 2014; 3: 101–119.
9 White R. Design environment for developmental care. *Clinics in Perinatology* 2011; 38: 745–749.
10 Littlefair P. The luminous efficacy of daylight: a review. *Lighting Research and Technology* 1985; 17: 162–182.

11 Figueiro MG, Appleman K, Bullough JD, Rea MS. A discussion of recommended standards for lighting in the newborn intensive care unit. *Journal of Perinatology* 2006; 26: 19–26.
12 Logvinov SV, Potapov AV, Varakuta EY, Drobatulina DA. Dynamics of structural changes in the retina during long-term exposure to bright light. *Bulletin of Experimental Biology and Medicine* 2003; 136: 411–414.
13 Rea M. Lighting for caregivers in the neonatal intensive care unit. *Clinics in Perinatology* 2004; 31: 229–242.
14 White RD, Smith JA, Shepley MM. Recommended standards for newborn ICU design. *Journal of Perinatology* 2013; 33: S2–S16.
15 Szczepański M, Kamianowska M. The illumination intensity in the neonatal intensive care unit. *Archives of Perinatal Medicine* 2008; 14: 47–50.
16 Blackburn S. Environmental impact of the NICU on developmental outcomes. *Journal of Pediatric Nursing* 1998; 13(5): 279–289.
17 Fielder AR, Moseley MJ. Environmental light and the preterm infant. *Seminars in Perinatology* 2000; 24(4): 291–298.
18 McGraw K, Hoffmann R, Harker C, Herman JH. The development of circadian rhythms in a human infant. *Sleep* 1999; 22: 303–310.
19 Mirmiran M, Ariagno R L. Influence of light in the NICU on the development of circadian rhythms in preterm infants. *Seminars in Perinatology* 2000; 24: 247–257.
20 Rivkees SA. Developing circadian rhythmicity in infants. *Pediatrics* 2003; 112: 373–381.
21 White RD, Smith JA, Shepley MM. Recommended standards for newborn ICU design. *Journal of Perinatology* 2013; 33: 2–16.
22 Pickler RH, McGrath JM, Reyna BA, Tubbs-Cooley HL, Best AM, Lewis M, Cone S, Wetzel PA. Effects of the neonatal intensive care unit environment on preterm infant oral feeding. *Research and Reports in Neonatology* 2013; 3: 15–20.
23 Glass P, Avery G B. Light, sleep, and development. *Pediatrics* 1987; 79: 1053–1054.
24 Shogun MG, Schumann LL. The effect of environmental lighting on the oxygen saturation of pre-term infants in the NICU. *Neonatal Network* 1993; 12(5): 7–13.
25 Bullough J, Rea MS. Lighting for neonatal intensive care units: Some critical information for design. *Lighting Research and Technology* 1996; 28: 189–198.
26 Peng N, Bachman H, Jenkins R, Chen CH, Chang YC, Chang YS, Wang TM. Relationships between environmental stressors and stress biobehavioral responses of preterm infants in NICU. *The Journal of Perinatal and Neonatal Nursing* 2009; 23: 363–371.
27 Del Río MG, Luna MS, Martínez ED, Macián II, Martínez AL, López JP. Revisión de los estándares y recomendaciones para el diseño de una unidad de neonatología. *Anales de Pediatría* 2007; 67: 594–602.
28 DiLaura DL, Houser KW, Mistrick RG, Steffy GR. *The Lighting Handbook*. New York: Illuminating Engineering Society of North America, 2011.
29 White RD. Lighting in the neonatal intensive care unit: Practical applications of scientific principles. *Clinics in Perinatology* 2004; 31: 323–330.
30 Commission International de l'Eclairage. *Spatial Distribution of Daylight—CIE Standard General Sky*. CIE Publication S 011/E. Vienna: CIE, 2003.
31 Córica L. *Comportamiento de la luz natural en entornos urbanos representativos del modelo oasis en regiones áridas*. Caso de Estudio: Ciudad de Mendoza. PhD Thesis, Universidad Nacional de Tucumán, San Miguel de Tucumán, Argentina, 2009.
32 Pattini A, del Rosso R, Lasagno C, Ferrón L, Rodríguez R, Braconi L, Chambouleyrón M, Cannavo D and Villalba A. Diseño de artefactos de iluminación natural. La utilización de la energía solar para iluminar espacios interiores. Informe final de proyecto. Proyectos bienales 2007–2009. Universidad Nacional de Cuyo, Secretaría de Ciencia, Técnica y Posgrado, 2009.
33 Villalba A. *Control de luz solar directa en la envolvente edilicia en climas soleados. Su impacto en el consumo diurno de energía eléctrica para iluminación en edificios no residenciales de ciudad oasis*. PhD Thesis, Universidad Nacional de

Tucumán, San Miguel de Tucumán, Argentina, 2014.
34 Köster H. *Dynamic Daylighting Architecture: Basics, Systems, Projects*. Basel: Birkhäuser, 2004.
35 McNeel R and Associates. *Rhinoceros Version 4.0*, Service Release 8, 2010.
36 Jakubiec A, Reinhart CF. *DIVA 2.0: Integrating daylight and thermal simulations using RHINOCEROS 3D, DAYSIM and ENERGYPLUS: Building Simulation, 12th Conference of International Building Performance Simulation Association*, Sydney, Australia, Nov 14–16: 2011, pp. 2202–2209.
37 Perez R, Seals R, Michalsky J. All-weather model for sky luminance distribution preliminary configuration and validation. *Solar Energy* 1993; 50: 235–245.
38 Mardaljevic J. Sky model blends for predicting internal illuminance: A comparison founded on the BRE-IDMP dataset. *Journal of Building Performance Simulation* 2008; 1: 163–173.
39 Laouadi A, Reinhart CF, Bourgeois D. Efficient calculation of daylight coefficients for rooms with dissimilar complex fenestration systems. *Journal of Building Performance Simulation* 2008; 1: 3–15.
40 Ochoa CE, Aries MBC, Hensen JLM. State of the art in lighting simulation for building science: A literature review. *Journal of Building Performance Simulation* 2012; 5: 209–233.
41 Berardi U, Wang T. Daylighting in an atrium-type high performance house. *Building and Environment* 2014; 76: 92–104.
42 Monteoliva JM, Pattini A. Iluminación natural en aulas: análisis predictivo dinámico del rendimiento lumínico-energético en climas soleados. *Ambiente Construido* 2013; 13: 235–248.
43 Monteoliva JM, Villalba A, Pattini AE. Uso de dispositivo de control solar en aulas: impacto en la simulación dinámica de la iluminación natural. *Ambiente Construido* 2014; 14: 43–58.
44 Reinhart CF. *Tutorial on the Use of DAYSIM Simulations for Sustainable Design*. Ottawa: Institute for Research in Construction, National Research Council Canada, 2006.
45 Reinhart CF, Mardaljevic J, Roger Z. Dynamic daylight performance metrics for sustainable building design. *Leukos* 2006; 3: 7–31.
46 Monteoliva JM, Villalba A, Pattini A E. Variability in dynamic daylight simulation in clear sky condition according to selected weather file: Satellite data and land-based station data. *Lighting Research and Technology* 2015. DOI: 1477153515622242.
47 Illuminating Engineering Society of North America. Lighting Measurements 83–12*, Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*. New York: IESNA, 2012.
48 Meek C, Brennan M. *Automated and manual solar shading and glare control: A design framework for meeting occupant comfort and realized energy performance*: *Proceedings 40th, National Solar Conference; SOLAR 2011*, Raleigh, NC, USA, 2011, pp. 794–801. Boulder, CO: American Solar Energy Society.
49 Konstantoglou M, Tsangrassoulis A. Dynamic operation of daylighting and shading systems: A literature review. *Renewable and Sustainable Energy Reviews* 2016; 60: 268–283.