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An artificial skylight compared with daylighting and LED: Subjective and objective performance measures☆

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A R T I C L E I N F O

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A B S T R A C T

In the last decade, innovative systems such as Artificial Skylights (AS) have been developed to reproduce the blue-sky effect and white sunlight, giving the impression that interiors are illuminated by natural light, even when this is not available because of construction- or climate-related reasons. Given the hybrid characteristics between natural and artificial lighting, the aim of this research is to compare an AS with daylight and with artificial lighting to identify similarities and differences in performances, pointing out the most suitable indicators to describe it and to provide useful feedback for the design and integration of these systems.

A monitoring campaign was conducted involving nine participants who spent entire work sessions in a full-scale living lab equipped as an office, with different lighting systems (AS, daylight and LED) and different furniture configurations, completing a total of more than 360 questionnaires and analysing the visual and non-visual effects.

AS and daylight share many similarities, which may be positive, such as pleasantness, circadian stimuli, colour perception, as well as, in some scenarios, also negative, such as glare perception. As a conventional artificial lighting system, even with AS, Unified Glare Rating correlates more strongly with users' perception of glare than Daylight Glare Probability, although both underestimate it. Overall, the workstation receiving diffuse light was found to be the most comfortable and the higher installed lighting power density of AS with respect to LED is well balanced by a better lighting quality.

Further research about AS is needed to define design guidelines and to support a holistic approach, fundamental to high-performing buildings.

1. Introduction

Many studies have investigated and demonstrated the numerous benefits of daylight (DL) in buildings such as the positive effects on visual comfort, psychological benefits, health, workplace productivity and energy savings [1–3]. As it is well known, people spend a lot of time indoors [4]. Since it is not always possible to provide daylight due to constructional, safety or hygiene reason [5], negative effects such as a reduction in alertness, drowsiness, psychological stress and lower job satisfaction can occur [6]. In addition, if proper lighting conditions are not regularly achieved for circadian stimulus effectiveness, zones can be labelled as "biologically dark" with the risk of disrupting the circadian system [7]. Natural environments have positive effects on people [8] but, in an attempt to connect with nature and reproduce the positive effect of natural daylight when it is not available, some solutions have been implemented that recreate the view outside, with poor results in terms of reproducing daylight [9]. One example is the Virtual Natural Lighting Solutions (VNLS), but the first and second generation prototypes tested ([10–14]) have not provided clear results [5]. Another solution is the artificial skylight, able to simulate a ceiling opening and daylighting, but there is little previous research on it [5], with different settings and goals. To our knowledge, two systems are studied in the literature. The former is a prototype made of LED (Light Emitting Diode) and covered by a blue optical structure. For clarity, it will be hereafter referred to as Artificial Skylight Prototype (ASp). The latter system consists of an artificial light source, spectrally similar to the visible part of sunlight (CCT – Correlated Colour Temperature 5770 K), and a nanostructured material that mimics the Rayleigh scattering process that occurs in the atmosphere. It is called Artificial Skylight (AS) and it is the system investigated in this research. Stokkermans [15] investigated an Asp capable of reproducing the blue sky effect and white sunlight,

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Nomenclature

AS	Artificial Skylight
ASp	Artificial Skylight prototype
CCT	Correlated Colour Temperature
CR	Contrast Ratio
CS	Circadian Stimulus
DGP	Daylight Glare Probability
DL	Daylighting
E	Illuminance level (lx)
E_{min}	minimum illuminance level (lx)
E_m	mean illuminance level (lx)
$E_{m,t}$	Mean illuminance of the task area (lx)
E_p	Punctual illuminance in the middle of the desk (lx)
Ev	vertical illuminance at the eye of the observer [lx]
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
FoV	Field of View
HDR	High Dynamic Range
LCD	Liquid Crystal Display
LED	Light Emitting Diode
L_b	background luminance [cd/m^2]
L_s	glare source luminance in the direction of the observer's eye [cd/m^2]
L_{ref}	reference luminance value
L_{si}	glare source luminance [cd/m^2]
MCCA	Main Colour Confusion Area
MPOD	Macular Pigment Optical Density
O_W	Desk orientation toward wall
O_F	Desk orientation toward fenestrations
O_D	Desk orientation toward door
p:	Guth position index
P	position index
P_D	workstation near the door
P_M	workstation in the middle of the room
P_W	workstation near the wall
Q1	General user data questionnaire
Q2	User initial conditions questionnaire
Q3	Hourly questionnaire
Q4	Ambient quality questionnaire
TES	Total Error Score
UGR	Unified Glare Rating
U_0	Uniformity factor
$U_{0,t}$	Uniformity of the task area
$U_{0,s}$	Uniformity in the immediate surrounding area
$U_{0,b}$	Uniformity of the background area
VNLS	Virtual Natural Lighting Solutions
ω	glare source surface –axis of sight solid angle [sr]
ω_{si}	solid angle subtended by the glare source I [sr]

and described two tests that measured both visual and non-visual parameters. The former test investigated whether people could appreciate an ASp in an office space by measuring ratings of lighting (attractiveness, suitability for work, glare), room conditions (attractiveness, atmosphere, visual clarity, uniformity, spaciousness), affect as well as perceived naturalness (daylight experience, naturalness of colours). Twenty-nine participants took part for 30 min in a test aimed at investigating the difference between a room with ASp and a room with standard office fluorescent lighting. The results of this first test showed that individuals preferred the standard room for an office activity due to greater uniformity of light, visual clarity and appropriate lighting. On further investigation through a funnel debriefing, it was found that individuals who had a better daylighting experience had previously recognized the ASp in a better way. Pooling the results of the latter test, which focused on comparing the sun pattern preferences of thirty people in an office and home environment, revealed that more realism was needed, especially in offices. Seuntiens [16] conducted an experiment to analyse the preference of 20 testers regarding daylight impression in a room, comparing images of different artificial skylight configurations for 70 side by side comparisons in total. Subjects preferred the larger rectangular skylights over the square skylights in terms of daylight impression, and a sky with visible sun was perceived more realistically than a partly cloudy one with no visible sun. Wang [17] studied the effect on alertness, mood, self-control and cognitive performance of twenty-five subjects, in an office setting during daytime with ASp. He compared four different lighting settings that varied the illuminance (E) and CCT at eye level, as well as the proportion of light in the blue spectral range. During the day, participants felt less tense and happier, had higher levels of self-control, and showed a faster response in various task activities under the effect of 400 lx and 9300 K light. The blue-enriched light has no relevant effects on alertness during the day (see the effects during the night found in other researches). Meerbeek [9] studied an ASp using a commercial led with an optical structure adapted to produce a blue-sky effect in combination with white sunlight. The ASp was compared with a Standard Panel without an optical structure and the same model with a Blue Filter. Thirty participants tested the 3 systems by performing various tasks and typing questionnaires. The test duration was approximately 60 min for each skylight system. 57% of participants felt that the ASp provided the strongest skylight experience, even though it was not compared to a real skylight. Canazei conducted two different experiments in 2016 [18] and 2017 [5], in which an AS was able to simulate a ceiling opening with a cloudless sky and sun and it was compared with a fluorescent lamp. In Ref. [18] one hundred people filled out 3 different questionnaires about room lighting, room atmosphere and connection to nature when exposed to an artificial skylight for 60 min. He found that room lighting of the AS is more pleasant, attractive and natural and glare perception is the same for fluorescent lamp and skylight even when the tester is sitting in the "sun" position (directly hit by artificial sun). Only the inhomogeneity is perceived as a negative aspect in an office. In the second study [5] attention was focused on non-visual aspects, with one hundred testers divided into two test rooms for 72 min. The main finding was that users felt more connected to nature with AS and perceived the office as more lively, less tense and more distant than with fluorescent lighting. Yasukouchi [6] tested the non-visual effects (brain arousal level, autonomic nervous activity, work performance, subjective response during day-time exposure and night-time release of melatonin) of an AS compared to a conventional fluorescent light in an office, involving ten healthy male adults. Table 1 summarizes the most important aspects analysed by reference literature on the subject of AS considered above.

Lit environments are very complex when it comes to analysing the correlation between photometric measurements and visual performance and comfort, especially when more than one visual task is present for the same position and daylighting is available [19]: visual quality can be determined by individual aspects, but with many difficulties due to the low correlation with subjective responses and limited validation [20]. Carlucci affirmed that visual comfort has been commonly assessed by measuring the amount and uniformity of light, the quality of light in colour rendering, and the prediction of the risk of glare for occupants, but all these indicators are measured separately and there is no possibility to summarise a global visual comfort with a single index [21].

During the monitoring campaign several parameters and aspects are measured, and this paper aims at addressing the following main objectives:

Table 1
Artificial skylight references. Research goal: E, illuminance; G, glare; CS, circadian stimuli; NV, non-visual effects.

References	Test room	Systems tested	No. Of Testers	Test duration	Research goal			
					E	G	CS	NV
Stokkermans [15] (2011) I test	2 Offices	ASp VS fluorescent light	29	30 min divided in 3 sessions	x	x		x
Stokkermans [15] (2011) II test	Home and office	Comparison of different sun patterns produced by an ASp	15 at home and 15 in the office	5 min				x
Seuntiens [16] (2012)	Office	Simulation with sketchup of different skylight dimension and different sky	20					x
Wang [17] (2012)	Office 3.75 × 6.10 × 3 m	ASp	25	4 different 1-h lighting treatments	x			x
Meerbeek [9] (2014)	Three Offices 3 × 3 × 2,40 m	ASp compared with a Standard Panel (SP) and blue filtered panel (BF)	30	About 60 min in each room	x			x
Canazei [18] (2016)	2 offices (3 × 4x2.4 m)	AS VS 3 louvre luminaries with fluorescent lamp	100 tested both systems	60 min in each room	x	x		x
Canazei [5] (2017)	2 offices (3 × 4x2.4 m)	AS VS 3 louvre luminaries with fluorescent lamp	50 per office = 100 tot	72 min				x
Yasukouchi [6] (2019)	Office (1.96 × 2.7 × 1.94 m)	AS VS fluorescent lights	10	36 min repeated twice during the morning and twice during the afternoon			x	x
This research	Office 6.4 × 3.7 × 2.95 m (l x w x h)	AS	9	3–7 h a day for 3 lighting systems in 3 configurations each	x	x	x	x

- characterize the performance of AS when monitored data and user preferences are compared with daylight and LED lighting to provide useful feedback for design and integration of these systems, testing the lighting pattern in different working positions. The most important factors of visual comfort and users feeling are evaluated: the amount and uniformity of light, glare, colour rendering, circadian rhythm and the user feedback;
- find out whether standard indicators can correctly represent an artificial skylight.

The monitoring campaign described in this paper involved nine participants who spent entire work sessions in a full-scale living lab equipped as an office, with different lighting systems (DL, AS, and LED lighting) and different furniture configurations, completing a total of more than 360 questionnaires and analysing visual and non-visual effects.

2. Method

2.1. Experimental campaign

The test experience was performed in a full-scale living lab room of about 6.4 × 3.7 × 2.95 m (l x w x h) equipped as an office (Fig. 1) located near Milan (45°23′N, 9°15′E), with white plaster and matte finish surfaces and furniture. From 20th of March to April 18, 2019, nine users spent whole working days testing 3 different lighting systems in 3 different furnishes configurations. All participants come from South Europe and have been selected in order to have a heterogeneous group considering age (average = 42 y ± 8.8), gender (5 males and 4 females), colour of eyes (5 light and 4 dark) and absence of eye pathologies.

Choosing a small number of participants is a compromise to satisfy two requirements. The former is an analysis based on within-subjects study design. The same participant tested all the conditions. The latter is the period chosen to concentrate the experiments in the period near the spring equinox, in order to conduct the entire campaign at the same times maintaining a solar path as constant as possible and similar natural light and solar radiation conditions.

All participants previously provided their informed consent for inclusion and the experiment was approved by the Ethics Review Committee of CNR (National Research Council of Italy) with registration number: 9397/2020.

2.2. Tested systems

Three lighting systems (Fig. 2) are installed in the test room and tested during different days: Daylighting (DL), Artificial Skylight (AS) and Artificial Lighting (LED). When the AS and LED are tested, the windows are darkened by 100% opaque rolling curtains (measured maximum illuminance below 2 lx). Each tested system is designed to represent a peculiar indoor lighting condition emphasizing specific

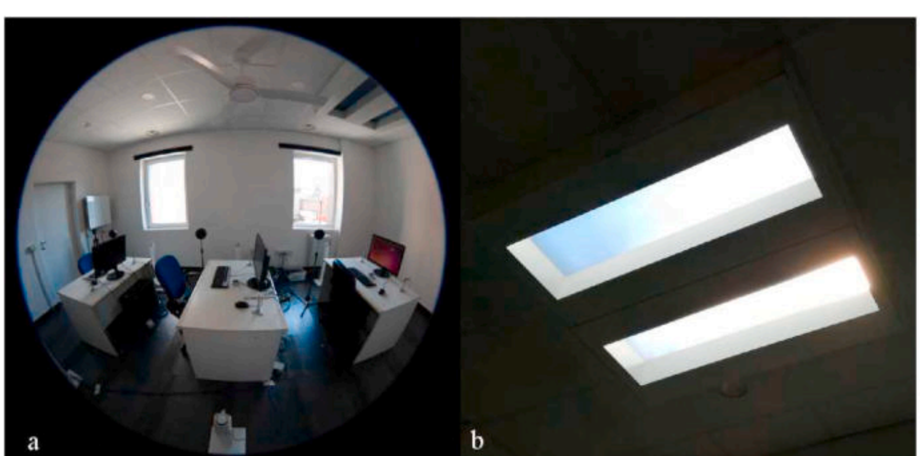


Fig. 1. Experimental campaing: a)Test room and equipment during DL session; b) detail of the AS.

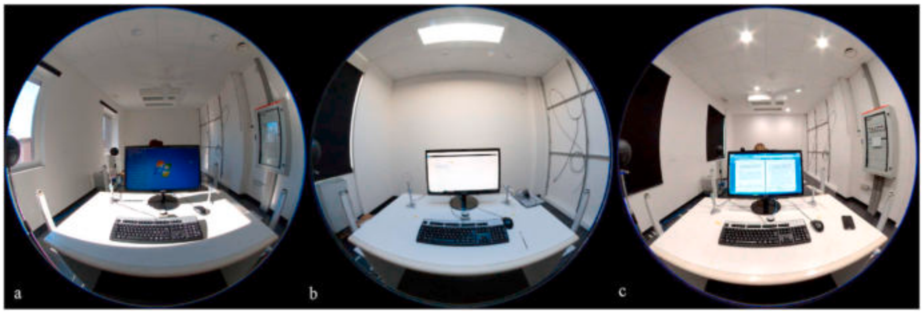


Fig. 2. The three lighting systems tested: a) DL; b) AS; c) LED.

lighting aspects.

1. Daylighting (DL): the DL lighting system consists of two 1.1 × 1.6 m low-emitting windows (τv = 54.3, g = 30.5, Ug = 0.6 W/m^{2}K) on the South-East facade. The total window to floor area ratio is 12.5% and represents the minimum value allowed by Italian technical regulations. To use the daylight hours to best advantage, experiments and participants involving were planned, for the same day, in the morning (4 h) and in the afternoon (3 h). This scenario represents the common natural lighting with a high variability over the time. It represents a situation with a potential high glare risk and an optimal colour rendering and visual appearance of objects.
2. Artificial Skylight (AS): static artificial light coming from AS (2 Coelux® LS modules 0,6 × 1,2 m with a 45° narrow angle). Participants tested this lighting system over a 3-h session. The AS tested is composed by artificial light source modules, spectrally very similar to the visible part of sunlight (CCT 5770 K), and of a nanostructured material which recreates the Rayleigh scattering process (that reproduce diffuse light) that occurs in the atmosphere. Each module provides a luminous flux of 3300 lm with a maximum electric energy consumption of 90 W. The modules are dimmable with a DALI-based protocol and a smartphone app but according to the scope of the research this function was not used. The system produces a uniform 45° tilted beam imitating the outdoor condition typical of a cloudless day. An intense yellowish light component (CCT 5000 K) mimics the direct sunlight and creates the shadows of illuminated object. At the same time, the diffuse skylight component creates blue-toned shadows. During the test, modules are placed above one working desk (see 2.3) and sized to ensure on it at least 300 lx (minimum value for office tasks according EN 12464-1) with diffuse light. Direct light beams are oriented towards the centre of the room with orientation SW-NO. This scenario represents a hybrid lighting condition between natural and artificial lighting with static light intensity over the time but high variability and discomfort risk related to illuminance, glare and colour rendering within the room.
3. Artificial lighting (LED): for the artificial lighting system 8 LED headlamps (14W power, φ = 1300 lm, CCT 4000K and CRI>90) distributed over a grid with dimension 1.2 × 1.2 m have been selected. The LED lighting system was designed with Dialux® software to ensure 300 lx at the desk level (+0.80 m above floor) with homogeneous distribution over the room, operating at the maximum power. Participants tested this lighting system over a 3-h session. This scenario represents the common artificial lighting condition with static lighting intensity and distribution over the time and within the room, potentially minimizing the discomfort risk related to illuminance and glare.

2.3. *Configurations and participants*

The three working desks are positioned inside the room in 3 different configurations (Fig. 3):

- O_W: workstations toward the South-West wall (shoulders toward the door);
- O_F: workstations toward the South-West facade (gaze on the fenestrations);
- O_D: workstations toward the South-West facade (gaze on the door).

During the different test configurations, the nine participants divided in groups of three always occupy the same workstation: P_D (near the north-east façade and entrance door), P_M (in the middle of the room) and P_W (near the South-West wall).

The position of the participants and the three configurations were chosen in order to consider peculiar lighting conditions for DL and AS lighting systems:

- For DL, configuration O_W and O_D ensure vertical lateral lighting while configuration O_F guarantees vertical front lighting with direct sun beam;
- For AS, P_W workstation ensures diffuse zenithal light, P_M direct "Sun" light and P_D diffuse ambient light. Specifically, the rotation in P_M allows to assess the effects on performances and perception in relation to direct light geometry changes.

On the contrary, the regular distribution of LED lighting elements keeps the lighting condition quite constant among workstations and configurations.

Participants carry out activities such as reading on the screen or paper, typing, writing and all the white coloured desks are equipped with the same furniture and hardware model: mouse, keyboards and 24″ black monitors set on all three workstations with the same settings of luminosity, contrast and light temperature.

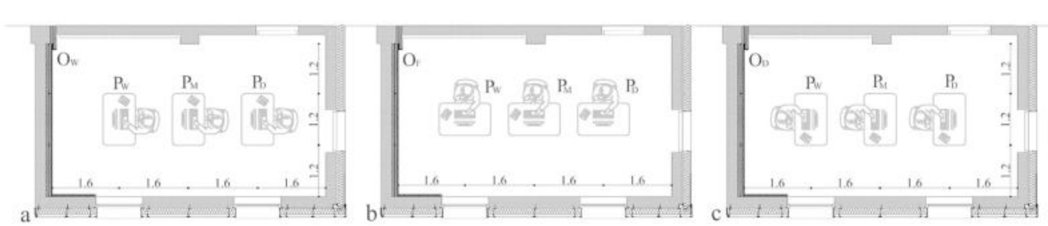


Fig. 3. Workstation configurations: a) O_W – gaze on the wall; b) O_F - gaze on the fenestrations; c) O_D – gaze on the door.

2.4. Monitoring setup

The monitoring setup is designed and applied to monitor the overall environmental data (IEQ, Indoor Environmental Quality) with a focus on the lighting data. Fig. 4 highlights the lighting monitoring setup. A fixed grid with 9 luxmeters (dotted line) is installed: 3 measuring points are located in the middle of each working plane and 6 other luxmeters are fixed on dedicated supports with the same height of the working plane (+0.75 m). These luxmeters have different ranges depending on whether they are directly illuminated by natural or artificial solar radiation (Table 2); measures are taken every 10 s and averaged every minute. Other 12 measures are recorded every hour with a Konica Minolta T-10 [22] portable luxmeter (Fig. 4 with "O"). The portable luxmeter is used also in vertical mode paired with a LMK Mobile Air Videophotometer [23] with 180° fisheye lens (4.5 mm focal length) at eyes height (1.20 m above floor) oriented towards the user's point of view. On days representative of clear, cloud and variable sky, indoor light spectrum measures are collected with a DeltaOhm HD30.1 spectroradiometer. Finally, a meteorological station is installed on the rooftop near the test room with two luxmeters to measure beam and diffuse external illuminance.

2.5. Experimental analysis

The experimental campaign is aimed at assessing the lighting satisfaction and perception of users by combining the DL, AS and LED lighting systems with the O_W, O_F and O_D workstation configurations. The evaluation is carried out based on the following analysis:

Table 2
Technical data – Luxmeters, Spectroradiometer and Videophotometer.

Sensors	Num.	Measuring range	Relative spectral response	Signal Output
Luxmeters low range	6	20 ÷ 2′000lx	<8% of the CIE spectral luminous efficiency V (λ)	4 ÷ 20 mA
Luxmeters high range	3	200 ÷ 20′000lx	<8% of the CIE spectral luminous efficiency V (λ)	4 ÷ 20 mA
Portable luxmeter	1	0.01 ÷ 29′900lx	<6% of the CIE spectral luminous efficiency V (λ)	LCD (Liquid Crystal Display) displayed value
Spectroradiometer	1	380–780 nm	5% for spectrum	
Videophotometer	1	1:30.000 HDR image (High Dynamic Range)		14 Bit RAW image - data as uncompressed Bayer structure
External luxmeters	2	0-150′000 lx	<4% of the CIE spectral luminous efficiency V (λ)	4 ÷ 20 mA

[1]CIE: Commission Internationale de l'Eclairage – International Commission on Illumination.

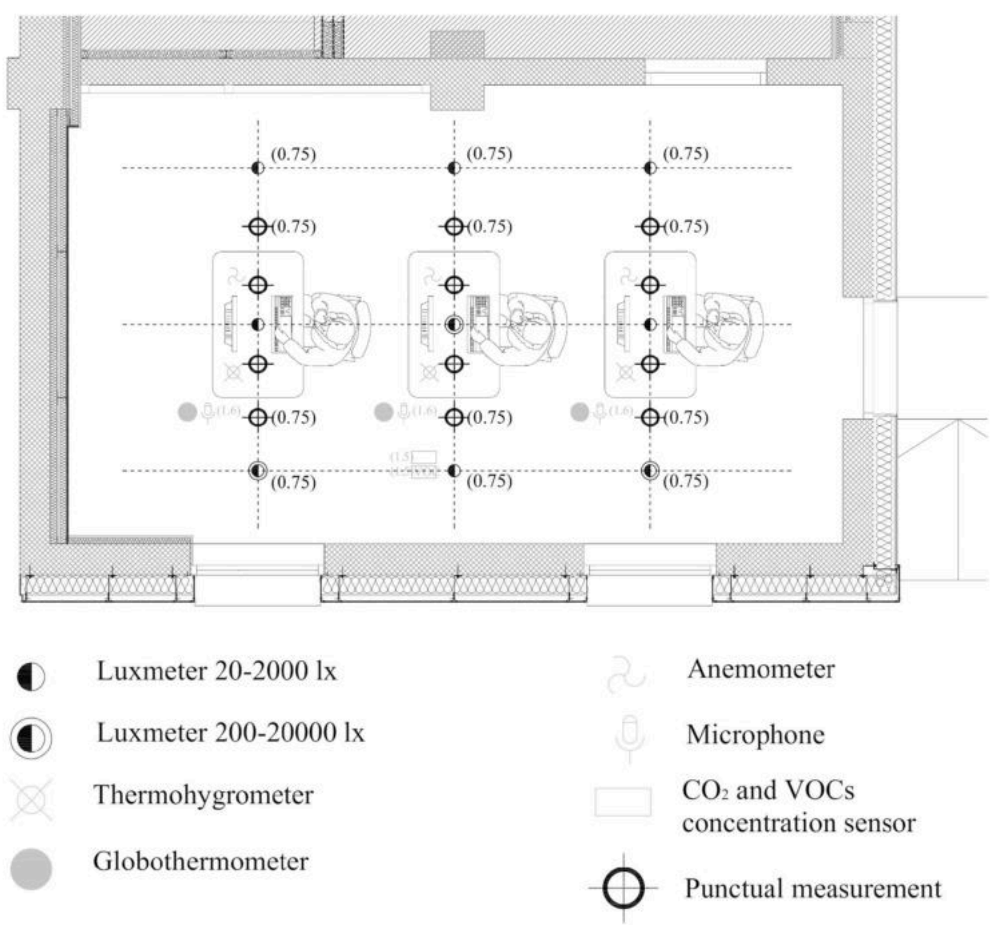


Fig. 4. Visual Monitoring asset.

- calculation, based on measured data, of the visual comfort indicators regarding the level of illuminance, the glare and the circadian rhythm.
- analysis of the user's perception of lighting through the colour perception test and questionnaires;
- correlation analysis between measured data and subjective perception;
- visual performances comparison of lighting systems.

2.5.1. *Illuminance*

Illuminance (E) is the physical quantity that describes the amount of light in a specific point of a given surface; a good level of visibility may be ensured by an adequate value of illuminance to accomplish a task [21]. The illuminance level and its distribution on the task and surrounding area were monitored in accordance to EN 12464 [24] to verify the visual comfort and the possibility to carry out the visual task. In particular, illuminance target and uniformity are verified. The illuminance uniformity factor, U_0, expresses the ratio between the minimum, E_{min}, and mean, E_m, illuminance values of a surface. The measurements in Table 3 are carried out and the limits for office activity are verified for each task area.

2.5.2. *Glare aspects*

Glare is the visual discomfort produced by an unsuitable range or distribution of high luminance or to extreme contrast in luminance. According to the European technical Standards ([24,25]), UGR – Unified Glare Rating is the reference indicator for the assessment of glare in spaces with artificial lighting sources, while, for daylighting, the DGP – Daylighting Glare Probability [26] is the reference indicator for glare assessment due to the light entering from the windows and skylight. In accordance with EN 12665 [27], glare can be caused by extreme contrasts and it can be calculated with the Contrast Ratio (CR) between the luminance of an object and the background.

The considered glare indicators are detailed in Table 4, reporting also the glare indicator/performance scale according to UNI 11665 for UGR [25], to EN 17037 for DGP [26] and to Refs. [28,29] for CR.

Table 4
Considered glare indicators details.

Indicator	Formula	Parameters description	Glare indicator/ perception scale
UGR		L_b = background luminance [cd/m^2]; L_s = glare source luminance in the direction of the observer's eye [cd/m^2]; ω = glare source surface – axis of sight solid angle [sr]; p = Guth position index.	10 - Imperceptible 13 - Just perceptible 16 – Perceptible 19 - Just acceptable 22 - Unacceptable 25 - Just uncomfortable 28 - Uncomfortable
DGP		E_v = vertical illuminance at the eye of the observer [lx]; L_{si} = glare source luminance [cd/m^2]; P = position index; ω_{si} = solid angle subtended by the glare source I [sr]; $c_1 = 5.87 \cdot 10^{-5}$; $c_2 = 9.18 \cdot 10^{-2}$; $a_1 = 1.87$; $c_3 = 0.16$.	≤0.35 - mostly not-perceived 0.35 ≤ 0.40 - perceived but mostly not-disturbing 0.40 ≤ 0.45 - perceived and often disturbing >0.45 - perceived and often intolerable
CR		L_s = luminance of the investigated area [cd/m^2]; L_b = background luminance [cd/m^2].	0.33 ≤ CR ≤ 3.00 - comfortable

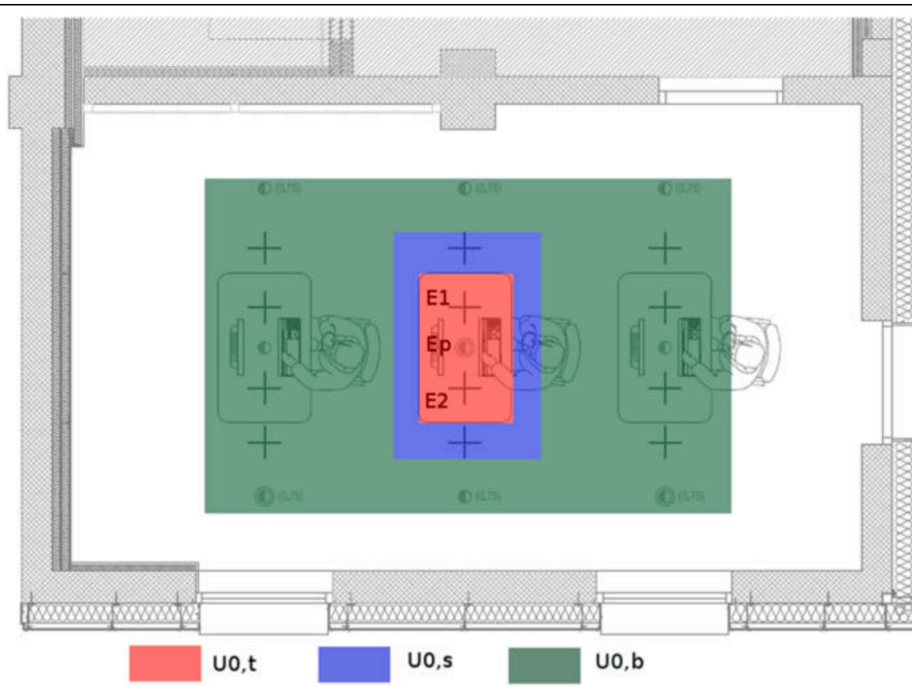
The previous glare indicators are calculated on the basis of the HDR images collected by the video photometer, then processed with the LMK Labsoft software [30]. E_v is measured with a portable Illuminance meter.
Glare source pixels are identified when their luminance value exceeds 4 times the reference luminance value (L_{ref}). L_{ref} alternatively refers to the average fisheye field of view luminance and to the average task area luminance.

2.5.3. *Circadian rhythm*

Natural and artificial lighting (depending on spectrum output) has other effects on human physiology and behaviour: for example, blue light affects the circadian rhythm ([31,32]) and, as a consequence, the nocturnal secretion of melatonin [17]. To evaluate the impact of light sources on melatonin production, the Circadian Stimulus (CS) parameter is used to measure the efficiency of the spectral irradiance to the cornea.

Table 3
Indicators and limits verified and graphical explanation (Example of the measure area in P_M in Configuration O_W).

Indicator	*Definition*	*Limit*
Ep	Punctual illuminance in the middle of the desk	500 lx
Em,t	Mean illuminance of the task area calculated as the mean of 3 values: $E_{m,t} = (Ep + E1 + E2)/3$	500 lx
$U_{0,t}$	Uniformity of the task area, calculated as the ratio between the minimum and the mean illuminance of the task area. $U_{0,t} = E_{min,t}/E_{m,t}$,	0.60
$U_{0,s}$	Uniformity in the immediate surrounding area, considering a band of at least 0.5 m and calculated as the ratio between the minimum illuminance of the task area and the mean illuminance of the surrounding area. $U_{0,s} = E_{min,t}/E_{m,s}$	0.40
$U_{0,b}$	Uniformity of the background area, considering a band of at least 3 m and within the limit of the space and calculated as the ratio between the minimum illuminance of the task area and the mean illuminance of the room. $U_{0,b} = E_{min,t}/E_{m,b}$	0.10



It varies between 0.1 and 0.7, where the former value is the minimum circadian stimulus threshold, while the latter is the saturation level. Conventionally, a value equal to or greater than 0.3 is considered optimal [33]. The offline version of the Lighting Research Center's CS Calculator Web tool [34] was used to evaluate this indicator, using the measured vertical illuminance to the eye of the observer and the spectral profile of the light sources. The default value of 0.5 of the Macular Pigment Optical Density (MPOD) was used.

2.5.4. Questionnaires

During their stay in the testing facility participants have completed 4 different questionnaires, as explained in Table 5.

Questions related to Q3 and Q4 are formulated in accordance with EN ISO 10551 Annex C [35], with a bipolar or unipolar scale. About Q3 (Table 6), in question 1, the lighting level is defined by a perception scale (7-point bipolar scale). Question 2 and 3 are about the glare based on a tolerance scale (5-point one-pole scale). Question 4 is built on the working appraisal based on a tolerance scale (5-point one-pole scale). In question 5, the colour perception of the working station is defined by a perception scale (7-point bipolar scale). Finally, question 6 is an open-ended question about the mood.

Q4 has the same questions of Q3 plus some others. In particular, in question 7 the visual well-being is defined by a perception scale (5-point one-pole scale). In question 8, the compilation of the colour test is defined by a tolerance scale (5-point one-pole scale), as in Table 7. Questions 9 and 10 were useful to understand the main cause of discomfort and the most important feature the users would like to change.

2.5.5. Colour perception

An interrelation between luminance and colour perception can be observed: Bezold and Brücke independently discovered that a variation in luminance can alter the tone, thus changing its colour appearance (Bezold–Brucke (B–B) hue-shift) [36]. The perception of colours is, in parallel with illuminance and glare, an important element in determining visual comfort. For the purposes of visual comfort, light sources, particularly artificial light sources, must illuminate objects and surfaces in such a way as to alter their original colours as little as possible.

During this experimentation, the Farnsworth-Munsell 100 Hue Colour Vision Test - FM 100 test [37] was carried out to verify the users colour perception with different lighting sources. Users had to execute the test at the end of every testing session, during the morning and the afternoon, in 5 min. At the same time, in the questionnaire, the users had to express a preference about the colour perception.

Table 5
Questionnaire type and schedule.

	Type of questionnaire	Data collected	Timing
Q1	**General user data**	age, gender, colour of the eyes, any visual problems, information about working habits (such as the kind of light they prefer to work with, natural, artificial or a combination of them)	Once at the beginning of the monitoring campaign
Q2	**User initial conditions**	quality and number of hours slept the previous night, type of clothing worn	At the beginning of each daily session
Q3	**Hourly questionnaire**	14 questions about IEQ (acoustic, lighting, IAQ – Indoor Air Quality, temperature etc.) of which 4 about visual quality: brightness, glare and colour perception, and 1 about the mood	At the end of each working hour
Q4	**Ambient quality questionnaire**	12 questions about the global well-being during the whole session: 4 questions about the light quality (brightness, colour, global visual well-being and difficulty to complete the "Farnsworth – Munsell colourtest") and the remaining questions about the appraisal of working conditions, the appraisal of the environment and the main cause of discomfort if any and, in this case, the change needed	At the end of each daily working session

Table 6
Q3 Hourly questionnaire – Lighting questions.

During the last hour, the light was:						
Too bright	Bright	Slightly bright	Neutral	Slightly dark	Dark	Too dark
−3	−2	−1	0	1	2	3
During the last working hour, how did you perceive the glare from frontal/right/left/top/bottom direction?						
During the last working hour, how did you perceive the glare from desk/screen/ceiling/floor/windows elements?						
Perfectly tolerable	Slightly difficult to tolerate	Fairy difficult to tolerate	Very difficult to tolerate	Intolerable		
1	2	3	4	5		
During the last hour, your working activity was:						
Perfectly tolerable	Slightly difficult to tolerate	Fairy difficult to tolerate	Very difficult to tolerate	Intolerable		
1	2	3	4	5		
During the last hour, the colour of your working station was:						
Too cold	Cold	Slightly cold	Neutral	Slightly warm	Warm	Too warm
−3	−2	−1	0	1	2	3
During the last working hour, how did you feel						
During the last working hour, how did you feel?						

3. Results

3.1. Monitoring-based data analysis

3.1.1. Illuminance level distribution

Analysing the recorded DL values of illuminance, DL-O_W and DL-O_D show a similar trend with a very high maximum level of E_p (around 1600 lx) during the morning, specifically in P_D and P_W that are in front of the windows (Fig. 5-a). $E_{m,t}$ and E_m remain above the limit threshold of 500 lx (Fig. 5-b) but a low uniformity of $U_{0,t}$ and $U_{0,s}$ is still highlighted, specifically in P_D and $P_{W,}$ because the direct solar radiation entering the room causes very sunny zones and darker ones on the desks (Fig. 5-*c*-d). Regarding DL-O_F (Fig. 6), once again, there is no uniformity on the desk area due to the screen shadow: in some days $U_{0,t,PD}$ and $U_{0,t,PW}$ are always below the threshold value (0.6).

With AS, in all the three configurations there is a very low uniformity in the room because P_D and P_W are the darkest positions both in terms of Ep and in terms of Em (about 200 lx), while P_M is the brightest one, with monitored illuminance values of one order of magnitude higher. The difference between the configurations is that in AS-O_F and AS-O_D, the uniformity on the desk area is equal to 1 (uniformly bright in P_M and uniformly dark in P_D and P_W) while in AS-O_W there is a low uniformity in P_M because of the screen shading. The trend of the illuminance value recorded by the different sensors is shown in Fig. 7.

3.1.2. Glare and contrast

Glare is assessed using DGP for DL, UGR for LED and both of them for AS, as illustrated in Table 8. Maximum (max), minimum (min) and

Table 7
Q4 Ambient quality questionnaire – Lighting questions.

How do you evaluate the visual well-being as a whole?				
Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable	Much uncomfortable
1	2	3	4	5
How do you consider the compilation of the colour test?				
Perfectly tolerable	Slightly difficult to tolerate	Fairy difficult to tolerate	Very difficult to tolerate	Intolerable
1	2	3	4	5
What was the major cause of discomfort?				
Which of the following features would you have liked to change?				

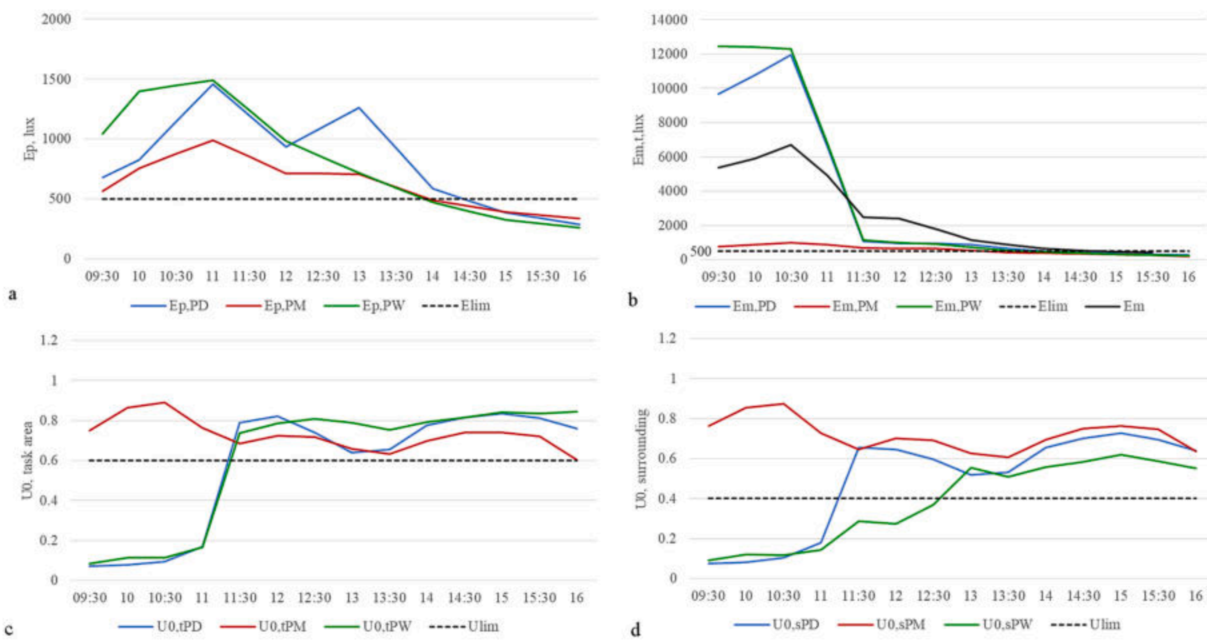


Fig. 5. DL- O_W illuminance and uniformity trend – 22nd of March.

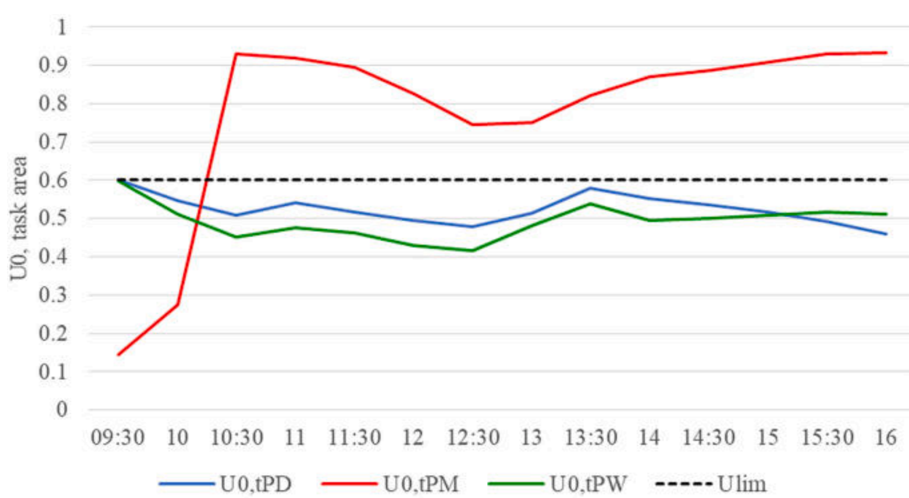


Fig. 6. DL-O_F illuminance and uniformity trend – 18th of April.

averaged values of each position in the 3 different configurations are listed for DL. For AS and LED, there are not the maximum, minimum and average columns cause they are artificial systems and the output is a constant value that varies only for each position and configuration.

As reported in Table 8, with DL, in all the three configurations, the DGP values are most of the time below the glare perception threshold (0.35). In particular, DL-P_M generally shows the lowest DGP values, quite below the previous threshold, in all the configurations. Only DL-P_D and DL-P_W show glare effects in the early period of the monitoring session (9.30–10.30 a.m.), with direct sunlight entering the room. The highest values are recorded in DL–OF–P_W and P_D, when light is frontal. As a result, only 3% of cases shows glare effects. For AS, DGP values are very low, always below 0.2, therefore very far from the threshold value; the UGR values exceed the threshold only in AS-O_W with one value

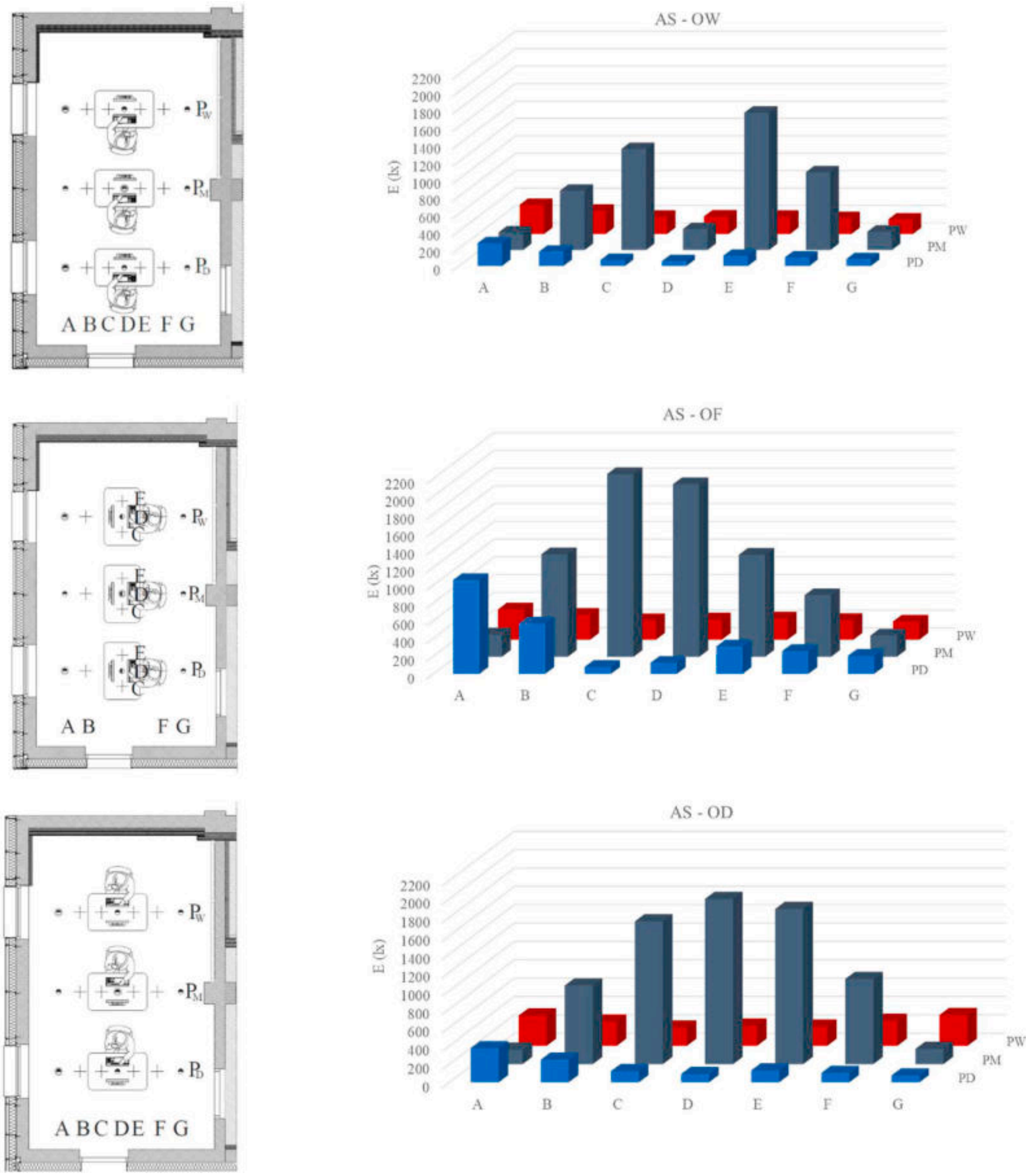


Fig. 7. AS: Illuminance distribution With LED-O_W (Fig. 8), the illuminance distribution is uniform with a range of 400–500 lx over all the reference surfaces.

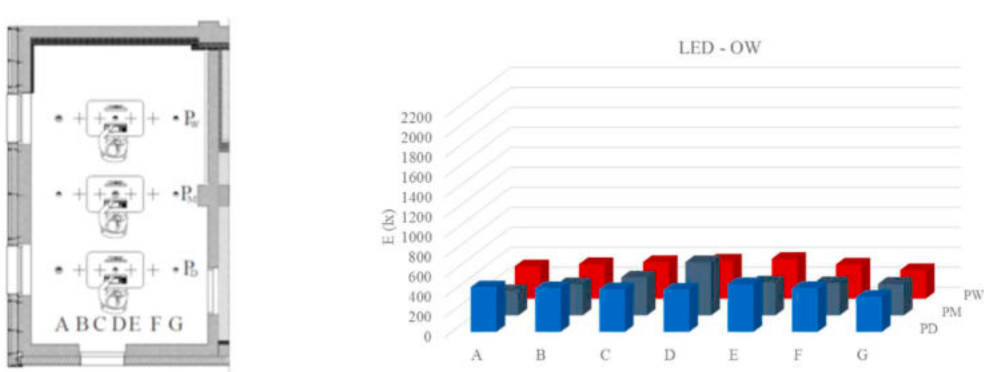


Fig. 8. LED: Illuminance distribution.

higher than "13-Just perceptible" (13.64 in AS-O_W-P_D) and one value higher than "16-Perceptible" (16.13, the highest one, in AS-O_W-P_M): all the others values are below 13 and in AS-O_F and AS-O_D no glare is perceived. So with AS, glare is perceived for front light. LEDs respect the limits with the highest value equal to 9.35, so neither the 10-imperceptible threshold is recorded.

Table 8
DGP and UGR values for the considered lighting scenarios – In bold type the values higher than the threshold value.

	DGP				UGR	
	DL			AS	AS	LED
	max	min	*avg*			
Ow						
PD	0.364	0.175	*0.229*	0.189	**13.64**	7.50
PM	0.228	0.184	*0.207*	0.190	**16.13**	6.08
PW	0.339	0.175	*0.230*	0.174	6.36	3.35
OF						
PD	0.405	0.222	*0.279*	0.181	7.16	2.39
PM	0.263	0.195	*0.239*	0.189	11.01	1.26
PW	0.503	0.216	*0.287*	0.172	6.23	9.27
OD						
PD	0.292	0.174	*0.200*	0.190	11.97	1.37
PM	0.203	0.173	*0.186*	0.189	10.52	9.35
PW	0.292	0.177	*0.205*	0.170	6.80	6.19

CR assessment results are illustrated in Fig. 9. Lighting pattern cases are grouped in relation to the geometry of the incident light with respect to the position of the user (in relation to DL, CR is calculated for the highest DGP value recorded for the considered configuration and workstation):

a. Front lighting: light rays come principally from in front of the user (cases DL-O_F-P_D/P_W and AS-O_W-P_M);
b. Side lighting: light rays come principally from the left or from the right of the user (DL-O_W-P_D/P_W and AS-O_F-P_M);
c. Rear lighting: light rays come principally from behind the user (DL-O_D-P_W/P_D and AS-O_D-P_M)
d. Zenithal lighting: light rays come principally from above (LED-O_W-P_W/P_M/P_D and AS-O_W/O_F/O_D-P_W).

The Field of View (FoV) is subdivided in five sector: frontal, right, left, top and bottom, based on the setting of the beginning of the peripheral vision zone considering a virtual cone with a 60° aperture angle aligned with the fisheye image centre considered as the central zone [38] (Fig. 10).

The most critical CR values for DL and AS are due to front or rear lighting (Fig. 9 a) and c)): with AS 30% of CR values exceed the threshold, with DL 55% of CR values are too high or too low. In the front lighting, glare is perceived from the windows or from the desk in DL. For AS, the Zenithal light (Fig. 9 d)) is critical too, with 44% of the cases with CR values too high with respect to the threshold value. Zenithal lighting gives always optimal CR values for LED. Side light incidence (Fig. 9 b)) always ensures good CR values.

3.1.3. Circadian rhythm

In relation to the characteristics of the lighting system, during DL monitoring, the CS value is variable (Fig. 11) while AS and LED provide a constant illuminance level and CS value (Table 9).

Analyzing DL, the maximum CS value is always near the saturation value (0.7) with a peak around 10:30 a.m. and then decrease but keeping a value above 0.3 in 95% of the cases. The lowest values are recorded in DL-O_W and DL-O_D in P_M and P_D: observing the graphs in Fig. 11, it can be observed that in DL-O_W the values are below 0.3 only after 14:30, while in DL-O_D the trend is different due the presence of a partially cloudy weather instead of a clear sunny weather recorded in the DL-O_W and DL-O_F configurations. On the contrary, with LED, the 0.3 threshold is never reached. AS stands in a middle way of previous scenarios: in the AS-O_W and AS-O_F, CS is higher than 0.3 in P_w and P_M, while it is always lower in P_D. In AS-O_D, that is with AS behind the field of view, the CS is never reached at any workstation.

3.2. Questionnaire-based data analysis

3.2.1. Hourly-based user feedbacks (Q3 questionnaire)

During DL tests, the three configurations confirm the data monitored: the users perceive the desk to be properly illuminated for more than 50% of the time in all the workstations. The users in DL-P_D and DL-P_W have an excessive bright perception during the morning (9:30–11:30), especially in DL-O_F when the gaze of the user is towards the windows. On the contrary, in DL-O_F-P_M there is a higher perception of right illuminance with respect to DL-O_W-P_M. For each lighting system, the graphs of Figs. 12–14 show the correlation between the lighting perception vote and the mean measured hourly lighting value. The score is averaged across the three configurations (O_W, O_F and O_D).

With DL, neutral perception increases from almost 50% in DL-P_D to almost 80% in DL-P_W. Perception is neutral even if the illuminance level is below or higher than 300–500 lx. With the artificial systems, the illuminance level is obviously constant but there is a difference between AS and LED. Within AS, a too dark lighting level is confirmed in AS-P_D, a

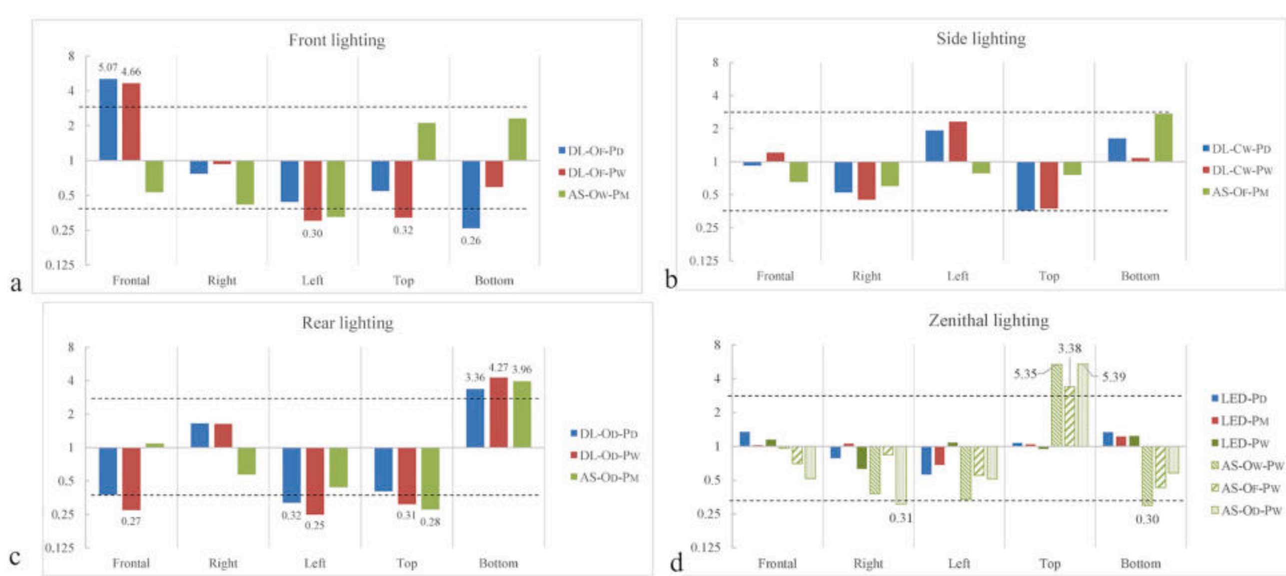


Fig. 9. CR assessment for different light incidence on workplaces: a) – Front, b) – Side, c) – Rear, d) – zenithal. Figure a), b) and c) do not consider LED, figure d) does not consider DL.

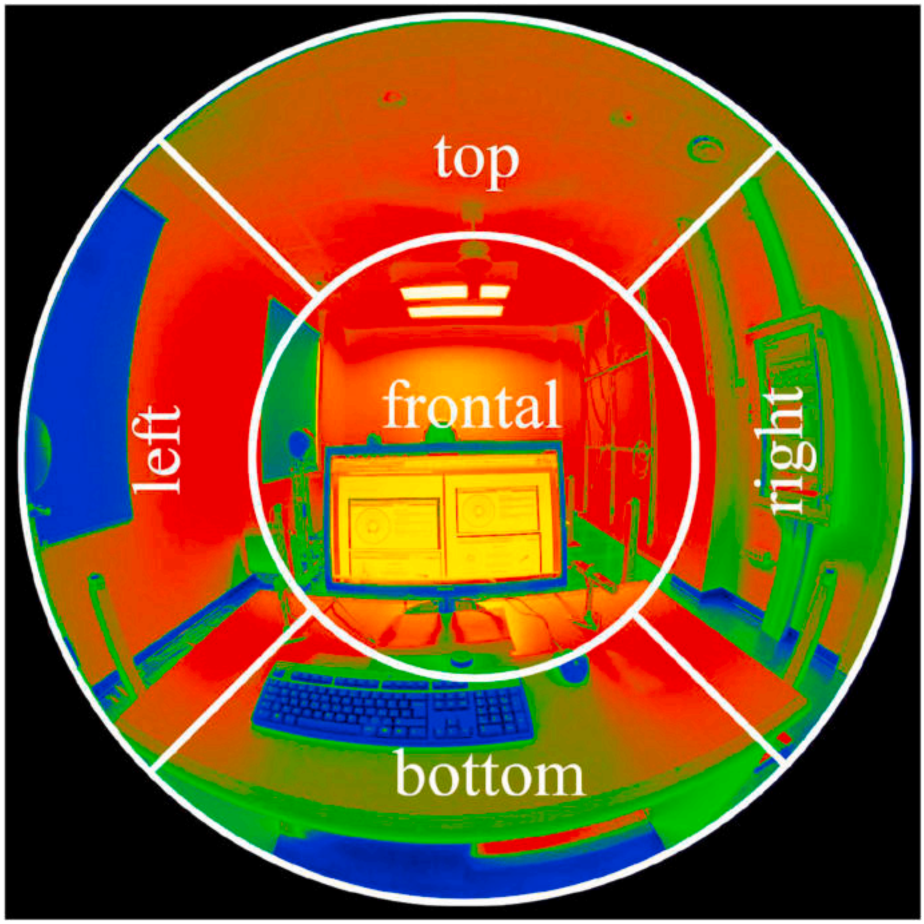


Fig. 10. Overlay of FoV subdivision on a false colour luminance image captured with the 180° fisheye lens. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

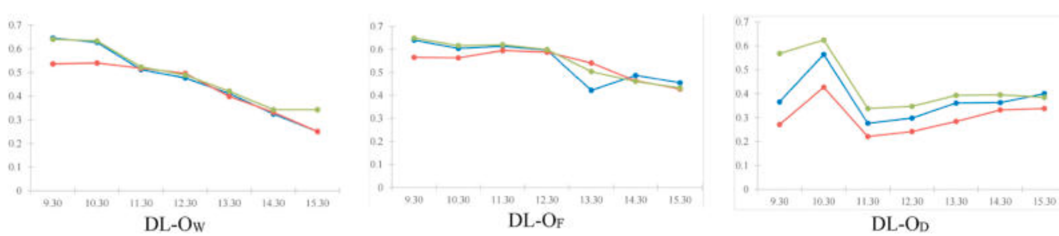


Fig. 11. Hourly mean CS values for DL for the three different configurations. Values are reported in blue for P_D, in red for P_M, and in green for P_W. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 9
Circadian Stimulus value for AS and LED (in bold type values below the reference CS value of 0.3).

	DL			AS	LED
	max	min	avg		
O_W					
P_D	0.645	**0.251**	0.500	**0.135**	**0.169**
P_M	0.544	**0.251**	0.461	0.303	**0.126**
P_W	0.640	0.343	0.518	0.407	**0.167**
O_F					
P_D	0.659	0.421	0.565	**0.178**	**0.206**
P_M	0.595	0.427	0.543	0.415	**0.155**
P_W	0.674	0.431	0.575	0.326	**0.199**
O_D					
P_D	0.639	**0.276**	0.431	**0.150**	**0.213**
P_M	0.558	**0.221**	0.372	**0.194**	**0.165**
P_W	0.636	0.338	0.484	**0.280**	**0.187**

too high lighting level is confirmed in AS-P_M and an almost acceptable level is illustrated in AS-P_W. It is highlighted that the trend is toward 1 ("slightly bright") in AS-P_D, even if the illuminance is equal to 0–199 lx, while in AS-P_M and AS-P_W the perception corresponds to the illuminance recorded: bright in AS-P_M and neutral in AS-P_W.

Within LED, illuminance levels are evenly spread across the room and the reference class is always 300–499 lx: except for LED-P_W with a neutral perception, in LED- P_M and P_D the trend is towards bright or too bright.

In relation to user feedback, a global glare perception score for each lighting system is considered. The vote is calculated by averaging, for each hour and for each user, the score assigned to each viewing direction (Fig. 15).

Comparing the lighting systems, the mean highest vote is in AS-O_W-P_M. Analysing the different lighting systems separately, the highest glare perceptions are reached in DL-O_F-P_D, AS-O_W-P_M and LED-O_W-P_D, all

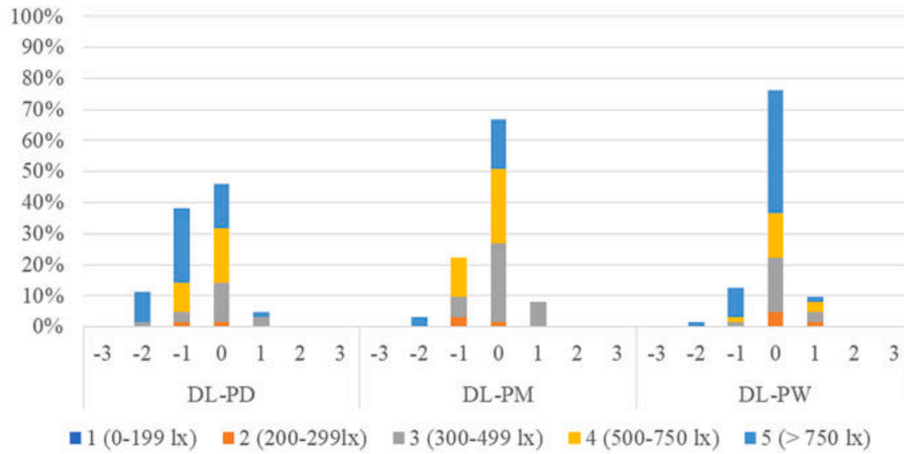


Fig. 12. Correlation between user perception of brightness and data monitored with DL.

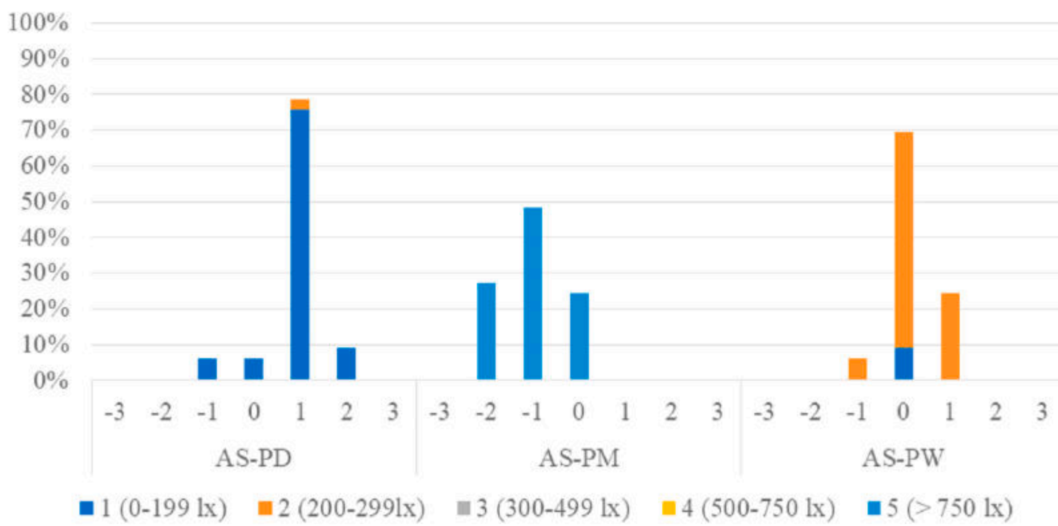


Fig. 13. Correlation between user perception of brightness and data monitored with AS.

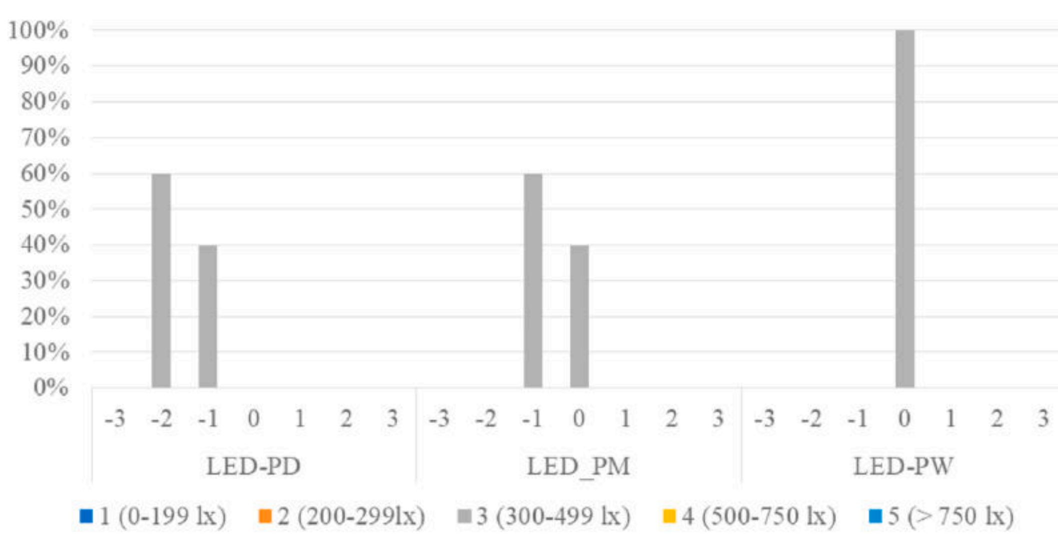


Fig. 14. Correlation between user perception of brightness (votes) and data monitored with LED.

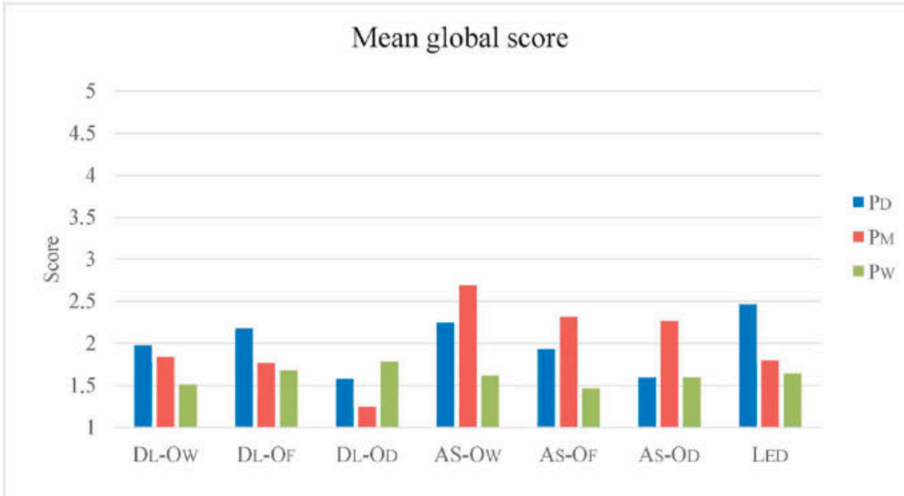


Fig. 15. Global glare perception vote, from 1 = perfectly tolerable to 5 = Intolerable.

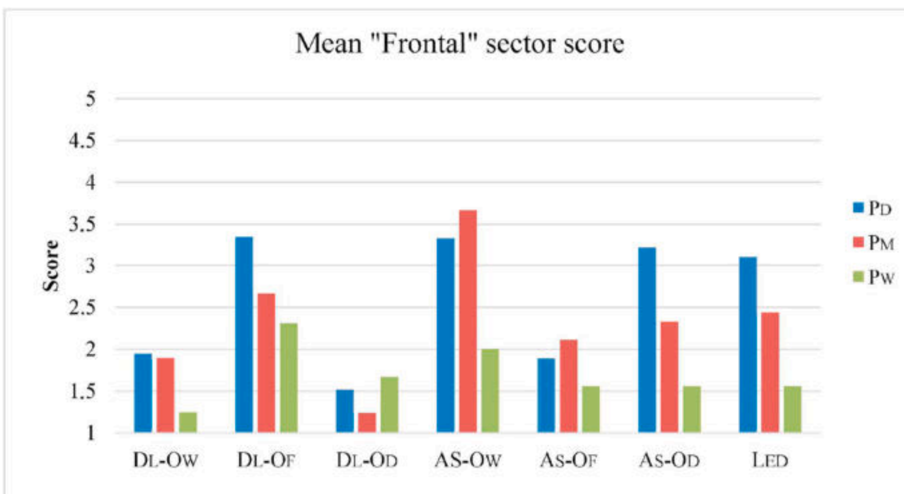


Fig. 16. "Frontal" field of view area glare perception score, from 1 = Perfectly tolerable to 5 = Intolerable.

situations where light is coming frontally with respect to the user. Analysing the "frontal" sector score, the highest values are recorded (Fig. 16): AS-P_M reaches a value higher than 3.5 and, on the whole, the P_D working desk results to be the most unfavourable with all the lighting systems showing values higher than 3 in DL-O_F, AS-O_W, AS-O_D and LED.

About the hourly work hardship (Fig. 17), with DL, for all the 3 configurations, the mean vote is between 2 in DL-O_D-P_W and 3.2 in DL-O_F-P_D but the highest standard deviation is recorded in DL- O_W-P_D (dv.st. 1.29): due to the large variation of the luminous values during the day, working conditions are perceived as very hard to tolerate or intolerable during the morning but tolerable during the afternoon. With AS, the difference is perceived for (the) workstation and AS-P_W is more comfortable in all the configurations. With LED, the perception is similar in all the workstations and the votes are concentrated between 2 and 3.5

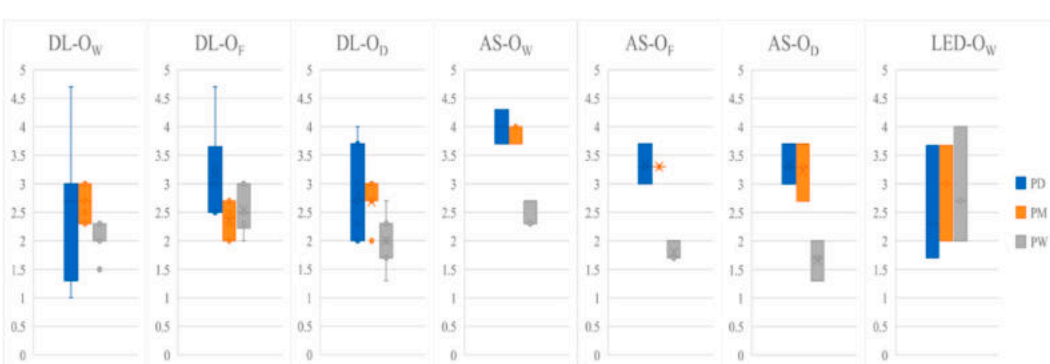


Fig. 17. Hourly work hardship, from 1 = Perfectly tolerable to 5 = Intolerable.

in the most of cases.

The analysis of hourly responses about mood does not give peculiar results in relation to the lighting scenario. Indeed, most of the answers are "relaxed" for each considered scenario.

The analysis of hourly colour perception feedback (Fig. 18) is performed considering the peculiar colour features of lighting scenarios. DL colour changes over the day so morning and afternoon feedbacks are treated separately. LED and DL light sources are chromatically and evenly spread across the test room (black and white coloured) so the workstation position is not considered as a variable. On the basis of the above, DL colour is mostly perceived as neutral both in the morning and in the afternoon (45%), while the second frequent perception is warmer in the morning and colder in the afternoon. LED colour perception is essentially slightly warm (70%), confirming the nominal CCT values of the lamps (4000 K). On the contrary, AS colour perception is more sensitive to the workstation position because the device emits light both at 3800 K (direct beam light) and at 30,000 K (diffuse "sky" light). The subjective feedback analysis confirms the previous concept. In the AS-P_M workstation, characterized by direct lighting, the most frequent perception is "slightly warm" (48%) and no "cold" perception is detected, while in the AS-P_W workstation, under diffuse light the "slightly cold" perception is the most frequent (52%) and neither "slightly warm" and "warm" feedbacks are provided. The AS-P_D workstation perception wavers halfway between the previous ones.

3.2.2. Session-based users' feedback (Q4 questionnaire)

The main results of the "Q4-Evaluation of the ambient quality" filled at the end of each session are summarized in Table 10.

According to the analysis of the work hardship, which confirms the trend of the hourly analysis, DL-P_D is perceived as "fairly difficult to tolerate" and the trend in DL-P_M and P_W is toward "slightly difficult to tolerate". AS-P_W is perceived as "slightly difficult to tolerate" while AS-P_D and P_M exceed "fairly difficult to tolerate". LED-P_D is perceived as "very difficult to tolerate" while LED-P_M and P_W are between "slightly and fairly difficult to tolerate". The visual well-being is perceived as uncomfortable with all the lighting systems: LED-P_D shows the highest value, almost "very uncomfortable", while AS-P_W and LED-P_W shows the lowest one. AS-P_D and P_M values are greater than 4. The most uniform perception is recorded with DL, with values around 3, in all working stations.

In Table 10 the major cause of discomfort is "None" with DL, followed by noise, "noise" with AS and "glare" with LED. A more uniform light, as LED, permits to identify other discomfort causes: the major cause of discomfort "None" is 12% with LED while it is equal or more than 30% with DL and AS. It is important to highlight that the participants knew that it was an experiment about lighting quality and this could have influenced their answers.

AS mean values gives better results than LED about lighting levels, colour perception and visual well-being. On the contrary, LED gives better results than AS in relation to work hardship. However it must be underline while LED lighting conditions are uniform within the room, with AS this is not true. In particular the P_D performances are the worst within AS for each of the considered aspects (the result was predictable since the workstation, the farthest from AS modules, receive only the reflected light from room surfaces) and confirm that AS mean performances of "useable" workstations (P_M and P_W) are clearly better than LED.

The second session-based user response regards the testing of colour perception, provided by the FM-100 test. There are two relevant test results: the absolute error and the Main Colour Confusion Area (MCCA).

The absolute error is defined by the mean Total Error Score (TES): the higher the TES value, the higher the colour sequencing error. Generally, a TES value equal to or below 40 means an absence of colour vision deficiency.

Scenarios mean measured TES are 43.5 (±23.5) for DL, 42.4 (±19.8) for AS and 30.5 (±12.6) for LED, respectively. Despite the low values, they denote how LED allows a slightly better colour perception with respect to DL and AS. In particular, while in LED the 71% of TES values are below 40, in DL and AS, the ratio drops to 57% and to 52%, respectively.

The MCCA identifies where, throughout the colour range, the user have the greatest difficulties in distinguishing colours: in this case, MCCA is the hue colour sector of the Colour Vision Deficiency Type diagram showing the highest error. The reference colour hue sectors are: R-RP (red to red/purple), RP-P (red/purple to purple), P-PB (purple-purple/blue), PB-B (purple/blue-blue), B-BG (blue-blue/green), BG-G (blue/green-green), G-GY (green-green/yellow), GY-Y (green/yellow-yellow), Y-YR (yellow-yellow/red) and YR-R (yellow/red-red).

Fig. 19 shows the MCCA for each lighting system. DL results are grouped in "Morning" and "Afternoon" in order to take into account the sky colour temperature variation during the day.

4. Discussion

The first main goal of this research is the characterization of the AS with respect to DL and LED, by analysing and comparing objective indicators and subjective analyses. About the illuminance level, the analysis of the monitored data shows non-uniform light zones in AS, like DL. With DL, the low uniformity depends on the hour of the day and varies during the day in the same workstation; with AS, it depends on the orientation of the lighting system and it is fixed for specific workstations. With LED, light is uniformly distributed.

Analysing the correlation between monitored data and users' perceptions with DL, the room is perceived well illuminated, which corresponds to the illuminance level recorded that nearly exceeds 300 lx; too high illuminance levels monitored during the morning are confirmed by the −1 and −2 users' votes. With AS, users' preferences confirm the non-uniformity of the lighting distribution, with a AS-P_D perceived as too dark, AS-P_M as too bright and AS-P_W as the most neutral working station. With LED, there is a discrepancy between monitored data and user perception: while the monitored illuminance levels are in the optimal range of 300–500 lx, users perceived the room as "too bright".

Focusing on glare aspects, with DL and AS, nearly all the DGP indicators measured are below the threshold value (0.35) and the main

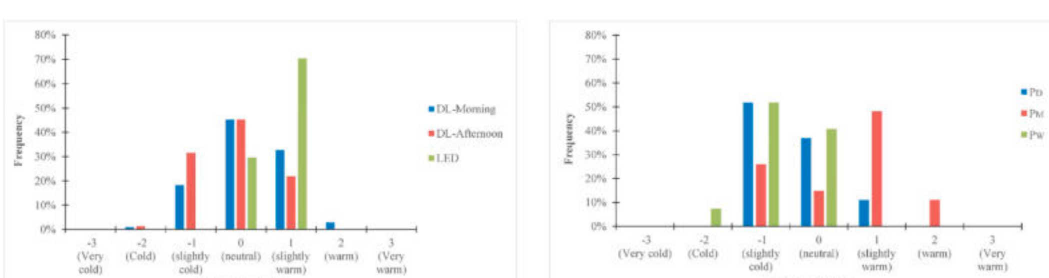


Fig. 18. Colour perception feedback analysis: DL and LED scenario (left), AS scenario (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 10
Q4-Evaluation of the ambient quality questionnaire results.

		Room lighting level (−3 = too bright, 3 = too dark)	Colour (−3 = too cold, 3 = too warm)	Work hardship (1 = perfectly tolerable, 5 = intolerable)	Visual well-being (1 = comfortable, 5 = much uncomfortable)	Major cause of discomfort
DL	**Mean**	|0.31|	|0.14|	2.75	2.92	33% None
	P_D	−0.71	−0.06	3	3.29	22% Noise
	P_M	−0.24	−0.06	2.88	2.94	20% Glare
	P_W	0.00	0.29	2.35	2.53	12% Air quality
						10% Air Temp.
						2% Relative Humidity
AS	**Mean**	|0.71|	|0.65|	3.04	3.57	35% Noise
	P_D	1.00	−0.75	3.50	4.38	30% Glare
	P_M	−1.00	0.57	3.71	4.14	30% None
	P_W	0.13	−0.63	2.00	2.25	4% Air quality
						0% Air Temp.
						0% Relative Humidity
LED	**Mean**	|0.89|	|0.78|	2.89	3.78	35% Glare
	P_D	−1.67	0.67	4.00	4.67	24% Noise
	P_M	−0.67	0.67	2.67	3.67	12% Air Temp.
	P_W	−0.33	1.00	2.00	3.00	12% None
						12% Relative Humidity
						5% Air quality

Analysing the room lighting level and colour, DL is perceived as the most neutral lighting system in all the working stations, with values between −1 and 0. With AS, AS-P_W is the more neutral working station, while AS-P_D and P_M are perceived as "slightly dark/slightly warm" and "slightly bright/slightly cold", respectively. With the LED system, all the workstations show a cold light perception with P_D showing the coolest light perception.

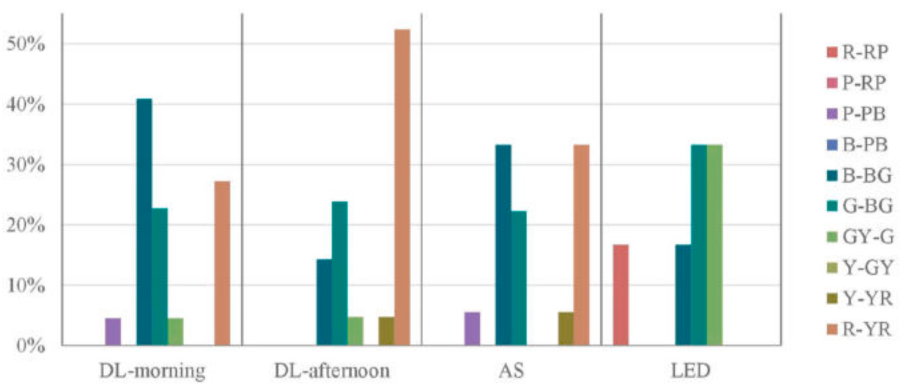


Fig. 19. MCCA results distribution.
Observing the graph, B-BG and BG-G are the most critical colour hue sectors. Focusing on specific scenarios, DL-Afternoon shows errors related to warmer hues (Y-YR, YR-R) with respect to DL-Morning. With LED, most of the errors are green-related (B-BG, BG-G, G-GY), while AS shows an error distribution similar to DL-Morning.

glare scores expressed by the users in the questionnaires are "1-Perfectly tolerable" or "2-Slightly difficult to tolerate". Glare is measured with front light source as to the field of view, both for DL and AS; for DL, however, glare is perceived also in P_M, therefore not only in workstations located in front of the windows. In Table 11 and Table 12 for DL and AS scenarios, respectively, the "2-Slightly difficult to tolerate" scores are grouped within "1-Perfectly tolerable" in order to have comparable 4-step glare preferences as for DGP indicators. The results are now more comparable:

- for DL the new "Perfectly tolerable" score is expressed by 85% of users and "Not perceptible" DGP indicator is recorded in 96% of cases;
- for AS the new "Perfectly tolerable" score is expressed by 77% of users and "Not perceptible" DGP indicator is recorded in 100% of cases;

In relation to the previous data, the personal perception score and the DGP classification provide similar results making DGP classification feasible to predict subjective glare sensation. However, DGP values tend to underestimate real glare perception, both in DL and in AS scenarios:

Table 11
User glare score/DGP rating matrix with aggregation of "perfectly tolerable" and "Slightly difficult to tolerate" users perception ratings for DL scenario.

			DGP				
			Mostly not perceptible	Perceptible/Moderate	Disturbing	Intolerable	%
		cases	<0.35	0.35-0.40	0.40-0.45	>0.45	
Glare score	**Perfect and slightly difficult to tolerate**	**<2.5**	132	3	0	1	***84.5%***
	Fairly difficult to tolerate	**2.6–3.5**	23	0	2	0	***15.5%***
	Very difficult to tolerate	**3.6–4.5**	0	0	0	0	***0.0%***
	Intolerable	**>4.5**	0	0	0	0	*0.0%*
	%		*96.3%*	*1.9%*	*1.2%*	*0.6%*	

Table 12
User glare score/DGP rating matrix with aggregation of “Perfectly tolerable” and “Slightly difficult to tolerate” users’ perception ratings for AS scenario.

			DGP				
			Mostly not perceptible	Perceptible/Moderate	Disturbing	Intolerable	%
		cases	<0.35	0.35-0.40	0.40-0.45	>0.45	
Glare score	**Perfectly and slightly difficult to tolerate**	**<2.5**	62	0	0	0	*76.5%*
	Fairly difficult to tolerate	**2.5–3.5**	19	0	0	0	*23.5%*
	Very difficult to tolerate	**3.5–4.5**	0	0	0	0	*0.0%*
	Intolerable	**>4.5**	0	0	0	0	*0.0%*
	%		*100.0%*	*0.0%*	*0.0%*	*0.0%*	

in particular, the lower the DGP value, the more pronounced the difference between measurement and subjective glare perception. This result is consistent with the previous study of Van Den Wymelenberg and Inanici [39].

The comparison of user mean glare score and UGR values for AS and LED (Fig. 20) shows an overall correlation of 0.70. For AS, while DGP was always low with respect to the glare detection threshold (0.35), the UGR was higher than 13 (glare detection threshold) in two situations: AS-O_W-P_M and AS-O_W-P_D. Comparing the output of the monitored data with the questionnaires and considering that the DGP indicator and related scale are validated for higher Ev values than AS, UGR values are more appropriate in describing the glare performance of this lighting system.

Circadian stimulus effects could influence working productivity and, indirectly, work hardship. The comparison of CS values with work hardship responses carried out in this experiment provides consistent results only for DL, which, in the specific case, is the best performing scenario. With AS, the output depends on the working position, with good performance in AS-P_W and P_M and poor performance in AS-P_D. With LED, the threshold value of 0.3 is never reached. However, the circadian stimulus exposure provided by lighting affects the sleep/wake cycle with medium/long term effects that cannot be clearly highlighted based on a single day’s subjective analysis. In addition, work hardship perception is affected by a combination of different variables that are not only related to lighting (temperature, air quality, noise, etc.).

The results of the analysis of the data relating to light colour are partially contradictory. In fact, while the best FM-100 TES values are related to the LED lighting scenario, the best “neutrality” in colour perception is reached in DL. The same comparison demonstrates that AS is the second preferable solution for both analyses. In any case, even the worst FM-100 values (43.4) are very close to the reference value of 40 (“None” colour vision deficiency threshold) and the worst Colour perception score (−0.78) is more neutral than the slightly cool perception value (−1). In this sense, objective indicators and subjective responses provide comparable results.

Focusing on the second main objective of this research, it emerges that a single indicator is not always a proper representation of the visual quality.

In detail, the illuminance level for DL is respected, the color perception is neutral, the DGP is less than 0.35 and the performance on the circadian rhythm is excellent. On the other hand, work hardship is perceived by the users due to the extreme variability of the lighting conditions and the glare problems in the first hours of the morning. It was chosen to leave out the shielding systems for this experiment, with a view to comparing the daylight beam with AS beam, however, the importance of a solar radiation control system has become evident. AS has, in general, a good performance recorded in terms of circadian stimulus, colour rendering and glare, but the output varies considerably with the workstation position and orientation. The main criticality is related to the uniformity of illuminance, essentially due to the tight beam of the light emitted. The performance of objective indicators was partly, though not in all cases, confirmed by the questionnaires: for example, glare is often perceived by the eye of the participants also from a position from where glare is not measured, especially under direct lighting conditions. This suggests that the causes of the discomfort experienced by the participant are mostly due to the non-uniformity of illuminance and luminance of the surfaces that is detected by moving the gaze direction during the activity (while the glare indexes are detected in a static way by directing the fisheye lens of the video-photometer towards the front direction). Therefore, the performance of the AS systems turns out to be very sensitive to the position of the system with respect to the workstation, as demonstrated by Canazei [18].

LED results analysis confirms the discrepancy between data and perception. Even if the best illuminance level (500 lux) and maximum

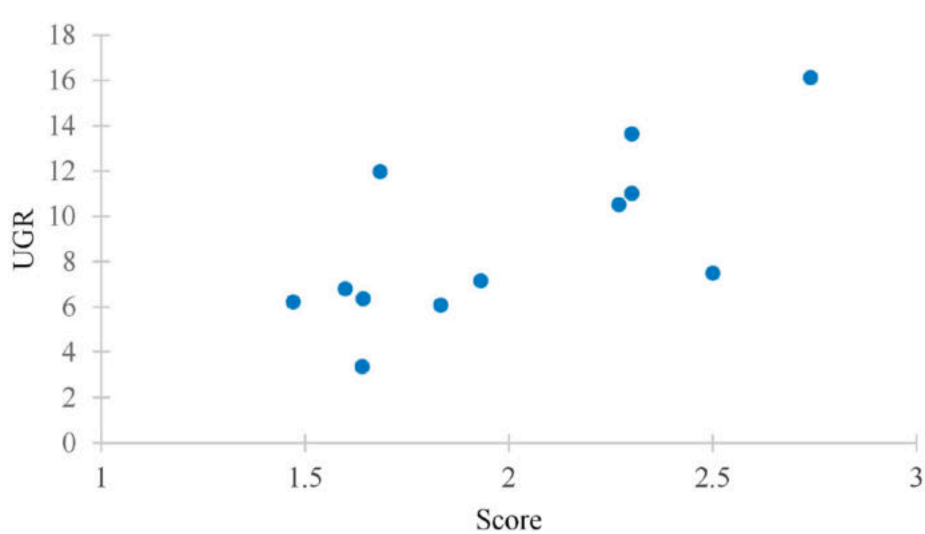


Fig. 20. UGR-Score scatterplot.

uniformity targets are reached, LEDs are perceived by users as the worst system in terms of visual comfort: it is resulted the system with the lowest circadian stimulus (≤0.2, Table 9). This can be related to the CCT equal to 4000 K that could be too low for office activities, as explained in other researches ([40,41]).

As reported in other studies, like [20,42], the need is highlighted for a monitoring protocol for lighting, especially for the assessment of glare [43].

5. Conclusions

This paper describes a monitoring campaign with the aim to compare the lighting performance of an Artificial Skylight respect to daylight and LED and users perception. Different configurations were chosen in order to consider peculiar lighting conditions, testing diffuse or direct beam or frontal or lateral light. Several indicators have been measured and compared with users perception to move a first step toward a definition of a global indicator.

This specific test highlighted that the performances of the artificial skylight share some similarities with daylight solar radiation, such as the good performance of the CS and in colour rendering. In relation to other metrics (illuminance level, glare, contrast, user's perception) the performances are in line with those provided by other considered systems. Given the impossibility of using lighting shielding, it is extremely important to properly orient it and correctly install the right number of systems to optimize lighting and working well-being. AS could be used in an office but, due to its peculiar lighting features, such as tight lighting beam and fixed inclination, the workstation orientation and position have a great impact on visual performance (in particular in glare indicators and subjective perception). P_W, receiving diffuse zenith light, ensures the best lighting performance. As far as measurements are concerned, the most critical issue regards AS glare assessment. Although DGP is designed for natural lighting and AS simulate it, its application on AS shows a lower correlation with subjective glare perception than UGR indicator, so the latter still remains preferable for glare evaluations. On the contrary, using HDR images captured with a fisheye lens allows to better analyse the human field of view and capture the luminance range perceived by the human eye; furthermore, the aggregation of the subjective glare ratings expressed for different FoV sector is a possible way for a coarse prediction of the glare indicator. Another point to investigate in further detail is the study of the main viewing direction and the eye pupil size that could help to make the subjective glare more consistent and better comparable to standard glare rating indicators. The comparison between questionnaires and monitored data highlights that compliance with the regulatory requirements does not always mean visual quality if different indicators are considered separately. A holistic analysis is needed and a dynamic evaluation will better represents the performance of a dynamic system. In order to expand this experience, the phase II of this experiment involves one hundred participants of different age, gender and training who were monitored in P_M and P_W workstations with O_W configuration and artificial skylight as lighting source. The focus was to investigate in depth the lighting (E and UGR/ DGP) and colour perception during a shorter period of stay.

There are several indoor environments where people work in absence or with poor daylight and AS could be a valid solution [44] or as integrated system with natural and artificial lighting. In high efficiency buildings and in particular in Zero Energy Buildings the optimum cooling, heating and lighting energy balance is the result of an holistic approach combining lighting and thermal aspects and the correct design of the transparent building envelope [45]. However, the higher installed lighting power density of AS respect to LED (7.5 W/m^2 vs 4.6 W/m^2) is well balanced by a better lighting quality, as demonstrated by the conducted analysis.

Focusing on the future work, the compliance potential of AS with ZEB requirements should be investigated. In particular a monitoring campaign about the integration of AS with DL could be performed in order to point out optimized dimming control strategies preserving colour rendering and lighting quality as well. Further studies and tests on Artificial Skylight in different configurations and compared with alternative technologies as sunlight tubes should be interesting to investigate and to define design guidelines.

CRediT authorship contribution statement

A. Bellazzi: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **L. Danza:** Supervision, Writing – review & editing. **A. Devitofrancesco:** Conceptualization, Investigation, Writing – review & editing. **M. Ghellere:** Methodology, Investigation, Data curation, Writing – review & editing. **F. Salamone:** Data acquisition and Management, Hardware Setup, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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